CIGRE Green Books
Compact Studies

CIGRE Technical Council

Electricity Supply Systems of the Future

cigre

Springer

CIGRE Green Books

Compact Studies

Series Editor

CIGRE, International Council on Large Electric Systems, Paris, France

CIGRE presents their expertise in compact professional books on electrical power networks. These books are of a self-contained concise character, covering the entire knowledge of the subject within power engineering. The books are created by CIGRE experts within their study committees and are recognized by the engineering community as the top reference books in their fields.

More information about this subseries at http://www.springer.com/series/15383

Nikos Hatziargyriou · Iony Patriota de Siqueira
Editors

Electricity Supply Systems of the Future

cigre

Springer

Editors
Nikos Hatziargyriou
Study Committee C6
National Technical University of Athens
Zografou, Greece

Iony Patriota de Siqueira
Study Committee B5
Tecnix Engineering and Architecture Ltd.
Recife, Brazil

ISSN 2367-2625 ISSN 2367-2633 (electronic)
CIGRE Green Books
ISSN 2509-2812 ISSN 2509-2820 (electronic)
Compact Studies
ISBN 978-3-030-44483-9 ISBN 978-3-030-44484-6 (eBook)
https://doi.org/10.1007/978-3-030-44484-6

© Springer Nature Switzerland AG 2020
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Foreword

The Electrical Power Industry, although seen as a conservative segment of the economy, in fact has been incorporating many innovative solutions at a regular pace into the market.

This CIGRE Green Book is written when we are facing the so-called 4.0 Industry Revolution, which by one possible definition comprises the system to systems approach embracing the integration of physical and digital systems with the addition of main aspects of cyber-physical systems (CPS), the Internet of Things (IoT), Industrial Internet of Things (IIOT), cognitive computing and artificial intelligence. Also, at this time, we seem to be at the edge of a completely new era which will result in a large-scale commercial feasibility use of hydrogen—the Power to Gas (P2G) era.

How the network of the future will be reshaped, what will be partially or dramatically changed, this is the main goal of this set of chapters produced by most talented professionals working in CIGRE.

It is not an easy task to perfectly predict the real trajectories the power industry will follow in 20 or 30 years from now. This is not the aim of this publication.

The 16 chapters elaborated and consolidated here aim at providing possible scenarios and sound elements for the technological, economic, regulatory and market progress of the power industry, under the concept adopted by CIGRE to be a end-to-end (E2E) organization dealing with the entire chain of the power system business.

In terms of range of options in front of us, regarding business arrangements, we might navigate in an energy system that will comprise a combination of a highly connected grid with globalized provision of electricity, as we see in the Internet systems, to a system dominated by loosely connected microgrids, which might be largely self-contained.

This last option, as an extreme is a radical change from the current market structures and risk management and requires the development of completely new settlement at the local grid level with net trading between the local grids. Power backup is a key aspect to be considered which may not turn this a practical approach.

Under all these uncertainties, how can we predict the future role of system planners, design and operators, as well as the incorporation of new materials and devices, testing techniques, computer tools and full digitalization, among others?

On the other hand, the dependence of the societies upon electricity has a unidirectional path, toward having the world fully electrified in the coming years.

This means that the electricity supply and permanent availability will play a fundamental role in the societies, with the same level of importance as drinking water and food.

In that direction, the electric power companies will be more and more demanded for good quality services, as it will be less tolerable staying a lapse of time without electricity service.

The Green Book on the network of the future represents, therefore, a real contribution from CIGRE to the entire community toward predicting possible key aspects of the end-to-end (E2E) electricity chain, in order to prepare ourselves for the challenging scenario the power industry has to deal with.

At the time we complete this version of the Green Book, we acknowledge the relevant contributions from the 16 Study Committee Chairs, as well as our two main Editors Nikos Hatzargyriou and Iony Patriota de Siqueira.

Hope you will enjoy the content of the Book!

Paris, France
Marcio Szechtman
CIGRE Technical Council Chairman

Presentation

As CIGRE enters its second century, the electricity energy market is undergoing changes never before experienced. The trends in technology, markets and devices using electrical energy as the primary source are changing in type and pace. It is often very difficult to make sense of these trends and how they affect your business or environment. CIGRE experts from each of the 16 technical domains have provided the best possible solutions to enable stakeholders to fully understand these trends and developments. The 16 domains include all the components and systems including markets and regulations that comprise the future grid. The reader of this Green Book will obtain a full understanding of the technology drivers as well as the technology trends, thereby having an overall view of the most likely future affecting their environment.

R. Stephen
CIGRE President

Contents

Introduction and Overview

Iony Patriota de Siqueira and Nikos Hatziargyriou

Abstract This chapter summarizes the main developments that are taking place in power systems, as a background to the main chapters of this book. After a brief review of recent developments in smart things and smart homes, as examples of technological changes with social impacts, the chapter presents an overview of the major convergence aspects of the main technologies that contribute to modern power systems. The major sections are dedicated to reviewing the current trends in electrical power systems, telecommunication, information and automation systems, as the main pillars that support the future of electricity supply systems.

Keywords Future electricity systems · Convergent technologies · Power system · Telecommunication · Information system · Automation system

1 Introduction

Electricity supply systems play a key role among all critical infrastructures in contemporary societies. From the supply of water, goods, gas, oil, medical services, home automation, telecommunication, security, and many other infrastructure sectors, all depend on the reliable and economic supply of electricity.

Following the current revolution brought by smart things, and the explosive growth of the Internet, electricity supply systems must keep pace with all these changes, in order to continue to provide the quality of service that has always been its main feature. Most of the changes and innovations in power system components and overall power system planning and operation methods are paralleled with developments in other industries, which have been adopted slowly from their relevant sectors,

---

On behalf of Study Committee C3.

I. P. de Siqueira (✉)
Study Committee B5, Tecnix Engineering and Architecture Ltd, Recife, Brazil
e-mail: iony@tecnix.com.br

N. Hatziargyriou
Study Committee C6, National Technical University of Athens, Zografou, Greece
e-mail: nh@power.ece.ntua.gr

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_1

e.g., power electronics, robotics, digitalization, etc. Therefore, power systems will gradually become more transactional, based around the concept of service provision, and this will require reliable and robust data to support the economic cost recovery mechanisms. A long-term vision of the future network is essential to this end, being the central motivation for this book.

1.1 Smart Things

Smart places are terms commonly used to refer to physical or cyberspaces that present behavior that could be seen as intelligent. This includes for instance the concept of a smart home, where energy optimization, hotspot reporting, home surveillance, smart lighting, perimeter checks, kids monitoring, etc. are performed by automatic or semiautomatic means. Other examples are smart health that includes personal tracker and in-home care; smart agriculture that includes water based on moisture level, pest control, and livestock management; smart city that provides waste management, parking, traffic control, pollution monitoring, smart bridges, and constructions with sensors; smart ports, smart buildings, for managing energy, surveillance, elevators, etc.; smart retail, including smart logistics, smart manufacturing, etc.

These places are possible due to the development of the concept of smart things, as devices with the capacity to take decisions and perform automatic tasks, but mainly, to communicate with other devices in a smart place. These concepts are currently referred as the Internet of Things (IoT), mimicking the previous concept of Internet (Fig. 1).

Fig. 1 Smart things. *Source* The Authors

1.2 Players in Smart Grids

Paralleling these concepts, the term Smart Grid has been used to refer to the concept of an electrical grid that is able to perform many automatic and intelligent operations. Nowadays, it refers also to the integrated operation of many players or stakeholders that need to interact in an intelligent way (Fig. 2), including:

- Generators—Bulk and distributed energy and ancillary providers
- Transmitters—Owners and possibly operators of electricity transmission assets
- Distributors—Owners and possibly operators of electricity distribution assets
- Consumers—Industrial, commercial, residential, and transportation users and users of electricity storage
- Operators—Independent system operators (ISO), regional (RSO), transmission (TSO), and distribution (DSO) operators
- Markets—Energy brokers, wholesale and retail energy sellers, buyers, chambers and balance responsible parties
- Service Providers—Third part suppliers of services required by other players.

1.3 Technological Convergence

To allow the development of all these functionalities, a set of technologies has evolved whose integration is granting the production of intelligent devices. This is particularly important for electrical power systems, whose evolution depends on the technological convergence of four major areas (Fig. 3):

- Energy technology
- Telecommunication technology
- Information technology
- Automation technology.

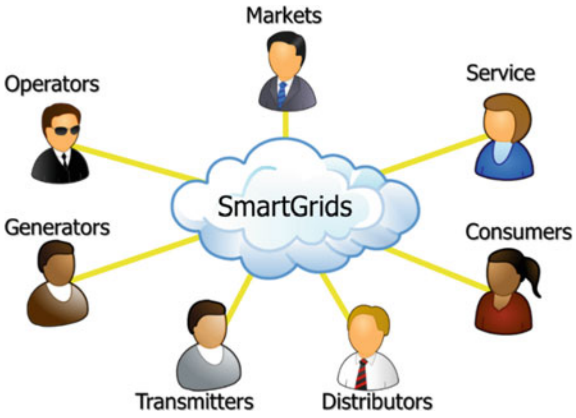


Fig. 2 Players in smart grids. *Source* The Authors

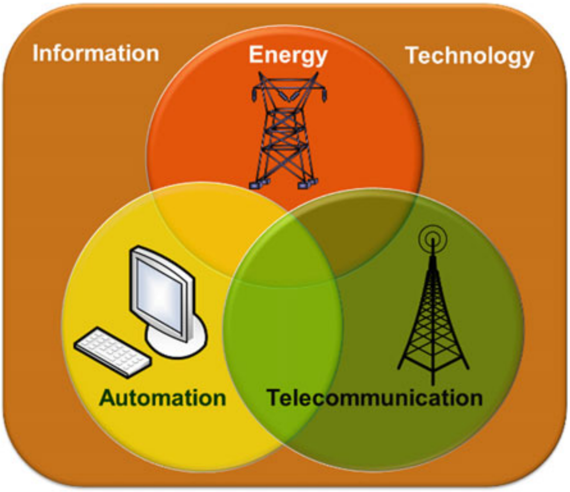


Fig. 3 Technological convergence. *Source* The Authors

1.4 Chapter Outline

The remaining paragraphs of this chapter are organized in the following subtitles:

- **Trends in Electrical Power Systems**—introduces the evolution, main technological and market tendencies of electrical power systems, and their requirements for automation and telecommunication
- **Trends in Telecommunication Systems**—presents the main technical solutions and tendencies in telecommunication systems applied to electrical power systems
- **Trends in Information Systems**—introduces the main tendencies in cyberinformation and informatics for automation systems applied to electrical power systems
- **Trends in Automation Systems**—presents the main technical solutions and tendencies in automation systems applied to electrical power systems
- **The Network of the Future**—introduces the joint result of merging the trends in electrical power grids to those in automation and telecommunications, in shaping the electrical networks of the future.

2 Trends in Electrical Power Systems

Traditionally, electrical power systems have been conceptualized as the joint operation of four different areas:

- Generation systems
- Transmission systems
- Distribution systems
- Electricity consumers.

where the term consumers comprise also the storage and local production of energy, sometimes referred as prosumers.

This paragraph intends to present the main trends related to generation, transmission, distribution, storage, and consumption of electrical energy and their requirements on automation and telecommunication systems, starting from a historical perspective.

The historical evolution of the electrical grid is usually described as the temporal sequence of five different generations, corresponding to the main technological change introduced in each generation:

- First generation—Direct current
- Second generation—Alternate current
- Third generation—Distributed generation
- Fourth generation—Flexible systems
- Fifth generation—Intelligent grid.

Additionally, the current structure of electrical grids is usually represented as a linear connection among the generation, transmission, distribution, and consumer, where the transfer of power occurs in a one-way direction (Fig. 4).

With the evolution of distributed generation and storage, the future electrical network is seen as a complicated smart grid, capable of interconnecting and transferring power between many different sources, in a two-way direction. The endpoints can vary from any kind of power plant like photovoltaic, small hydro, Stirling machines, nuclear, battery storage, geothermal, wind, fuel cell, combined cycle, combustion turbines, reciprocating engines, tidal power, etc. These distributed sources and destinies can also be combined as virtual power plants, and managed as a unique source, and also operated interconnected or isolated from the rest of the grid in case of emergencies, as a microgrid (Fig. 5).

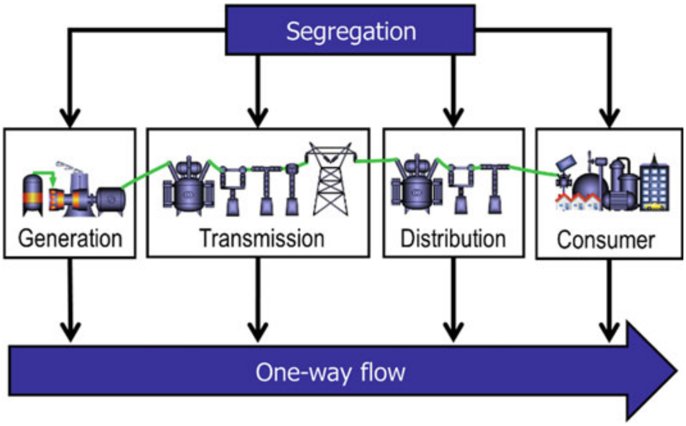


Fig. 4 Current structure of electrical grids. *Source* The Authors

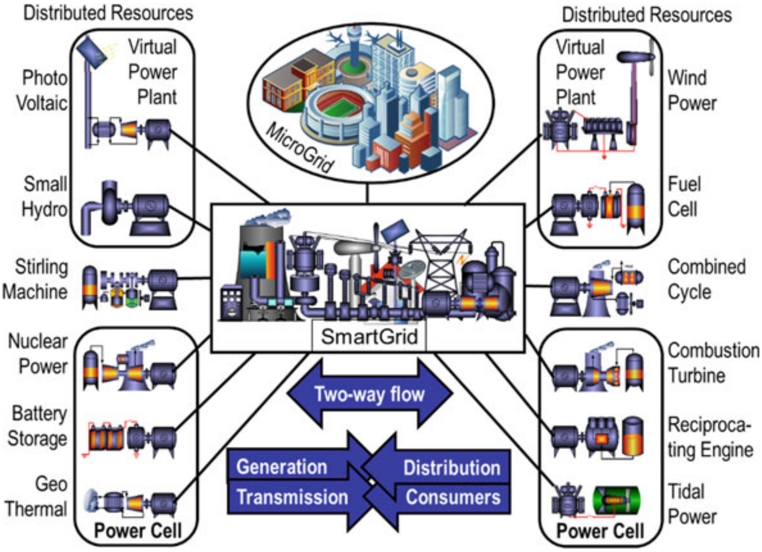


Fig. 5 Future network. *Source* The Authors

A segregated view of the network of the future can be seen as an integration of the traditional areas of generation, transmission, distribution, and consumer, with two additional domains of markets, operation, and service providers, as shown in Fig. 6.

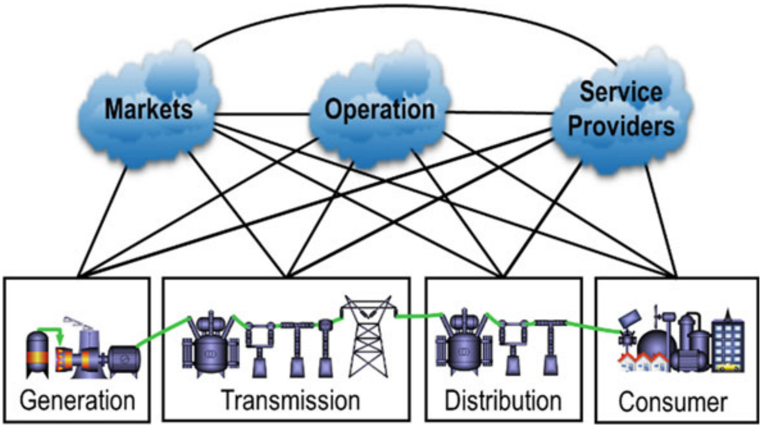


Fig. 6 Domains of smart grids. *Source* The Authors, Adapted from NIST Roadmap

2.1 Generation Systems

Perhaps the most prevalent characteristic of the evolution of the electric power grid is the increase in renewable generation in all systems mainly driven by policies to combat climate change [1]. This range includes small hydro-generation, using double-fed asynchronous generators, with induction generator with variable rotor frequency and the stator directly connected to the grid. Figure 7 shows a typical connection of this type of power plant; there the maximum efficiency of the turbine is achieved for different speed and water flow in the water stream.

The last decade has witnessed the widespread penetration of on-shore and off-shore wind power as an economical and ecologically oriented source of electricity. A typical configuration of these sources features an asynchronous generator (usually a variable speed double-fed induction generator), where variations in rotor current control real and reactive power, producing power at rotor speeds less than and greater than stator field. Figure 8 shows the typical assembly of the nacelle of a wind power turbine, with the common controls of nacelle direction and blade pitch. This also allows the full exploitation of the maximum wind power available, at variable speed of the turbine. Variable speed synchronous generators (ENERCON type) with similar properties are also very common.

Following the same impetus of wind power, solar power is growing as an alternative power source around the world. Modern solar power plants allow the full tracking of the most efficient direction of the cell panel, using altitude and azimuth control, for two-dimensional sun tracking even on regions far from the equator (Fig. 9).

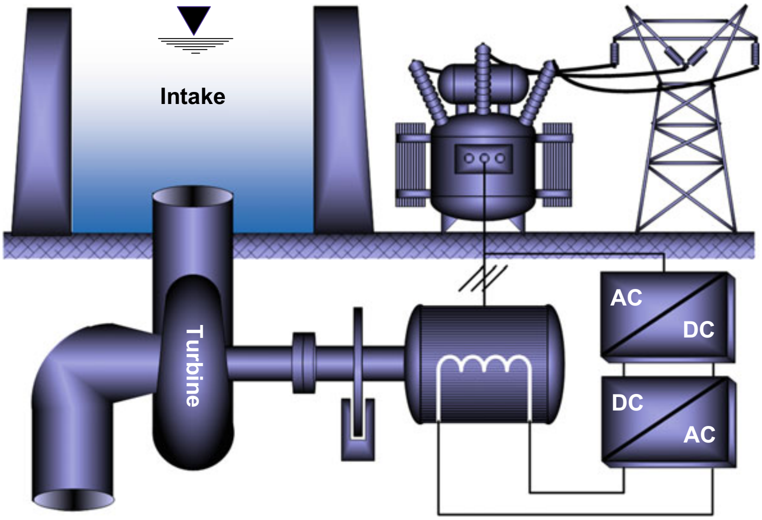


Fig. 7 Double-fed asynchronous hydro-power. *Source* The Authors

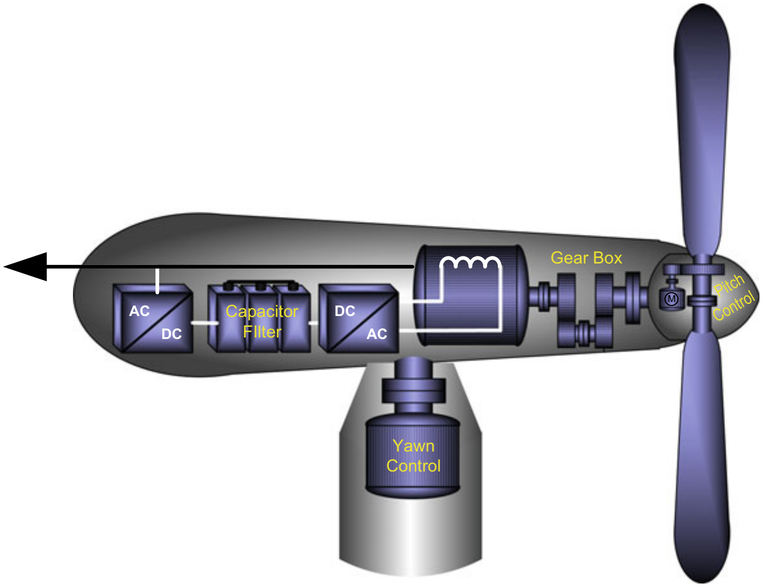
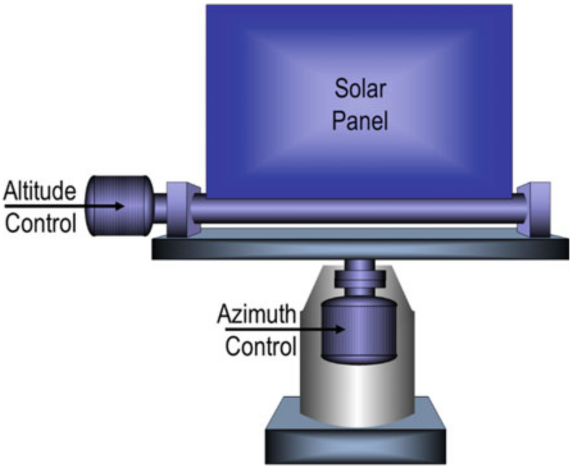


Fig. 8 Double-fed asynchronous wind power. *Source* The Authors

Fig. 9 Solar with dual axis tracker. *Source* The Authors



A promising technology is the generation of electricity using fuel cells, using a conversion device like a battery, but designed for continuous replenishment of the reactants. It produces electricity from an external supply of fuel and oxygen as opposed to the limited internal energy storage capacity of a battery. Figure 10 shows the typical assembly of a fuel cell, with an electrolyte as a catalyzer between the anode and cathode forming an electrocatalyzer capable of generating electrical current from a combustible reagent.

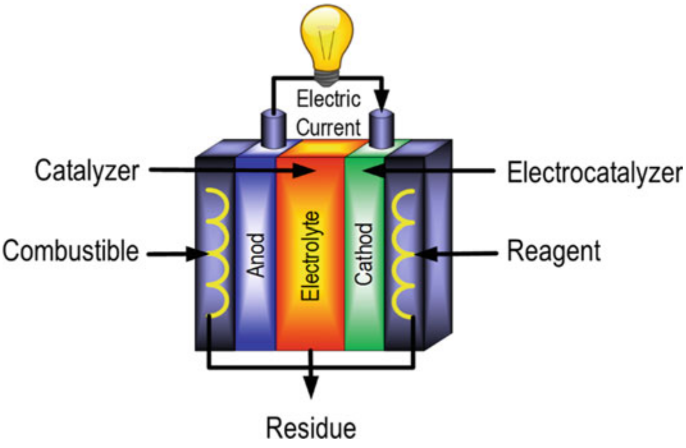


Fig. 10 Combustible cell principle. *Source* The Authors

In addition to these sources, many different generation types are being used to connect to the grid, including:

- Combustion turbines—Fueled by natural gas, oil, or combination of fuels
- Internal combustion engine—Also known as reciprocating engines
- Stirling engines—Classed as external combustion engines, sealed systems with inert working fluid, helium or hydrogen
- Energy storage/UPS with dynamic or static inverters—Stacks of storage containers: batteries, flywheels, superconductors, supercapacitors, compressed air, that powers a dynamic DC/AC energy converter.

These sources can also be combined in different cycles that recovers heat from the process of generating electricity. The following combined heat and power (CHP) are usually being employed to generate power, to improve performance and efficiency:

- CHP based on reciprocating machine—Combined Internal Combustion Engine (ICE) with heat recovery cycles
- CHP based on fuel cell—Combined fuel cell with heat recovery from water
- CHP based on gas turbine—Combined gas turbine with heat recovery and steam turbine
- CHP based on recuperated microturbine—Combined microturbine with heat recover
- Geothermal power—Uses natural heat from volcanos, etc. Cold water is pumped into the ground, while hot water returns from the ground. Mostly experimental in small scale.

Some new sources of power are also being developed based on the ocean waves and currents, like:

- Tidal power (TP)—Uses energy from sea tidal, that is more predictable than wind and solar power, but currently mostly experimental.
- Wave power (WP)—Uses energy from sea waves; more predictable than wind and solar power; it is currently mostly experimental; using several methods of mechanical motion.
- Ocean current power (OCP)—Uses energy from submarine currents that is more predictable than wind and solar power, being mostly experimental.

As an example, Fig. 11 shows the assembly of a CHP based on reciprocating machine, a combined ICE with heat recovery cycles using a boiler and cooling towers.

Besides these new technologies, the generation systems are experimenting intensive use of digital tools for the design of new machines, like finite element modeling (FEM), computational fluid dynamics (CFD), long-term reliability analysis, big data, artificial intelligence (AI), self-learning algorithms, equivalent digital twin circuits, design of experiments (DOE) and response surface method (RSM). A more detailed review of the current and future status of the design and research in this area can be found in the chapter "rotating electrical machines" of this book.

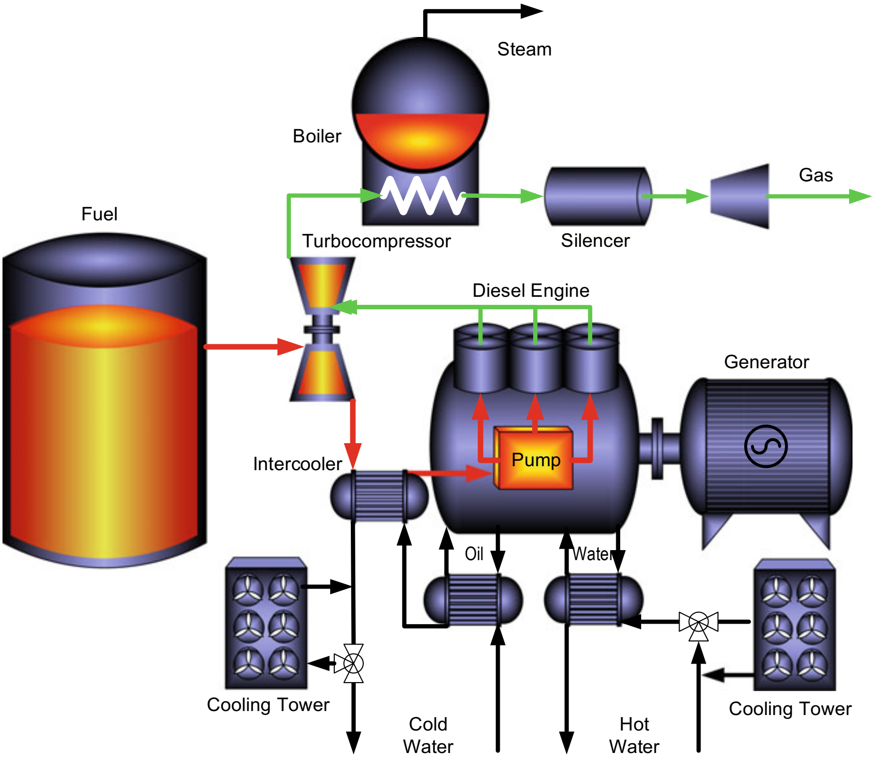


Fig. 11 CHP based on reciprocating machine. *Source* The Authors

2.2 *Transmission Systems*

A distinctive characteristic of the evolution of transmission system is the growing application of Flexible AC Transmission Systems (FACTS). Figure 12 shows the impressive range of possible applications for FACTS, mapped to a matrix relating the four standard domains of power systems to the hierarchical interoperability proposed by the Smart Grid Architecture Reference (SGAM) [2] of the European Union. The increasing application of FACTS reflects also the general trend in the application of power electronics for the control of the electrical grid.

Four generations of FACTS have evolved with the introduction of new technologies, mainly related to the control of the conversion process, and the type of static device used:

- **First Generation**
  - TCR—Thyristor Controlled Reactor
  - TSC—Thyristor Switched Capacitor
- **Second Generation**
  - SCV—Static Var Compensator
  - TCSC—Thyristor Controlled Series Capacitor
  - SCCL—Short-Circuit Current Limiter
  - TCPAR—Thyristor Controlled Phase Angle Regulator
- **Third Generation**
  - STATCOM—Static Compensator
  - SSSC—Static Synchronous Series Compensator
- **Fourth Generation**
  - UPFC—Unified Power Flow Controller
  - IPFC—Interline Power Flow Controller
  - GIPFC—Generalized Interline Power Flow Controller
  - CSC—Convertible Static Compensator.

In the first generation of FACTS, a TCR switches a shunt reactor by a thyristor column, and a step-up transformer connects the FACTS to the grid. Similarly, in a TSC, a shunt capacitor is switched by a thyristor column, and a step-up transformer connects it to the grid.

The second generation of FACTS introduced the SVC that switches both a shunt reactor and capacitor by thyristor columns, connected to the grid by a step-up transformer. In a TCSC, a series reactor is switched by a thyristor column, in parallel with a series capacitor, and in series with a transmission line. In a SCCL, a series capacitor is short-circuited by a thyristor, in series with a reactor in a transmission line, to control power and short-circuit current. In a TCPAR, a transformer with phase-shifting windings is switched by internal or external thyristors, in series with a transmission line, to dynamically control the power flow.

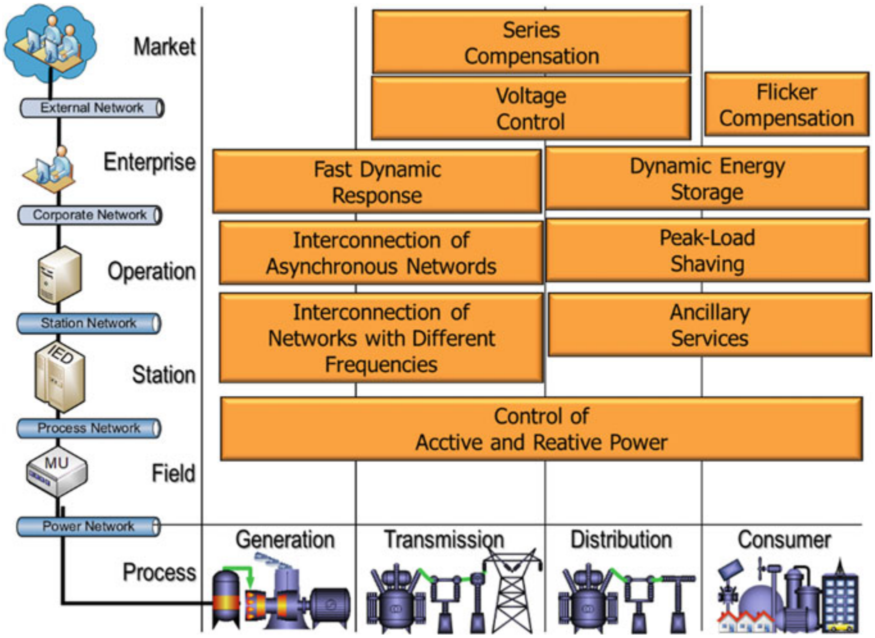


Fig. 12 FACTS applications. *Source* The Authors

The third generation of FACTS introduced the concept of a STATCOM, with a shunt capacitor controlled by thyristors, to fine control the injected reactive power, for control of power flow, voltage, power factor, flickers, and unbalanced loads. In a different way, a SSSC uses a series capacitor controlled by thyristors, connected by a series transformer to the transmission line, to control the active and reactive power flow.

The fourth and more recent generation of FACTS, still under development, introduces the UPFC, merging the architecture of a STATCOM with a SSSC, with a capacitor controlled by thyristors, connected by a series transformer to a transmission line or parallel transformer to a bus bar, to control voltage, active and reactive flow. Another possibility under development is to use an IPFC, where two SSSC in distinct lines use a common capacitor bank, to control power flow in the lines. An alternative to this assembly is the GIPFC, where two SSSC are in distinct lines, and one STATCOM on the common bus, sharing a common capacitor bank, to control voltage and power flow. One additional development is the CSC, with a capacitor bank multiplexed by circuit breakers into multiple static compensators. This configuration is illustrated on Fig. 13.

In addition to FACTS, there is a clear trend to employ long-distance high-voltage DC transmission systems (HVDC), mainly from power sources far from the consumer centers, and to connect networks with different frequencies. Figure 14 shows some possible application of HVDC in the SGAM reference framework.

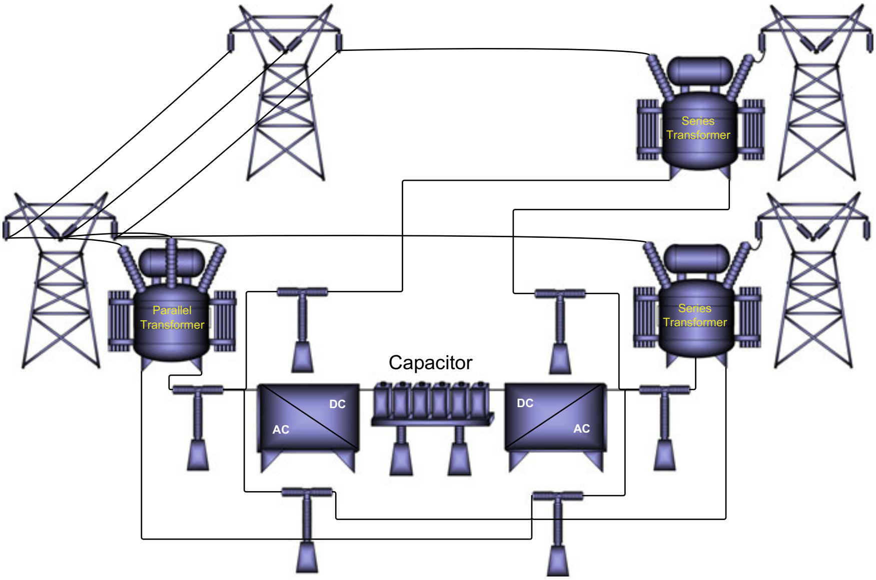


Fig. 13 CSC—Convertible static compensator. *Source* The Authors

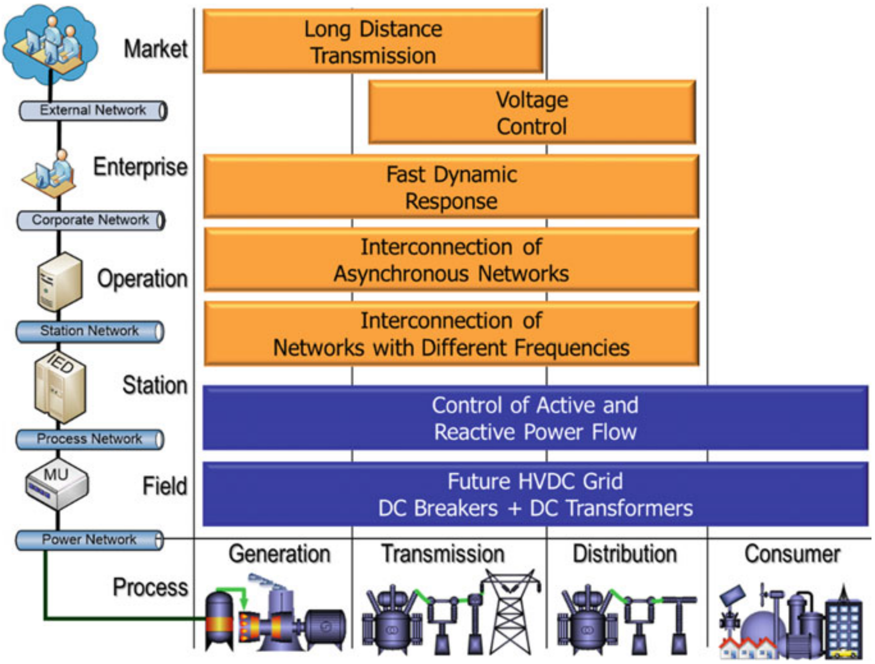


Fig. 14 HVDC applications. *Source* The authors

HVDC technologies are mainly composed of three different types:

- Current Source Converter (CSC)
- Voltage Source Converter (VSC)
- Capacitive Commutated Converters (CCC).

Current source converter (CSC), also known as line-commutated converter (LCC), is the technology used in most of HVDC systems in operation today. It uses thyristors which can withstand voltage in either polarity, and the output voltage can be either polarity to change power direction, while current direction does not change. CSC does not allow independent control of active and reactive power. Figure 15 shows the typical assembly of a CSC station.

Voltage source converter (VSC) use reactors inserted between the converter transformer and the converter valves. Transistors control the current in either direction, but the output DC voltage polarity does not change. Current direction changes to revert the power direction, allowing the independent control of active and reactive power. Figure 16 shows the typical assembly of a VSC station.

Capacitive commutated converters (CCC) employ capacitors inserted between the converter transformer and the converter valves, for generating some of the voltage required for thyristor valve commutation. The converter can only draw an inductive current from the AC network. The valve cannot be turned off actively, and the current through one valve must be brought to zero to turn it off. Figure 17 shows the typical assembly of a CCC station.

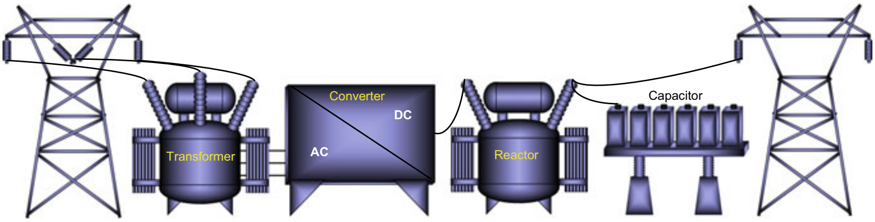


Fig. 15 Current source converter (CSC). *Source* The Authors

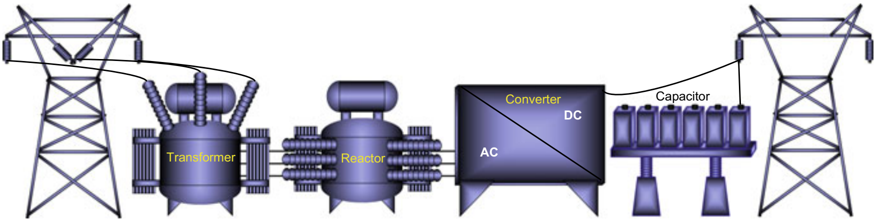


Fig. 16 Voltage source converter (VSC). *Source* The Authors

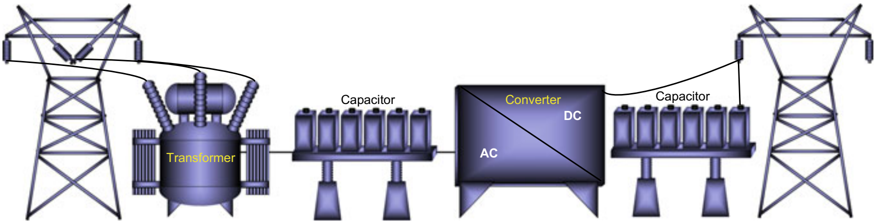


Fig. 17 Capacitive commutated converters (CCC). *Source* The Authors

In addition to the use of power electronics in HVDC and FACTS technologies, research is underway for increasing the transmission capacity of AC lines for the same right-of-way, by using multiphase systems. This technology needs more transpositions than three-phase lines, special transformers, and towers.

Another research area is the use of superconductors for power transmission. The main challenge is the cost for the conditioning of the conductor. Figure 18 shows the typical assembly of a superconductor cable, showing the stacked layers of shielding, isolation, and temperature control.

A similar development is underway for gas-insulated lines (GIL), mostly for short distances and urban areas. Figure 19 shows the typical assembly of a gas-insulated cable, showing the metal housing for the gas.

Besides these new technologies, the transmission systems are rapidly absorbing most of the new design methods offered by standards like building information modeling (BIM) [3] and geographical information systems (GIS) [4].

Fig. 18 Superconductor line. *Source* The Authors

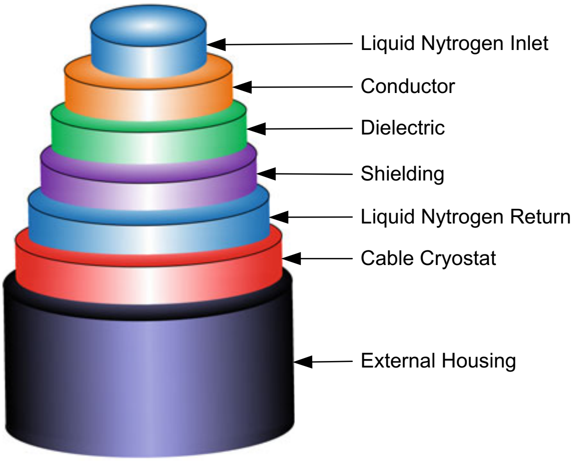
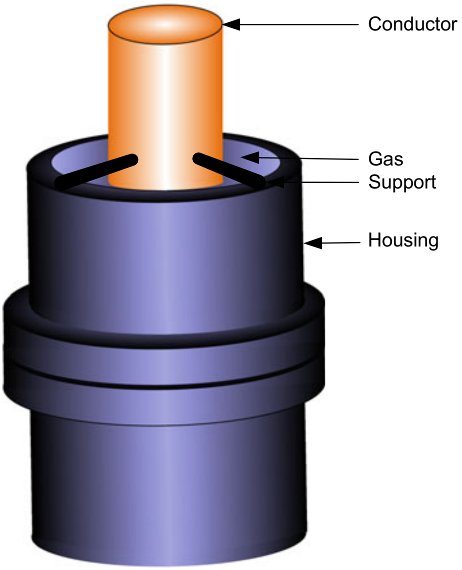


Fig. 19 Gas-insulated line (GIL). *Source* The Authors



2.3 Energy Storage

With the environmental restriction for building large power plants, even those based on renewable hydro-power, and the rapid penetration of non-dispatchable and intermittent green power, research on alternative ways of storing energy has become a priority. Many applications are possible for distributed and centralized storage of energy. Figure 20 shows the main applications, mapped to the SGAM framework.

Among many possibilities of energy storage, the following are the main technologies, some with proven applications, others still under research:

- Pumped hydro-energy storage (PHES)
- Flywheel energy storage (FES)
- Battery electric storage system (BESS)
- Hybrid flow battery (HFB) power plant
- Ultra-capacitor storage system (UCSS)
- Compressed air energy storage (CAES)
- Compressed gas energy storage (CGES)
- Superconducting magnetic energy storage (SMES)
- Gravity energy storage (GES)
- Thermal energy storage (GES).

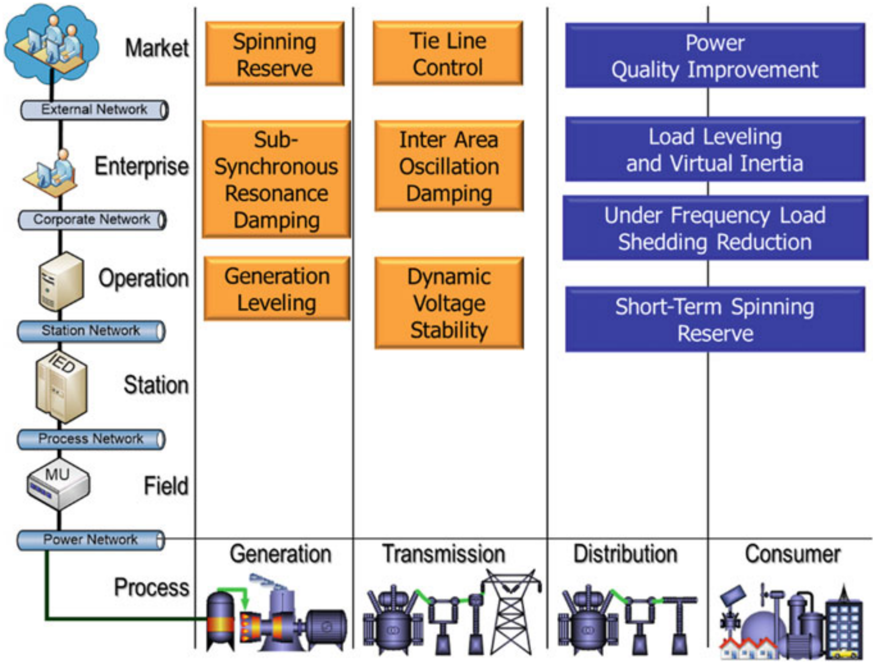


Fig. 20 Energy storage applications. *Source* The Authors

Pumped hydro-energy storage (PHES) is a standard way of energy storage that depends on the availability of a specific location for upper and lower dams; it is practically the only technology capable of storing large quantity of energy, in a single place. Compressed air energy storage (CAES) and compressed gas energy storage (CGES) are also large storage possibilities that depend on an adequate location; they can be used to smooth daily load variability.

The other methods can store a reduced amount of energy, mainly for distributed locations. Flywheel energy storage (FES) has a high specific power with reduced response time, being ideal for angular and voltage stability control. Battery electric storage system (BESS) is expensive, but stores and releases power across a broad range of time scale, being suitable for a wide spectrum of applications, from providing primary frequency reserves and smoothing rapid voltage fluctuations to storing excess renewable power and mitigating daily load variability. Hybrid flow battery (HFB) employs rechargeable batteries provided by two chemical components dissolved in liquids contained within the system and separated by a membrane. Ultracapacitor storage system (UCSS) has a high specific power but reduced response time; it is ideal for angular and voltage stability, requiring series capacitors for voltage equalization. Superconducting magnetic energy storage (SMES) is based on low resistance of superconductors, still under development. Gravity energy storage (GES) is a possibility of using a very large piston suspended in a deep, water-filled shaft, with sliding seals to prevent leakage around the piston, and a return pipe connecting to a pump-turbine at ground level. Thermal energy storage (GES) collects and focuses sunlight onto a receiver by an array of mirrors, converting solar energy into heat. A heat transfer material, usually a fluid, is used as a heat storage media that may or may not be the same as the heat transfer material.

2.4 Distribution Systems

Distribution networks cover electricity infrastructure for delivering energy from the transmission system to end-users (customers) at medium voltage (MV) and low voltage (LV). Worldwide, there are different voltage levels that are considered as low voltage (LV), medium voltage (LV) or high voltage (HV). Active distribution *systems* are distribution networks in which distribution system operators (DSO) can actively control and manage distributed energy resources (DER). These include small generators connected directly to their networks—from domestic solar panels and wind farms to batteries and electric vehicles, while enabling customers to play a more active and participatory role.

Traditionally, distribution networks were designed to transport electricity in one direction: from the generation connected to the transmission system to customers at the endpoint of the network. This type of system did not require extensive management and monitoring tools. But with solar panels on residential rooftops and wind turbines integrated into industrial sites, customers are increasingly generating electricity themselves. By becoming "prosumers," they are moving from the endpoint to the center of the new value chain. This new operating environment imposes to DSOs active management and operation of a smarter grid, rather than just "burying copper in the ground." This also requires making use of the grid's and consumers' flexibility potential to solve grid constraints, optimize network performance and investments, and make the most of existing network assets. Active distribution networks also benefit from the implementation of ICT innovations to enable fast identification, isolation and sometimes remote tackling of network problems. Figure 21 depicts the transformation of passive to active distribution systems.

Among the trends in distribution system operation and control, the following are mentioned as characteristic of the future evolution of this energy domain:

- More and more similar to transmission automation
- Increased use of monitoring and automatic reclosing
- Constant movement to underground substations
- Increased use of wireless telecommunication
- Adoption of IEC 61850 [5] in substations and CIM [6, 7] for DMS.

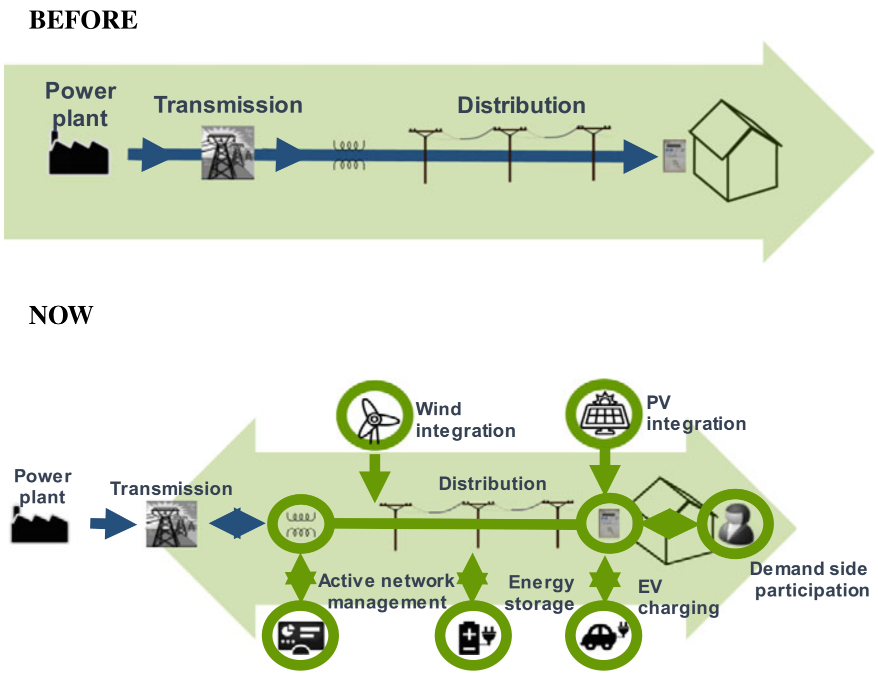


Fig. 21 The transformation of the passive distribution network to the active distribution system. *Source* "European Distribution System Operators for Smart Grids, Future-ready, smarter electricity grids. Driving the energy transition. Powering customers", brochure 2016

Figure 22 shows a pictorial view of a typical compact underground urban substation for a distribution system, with the typical devices for control and automation.

Microgrids are novel distribution network paradigms that is expected to affect drastically the building and operation of distribution systems. Technically, microgrids comprise parts of distribution systems with distributed energy sources, such as microturbines, fuel cells, PVs, etc., together with storage devices, i.e., flywheels, energy capacitors and batteries, and controllable loads, offering considerable control capabilities over the network operation. They operate mostly interconnected to the upstream system in a single connection point, but they can be also operated isolated from the main grid, in case of faults or major disturbances enhancing the reliability and resilience of power supply to critical loads. From the customer point of view, microgrids can provide both thermal and electricity needs, and in addition enhance local reliability, reduce emissions, improve power quality by supporting voltage and reducing voltage dips, and potentially lower costs of energy supply. From the utility point of view, application of distributed energy sources can potentially defer investments for distribution and transmission assets and provide network support in times of stress by relieving congestions and aiding restoration after faults. The main applications found today are in remote and isolated areas, non-interconnected islands, campuses, military facilities using distributed generation (renewable and conventional), distributed storage and controllable loads. They also form the technical basis for the operation of local energy communities. Figure 23 shows a pictorial view of a typical microgrid, with several local and complementary sources of generation, feeding a local load, with possible connection to the bulk power grid, being controlled as a virtual power plant.

2.5 Electricity Consumers

With the automation and connectivity of all kind of home appliances, it is in the consumer side of electricity supply that most impacts are expected in the future. Among these changes, the rapid dissemination of electric vehicles (EV) deserves a special place in the future of electrical power systems. Besides the intended reduction of emission of CO_2 coupled to cleaner energy production, EV can store energy and serve as an ancillary source of power from the vehicle to the grid (V2G). Figure 24 shows the possible applications of EV and V2G in power grids, using the SGAM framework.

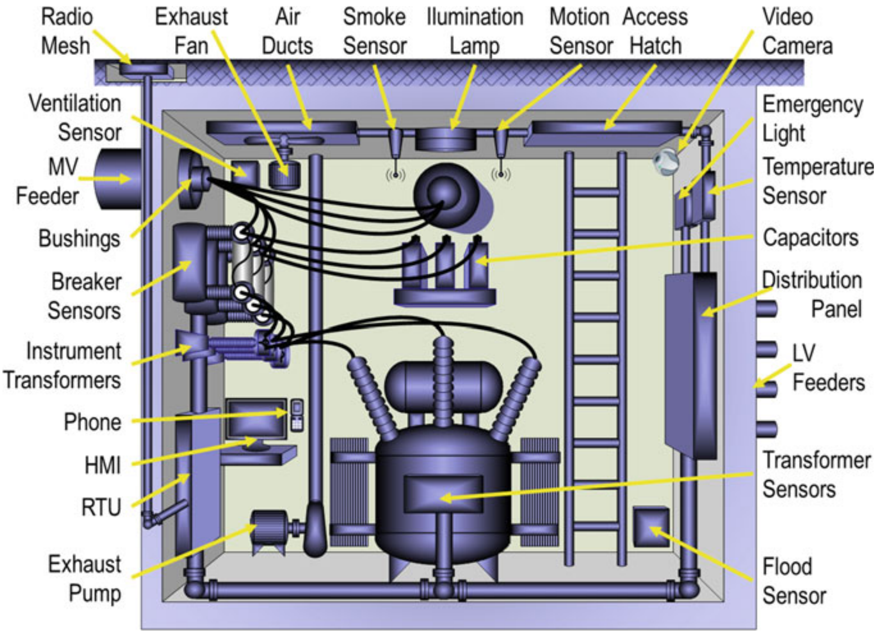


Fig. 22 Underground substations. *Source* The Authors

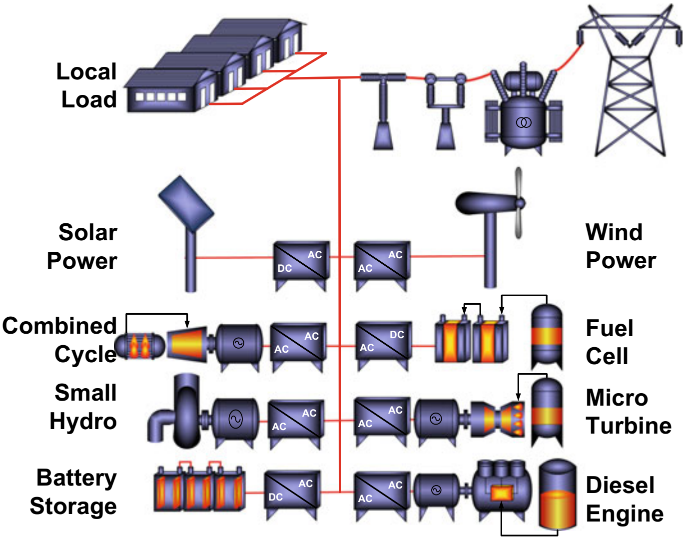


Fig. 23 Microgrid and virtual power plant. *Source* The Authors

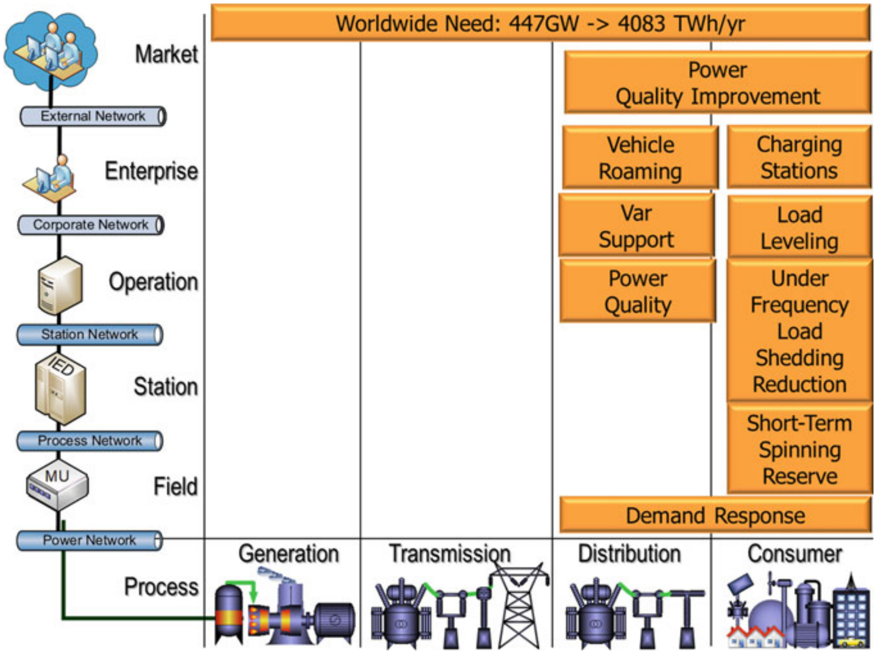


Fig. 24 Electrical vehicle applications. *Source* The Authors

Many concurrent technologies are competing for the EV market, such as:

- EV with rechargeable battery
- Hybrid EV with parallel power flow
- Hybrid EV with series power flow
- Hybrid EV with double traction
- EV with battery and flywheel
- EV with battery and supercapacitor
- Hybrid EV with battery and fuel cell.

All of them use part of the internal combustion engine (ICE) structure as a proved technology with advanced control, but high emission of CO_2, as a base for the structure of electrical vehicles. Pure EV with rechargeable battery use rechargeable batteries to power DC electrical drives, where the motor can also operate as a generator for recovering power during the vehicle braking.

Hybrid EV with parallel or series power flow uses an internal combustion engine and rechargeable batteries with electric drives, where the motor can operate as generator to recharge the batteries from the ICE. An alternative is the hybrid EV with double traction where the motor and ICE drive different traction axis on the vehicle structure.

In substitution to the ICE, hybrids EV can use supercapacitors or flywheels to store fast response energy; the motor can operate as generator to recharge the batteries, capacitor and flywheel, during vehicle braking.

Finally, a hybrid EV with battery and fuel cell can use hydrogen to power an internal combustion engine and fuel cells; the motor can operate as generator to recharge the batteries in parallel with the fuel cells.

Figure 25 shows the typical assembly of a hybrid electric vehicle with series power flow.

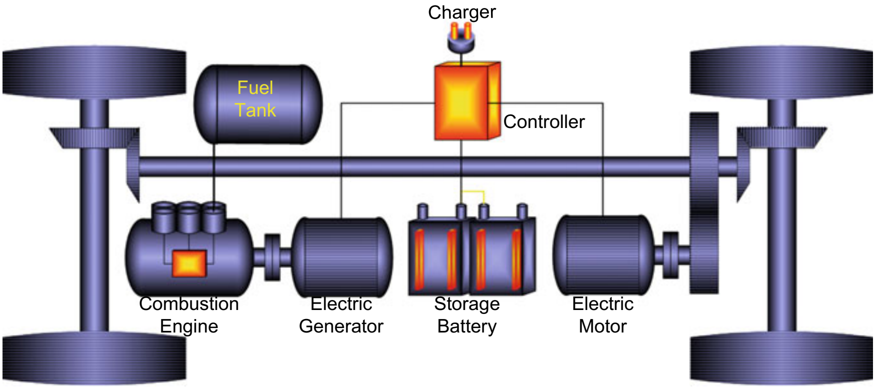


Fig. 25 Hybrid electric vehicle with series power flow. *Source* The Authors

3 Trends in Telecommunication Systems

The full exploitation of all new technologies available in the generation, transmission, distribution, and consumer domains of power systems is only possible with the availability of modern resources for communication among devices, systems and players, as one of the pillars of a smart grid. The following paragraphs present the main trends in telecommunication for power systems, the automation requirements for communication, the needs for advanced metering infrastructure (AMI) and inter-substation communication, and the network convergence of telecommunication as a common tendency. As a frame of reference, Fig. 26 shows the main communication networks necessary for the future of the electricity grid, mapped to the SGAM framework.

These networks are currently designed to supply the needs of automation, AMI and inter-substation communication, described in the following paragraphs.

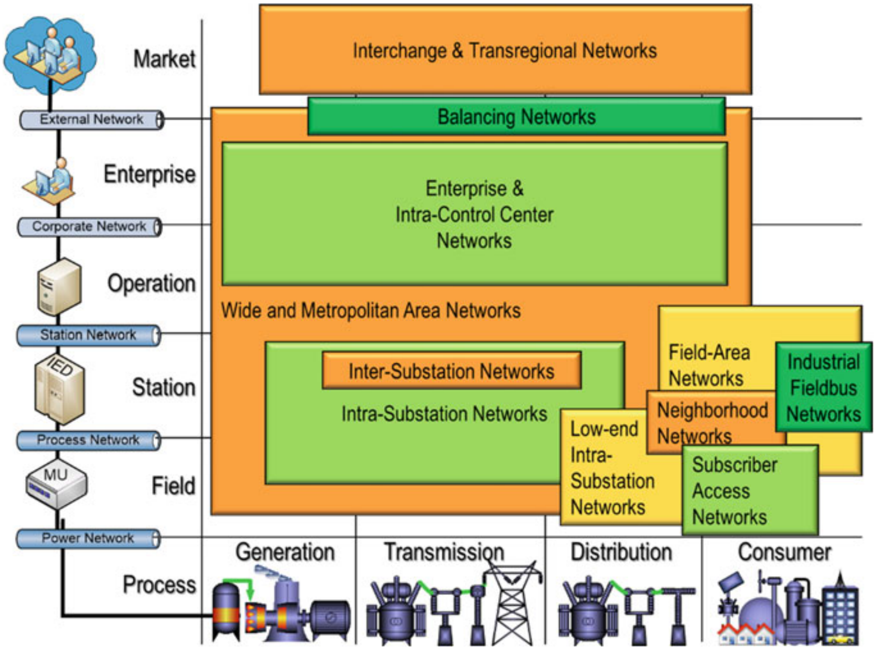


Fig. 26 Smart Grid telecommunication networks. *Source* The Authors

3.1 Automation Requirements

The most demanding requirements for telecommunication in the future of power grids come from the automation field. These demands can be classified in the following features:

- **Interoperability**

The ability of devices, computer systems or software to exchange and make use of common information.

- **Quality of Service**

The description or measurement of the overall performance of a service as seen by the users of the network.

- **Timing Accuracy**

Maximum allowed error (jitter) in transmission time.

- **Bandwidth**

Bit transfer rate, or number of bits that can be carried from one point to another in each time period (usually a second).

- **Latency**

Time it takes for a data packet to cross a network connection, from sender to receiver.

Figure 27 shows the typical latency requirements for major applications of automation in electrical power grids, mapped to the SGAM framework.

3.2 Inter Substation Communication

In addition to the communication with the consumers, transmission and distribution automation requires advanced means for exchanging information among substations, mainly for protection and automation. Traditionally, this has been achieved by the following physical media:

- Pilot wires/copper wires
- Power line carrier (PLC) links
- Microwave radio links
- Optical fiber links
- Satellite links.

Figure 28 shows the typical hierarchy of application of these media by electric utilities, mapped to the SGAM framework.

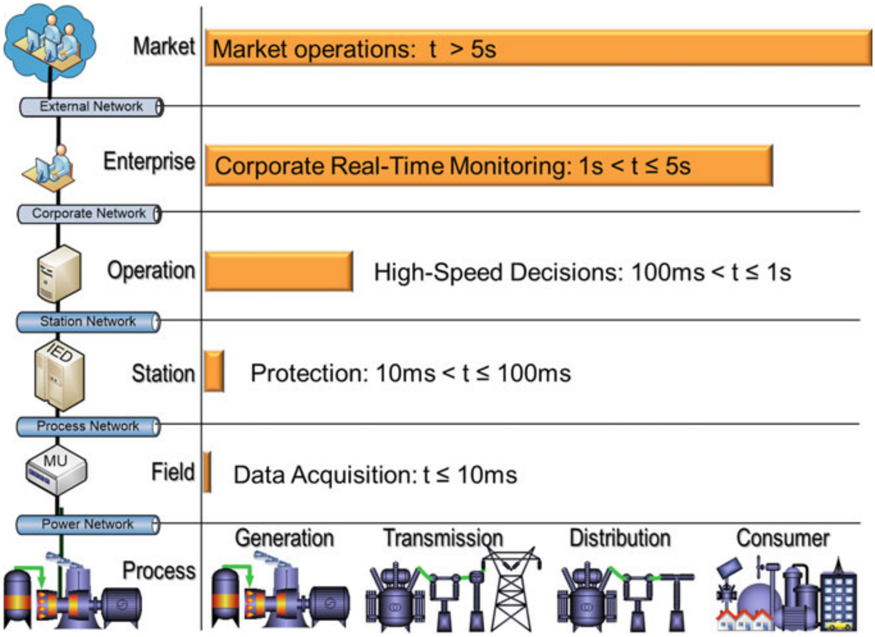


Fig. 27 Hierarchical requirements for latency. *Source* The Authors

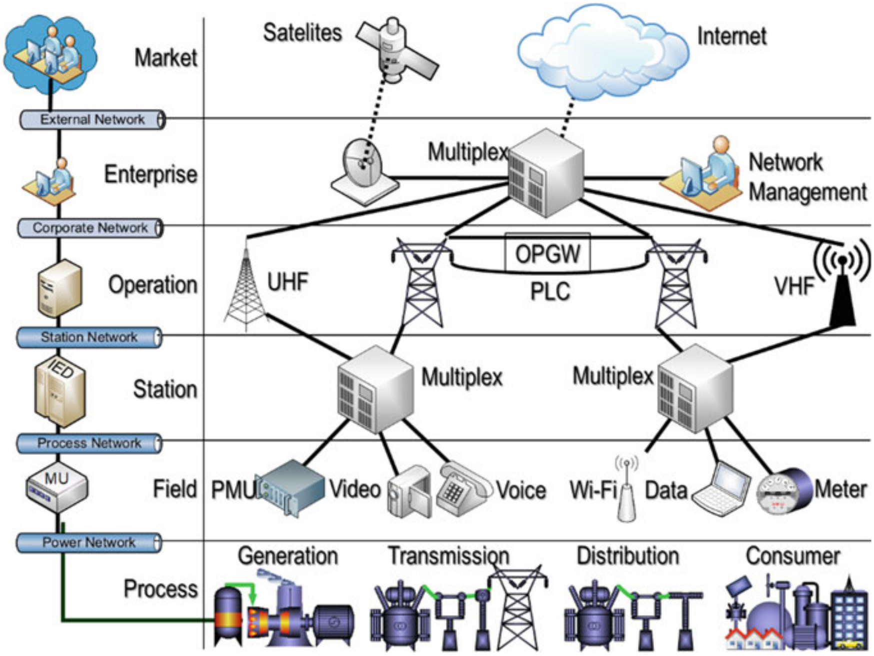


Fig. 28 Traditional utility telecommunications. *Source* The Authors

Independent of the physical media used for communication, current and future automation applications have strict demand mainly for latency. Figure 29 shows the typical latency requirements for typical teleprotection between two substations, from the message source of intelligent electronic devices (IED) to the remote breaker in a remote substation.

To attain these requirements, future networks are expected to make extensive use of the convergence of all available telecommunication media.

3.3 Network Convergence

To provide standardized services for all envisaged applications in a smart grid, the telecommunication sector is adopting steadily the concept of the next-generation network (NGN). It is generically defined by the International Telecommunication Union (ITU) as a packet-based network able to provide telecommunication services and able to make use of multiple broadband QoS-enabled transport technologies and in which service-related functions are independent from underlying transport-related technologies. Figure 30 illustrates the concept of telecommunication convergence as a packet switching network capable of transmitting data, voice, and video simultaneously.

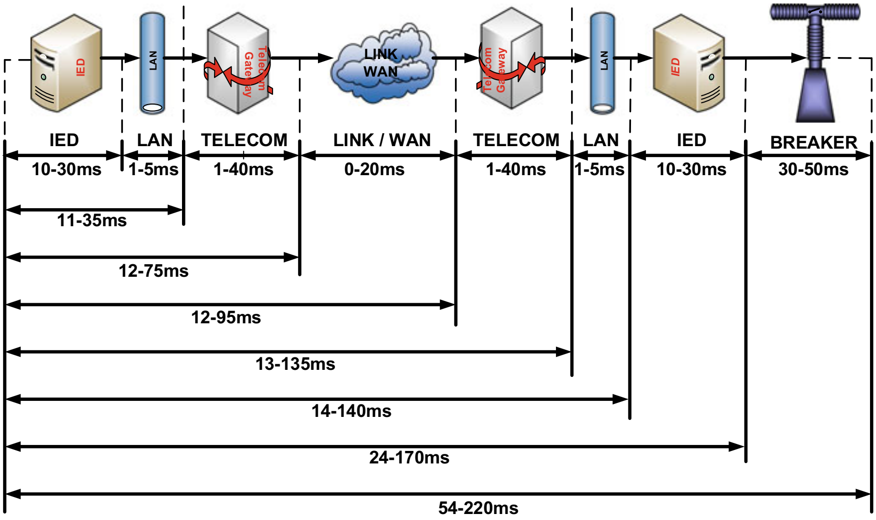


Fig. 29 Teleprotection speed requirements. *Source* The Authors

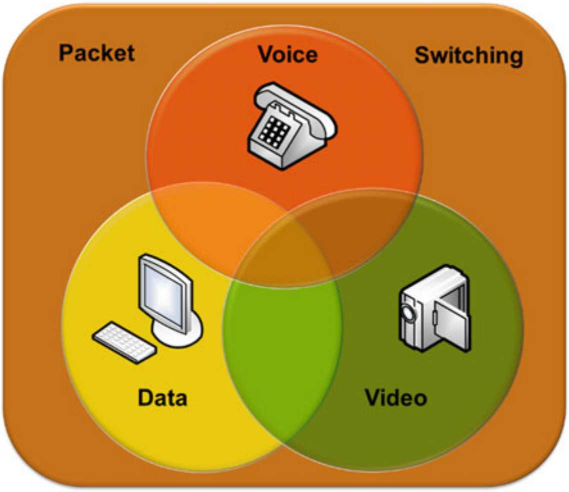


Fig. 30 Telecommunication convergence. *Source* The Authors

4 Trends in Information Systems

Paralleling the trends in telecommunication convergence, the information processing in the power sector is steadily adopting the main developments from informatics. The following paragraphs summarize the main aspects of this evolution:

- Informatics evolution
- Distributed systems
- Service-oriented architecture
- Cloud computing
- Cybersecurity.

4.1 Informatics Evolution

The evolution of information processing can be seen as a movement through five generations of hardware and software innovations. Table 1 shows the main technologies introduced in each generation.

The fifth generation, featuring distributed hardware and software, is the current technology being deployed in digital substation, and seen as the main paradigm for the development of future applications.

Table 1 Informatics evolution

Generation	Hardware	Software
First	Vacuum tubes	Bits and bytes
Second	Transistors	Assembler languages
Third	Integrated circuits	High-level languages
Fourth	Microprocessors	Object-oriented languages
Fifth	Distributed systems	Distributed software

Source The Authors

4.2 Distributed Systems

Several architectures of substation and power plant automation are possible, using the technology of distributed systems (DS):

- Remote access systems (RAS)
- Client–server systems (C/SS)
- Remote procedure calls (RPC)
- Distributed object systems (DOS)
- Peer-to-peer systems (P2P)
- Publish-subscribe systems (PSS)
- Service-oriented systems (SOS)
- Distributed real-time systems (DRTS).

Remote access systems (RAS) provide distributed access to central facilities, or servers acting as a mainframe with processor, memory, files, and applications shared by users connected to remote terminals or dumb monitors and keyboard connected to the central facility by communication lines.

Client–server systems (C/SS) use applications modeled as a set of services provided by servers and a set of clients that use these services. Clients know about servers, but servers do not need to be aware of clients they serve. Clients and servers are logical processes that need not map to specific processors.

Remote procedure calls (RPC) mask distributed computing system using a "transparent" abstraction that looks like a normal local procedure call but hides all aspects of distributed interaction, supporting an easy programming model, being the main technology behind many client/server systems in operation.

Distributed object systems (DOS) make no distinction between clients and servers. Any object on the system may provide and use services from other objects, using a middleware system called an object request broker to exchange messages.

Peer-to-peer systems (P2P) use decentralized systems where computations may be carried out by any node in the network. It takes advantage of the computational power and storage of many current networked computers.

Distributed real-time systems (DRTS) are a distributed system, located on computers in different places, with well-defined requirements regarding response time for some real-world events.

Publish-subscribe systems (PSS) are decentralized systems where some servers (publishers) broadcast information to be acquired only by those registered recipients (subscribers), to make available information required in real time by subscribers of a given publisher without request. It makes use of an architecture similar to service-oriented systems (SOS), described in the following paragraph.

4.3 Service-Oriented Architecture

The development in information system that most impact the future applications in power systems is the concept of a service-oriented architecture (SOA). It consists of a distributed system based around the notion of externally provided services (web services). A web service is a standard approach to making a reusable component available and accessible across the web. Among the main SOA features, the following are of special interest for power system applications:

- Provider independence
- Public advertising of service availability
- Run-time service binding
- Opportunistic construction of new services through composition
- Pay for use of services
- Smaller, more compact applications
- Reactive and adaptive applications.

Figure 31 shows the main agents involved in a SOA system, with their interaction. SOA is closed related to the concept of cloud computing, described in the sequel.

4.4 Cloud Computing

"Cloud" is the common name given to the aggregation of servers and storage hosting programs and data provided "as a service" over the Internet. As such it is both user centric, making easier for group members to collaborate, and task centric, where the user's need is more important than the features of an application. In a cloud solution, all resources together create a wealth of computing power offering a programmable automated distribution of computing power and data across the cloud. Typically, the following actors are involved in a cloud solution:

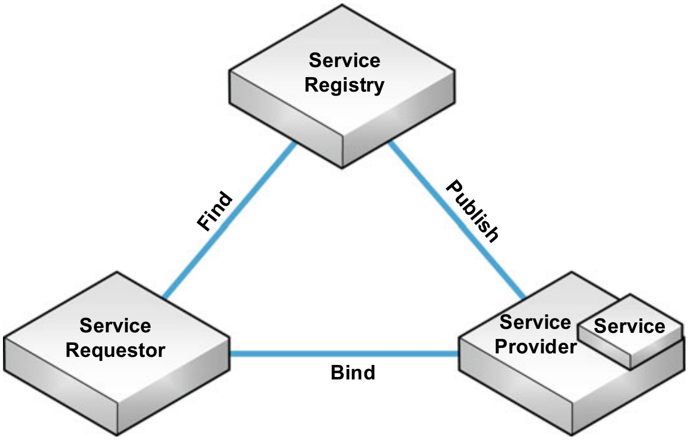


Fig. 31 Service-oriented architecture. *Source* The Authors

- **Cloud Consumer**
  - A person or organization that maintains a business relationship with and uses service from cloud providers.
- **Cloud Provider**
  - A person, organization, or entity responsible for making a service available to interested parties
- **Cloud Auditor**
  - A party that can conduct independent assessment of cloud services, information system operations, performance and security of the cloud implementation.
- **Cloud Broker**
  - An entity that manages the use, performance and delivery of cloud services, and negotiates relationships between cloud providers and cloud consumers.
- **Cloud Carrier**
  - An intermediary that provides connectivity and transport of cloud services from cloud providers to cloud consumers.

Currently, three types of cloud models are offered:

- **SaaS—Software as a Service**
  - Applications, typically available via the browser.
- **PaaS—Platform as a Service**
  - Hosted application environment for building and deploying cloud applications.

- **IaaS—Infrastructure as a Service**
  - Utility computing data center providing on-demand server resources.

4.5 Cybersecurity

The availability of all these facilities may expose vulnerabilities of the network to cyberattacks, common to all distributed networks, but especially dangerous to electric power grids due to the criticality of their operation. Figure 32 shows the major strengths (in yellow color) and weakness (in green color) of power grids to cybersecurity, mapped to the SGAM framework.

A similar mapping is shown in Fig. 33 for the opportunities (in yellow color) to protect the grid, and the threats (in green color) of cybersecurity attacks to power grids, mapped to the SGAM framework.

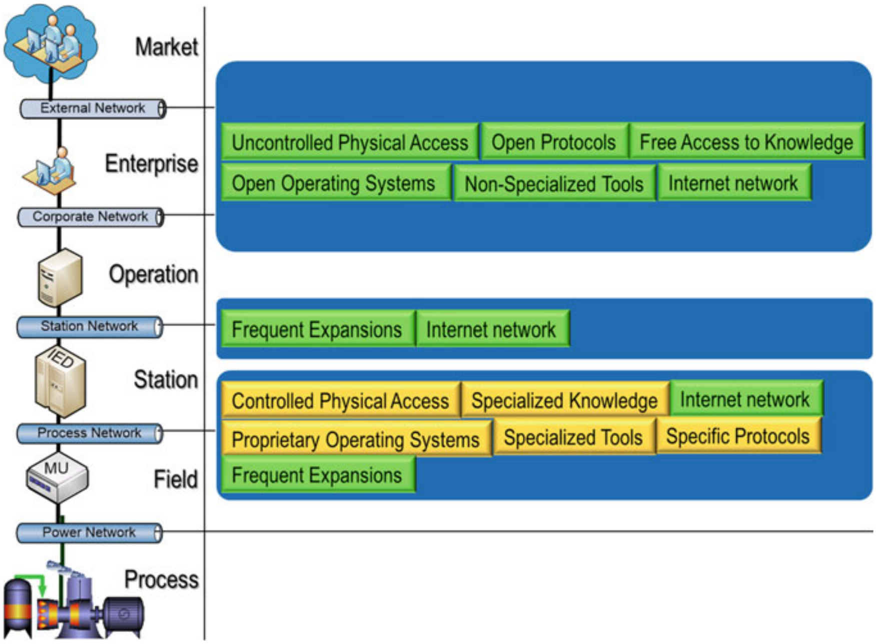


Fig. 32 Automation security strengths and weaknesses. *Source* The Authors

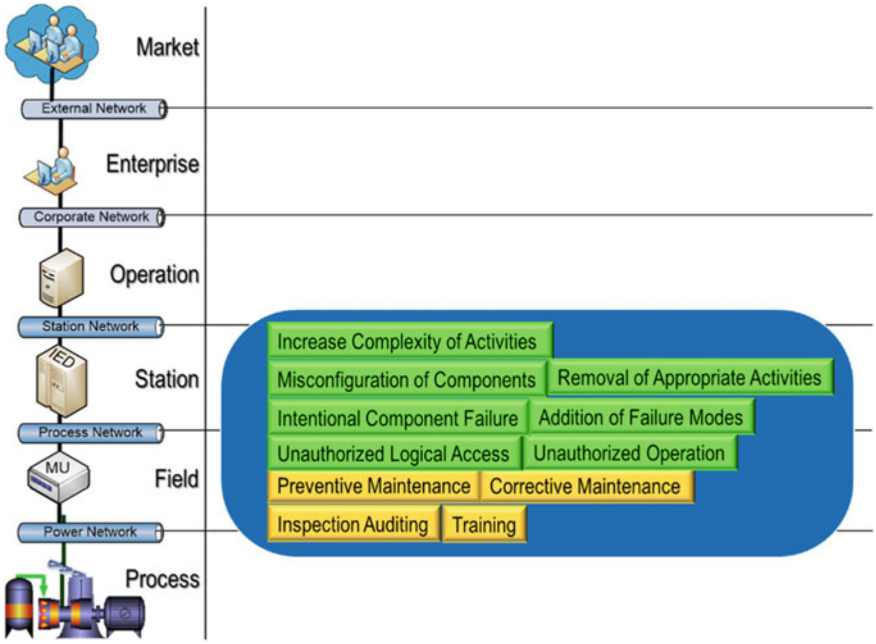


Fig. 33 Automation security opportunities and threats. *Source* The Authors

5 Trends in Automation Systems

To review the future of power system automation, with the trends in sensor and advanced metering, and their impact on home, substation and control centers, the next paragraphs present the following trends:

- Trends of automation systems
- Trends in sensor systems
- Trends in metering systems
- Trends in home automation
- Trends in substation automation
- Trends in control center automation.

5.1 Generations of Automation Systems

Mirroring the evolution of informatics, the evolution of power system automation can be mapped to five generations related to specific technologies used for implementation. Table 2 correlates these generations to the hardware and automation main characteristic.

Table 2 Automation evolution

Generation	Hardware	Automation
First	Vacuum tubes	Electromechanical
Second	Transistors	Static
Third	Integrated circuits	Digital
Fourth	Microprocessors	Virtual
Fifth	Distributed systems	Distributed software

Source The Authors

5.2 Trends in High-Voltage Sensor Systems

In parallel with the developments in automation, new types of high-voltage sensor systems are being employed, such as:

- Rogowski coils
- Gas voltage sensors, and
- Optical sensors.

A Rogowski coil is typically a winding on a closed toroidal epoxy core where an induced voltage is generated proportional to variation in the current. Its main advantages are the absence of saturation, losses and hysteresis, offering excellent linearity due to the absence of iron in the core.

A gas voltage sensor is a cylindrical metal electrode molded into the sensor where an induced voltage is generated proportional to the primary voltage. Its main advantages are the absence of ferro-resonance and DC components, with excellent linearity due to absence of iron in the core.

Perhaps the most promising measuring high-voltage device is the optical sensor. It is formed by a free or magnetic shaping field gap where an optical signal flows in a fiber, where the wave phase is shifted proportional to the current in the primary circuit. Its main advantages are the absence of saturation, oil, explosions, losses, and hysteresis, common to the conventional instrument transformers. In addition, they offer excellent linearity due to the air gap, high accuracy and dynamic range, bandwidth and isolation, with low cost, low size and reduced weight. Figure 34 shows the typical assembly of an optical sensor.

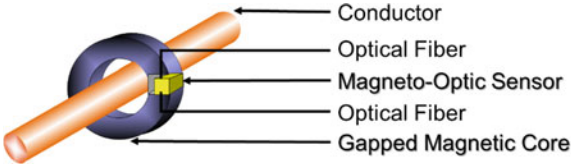


Fig. 34 Optical current sensors. *Source* The Authors

5.3 Advanced Metering Infrastructure

Advanced metering infrastructure (AMI) is the much-needed development to bring to the consumer most of the benefits offered by an intelligent or smart grid. An AMI is a system that measures, collects, and analyzes energy usage, and communicate with metering devices such as electricity meters, gas meters, heat meters, and water meters, either on request or on a schedule in order to manage, account and control the consumption of electricity. It is mainly composed of advanced meters, a two-way communication network to transfer the data to/from the advanced meters to/from the utility, and a meter data management (MDM) application to handle the large volumes of interval data provided by the system.

Figure 35 shows the typical hierarchy of resources used by AMI, mapped to the SGAM framework.

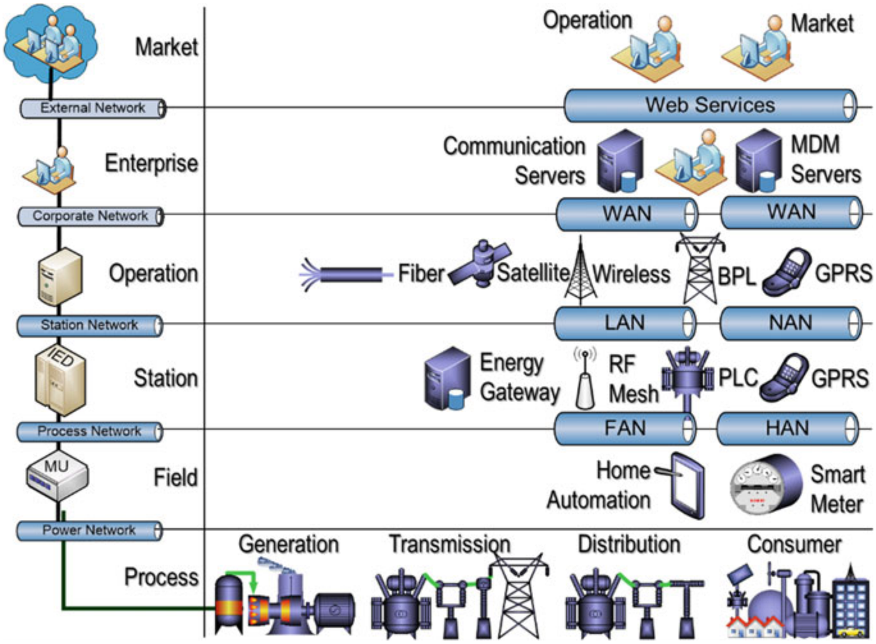


Fig. 35 Advanced metering infrastructure (AMI). *Source* The Authors

In an AMI, the meter data management (MDM) System is the central processing facility that provides several services for the utility and consumers:

- Multi-channel support (kWh, kW, kVAR, …)
- Meter asset, event, and data management capabilities
- Support for demand response and management programs
- Data aggregation, validation, editing, and estimation (AVEE)
- Multi-utility support (gas, electric) for different interval lengths
- Ability to maintain meter reading schedules
- Support for regulated and de-regulated markets
- Outage management and restoration support
- Complex billing capability and real-time pricing
- Web-based customer portal support
- Distribution asset optimization.

Figure 36 shows the major possibilities offered by modern metering systems, mapped to the SGAM framework.

At the consumer side of AMI, complementing the traditional meters used for consumption gauging, are the energy gateways, devices acting as an interface between the utility and the home area network for managing the power consumption. Figure 37 shows the typical architecture of a modern energy gateway, with multiple ports for communication with different home appliances.

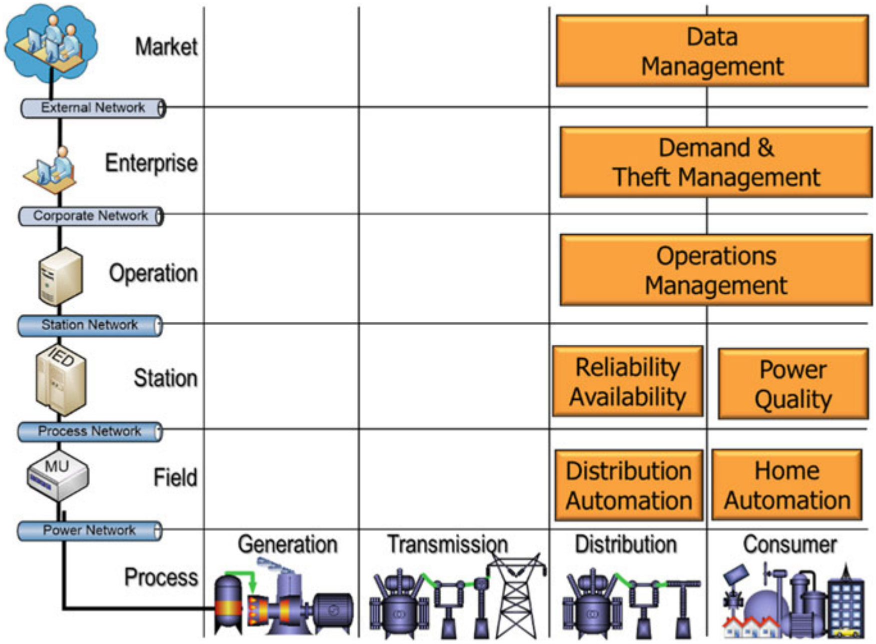


Fig. 36 Trends in metering systems. *Source* The Authors

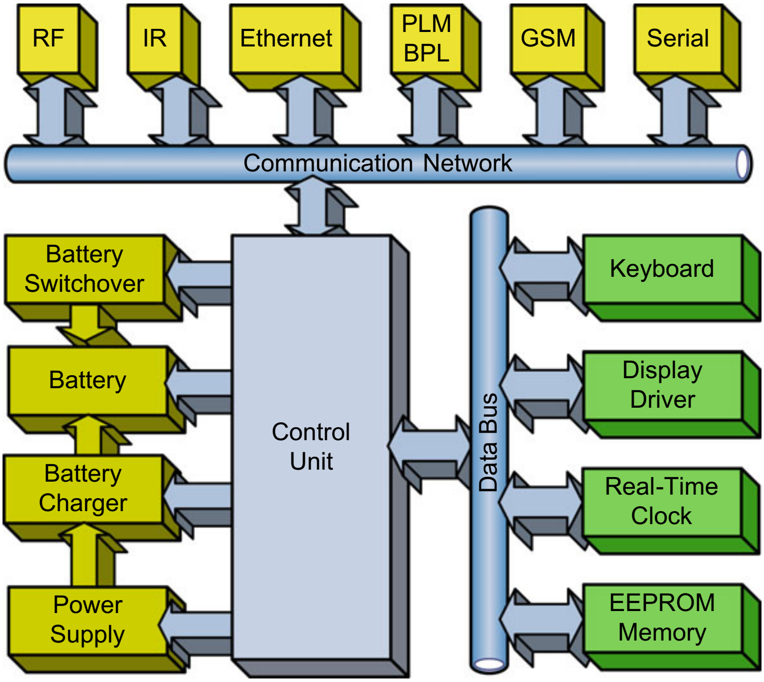


Fig. 37 Energy gateway. *Source* The Authors

Current and future capabilities of these intelligent (smart) meters include:

- Multi-tariff
- Adaptable viewer
- Energetic balancing
- Energy and demand limits
- Debit management
- Active and reactive meter
- Demand and power factor
- Supplier selection
- Consumption estimation
- Demand and fault alerts
- Pre-paid and control plans
- Energy, demand and credit time profiles
- Bidirectional metering
- Power quality
- Remote access and update
- Bidirectional communication
- Demand response

- Consumption analysis
- Home automation gateway.

Besides being a gateway to the utility MDM, the smart meter can also act as a home automation server.

5.4 *Trends in Home Automation*

Home automation is the next frontier for the full integration of the power grid, as it offers the possibility of bidirectional actions and benefits for the utility and consumers. Figure 38 shows a typical assembly of a home automation, where all home appliances are connected to the residential gateway using a home area network (HAN) and from there to the utility control center, offering also the possibility of connecting to the Internet, allowing home access to external services.

Figure 39 shows some of the major applications possible with the integration of home and utility automation, mapped to the SGAM framework.

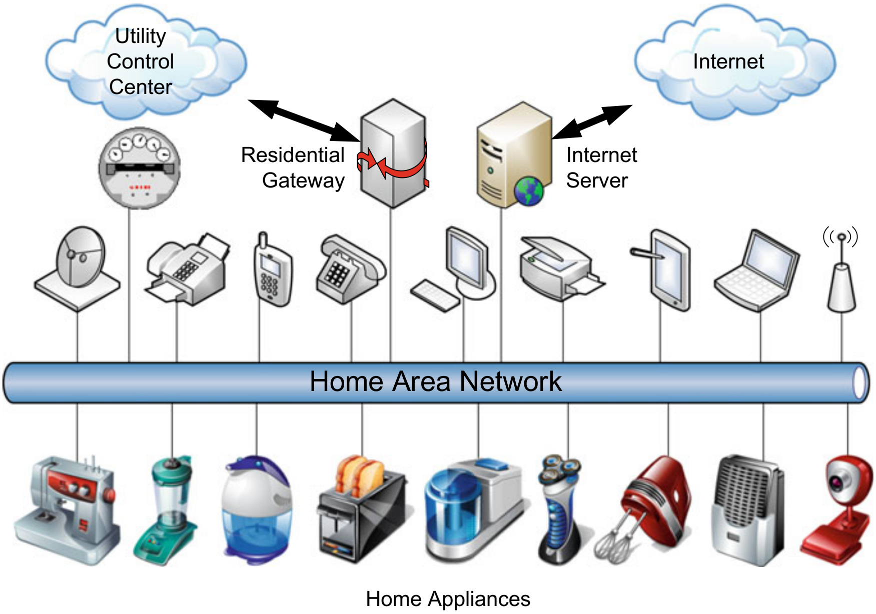


Fig. 38 Typical home automation. *Source* The Authors

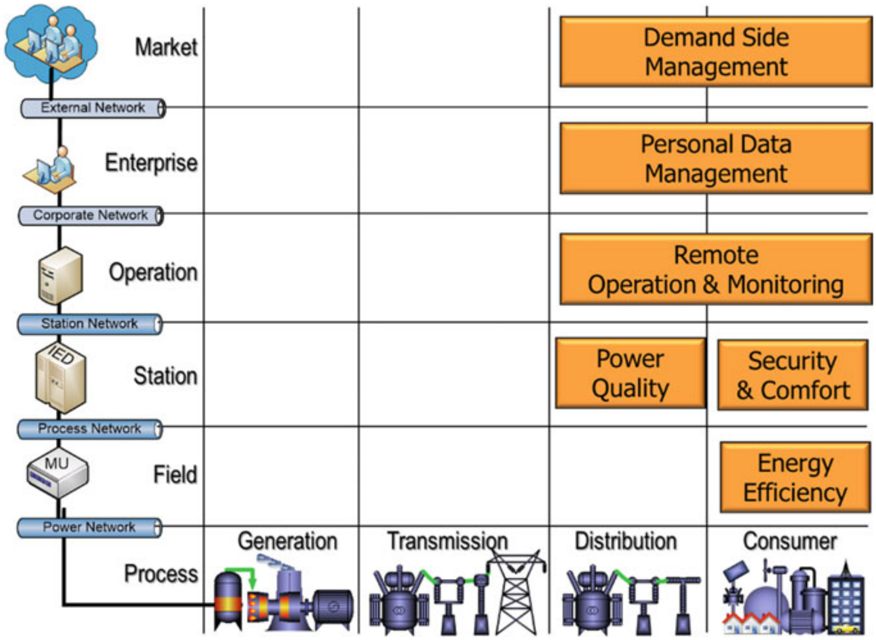


Fig. 39 Objectives of home and building automation. *Source* The Authors

5.5 *Trends in Substation Automation*

Besides employing all new developments in informatics and telecommunication, mainly guided by the standard IEC 61850, substation and inter substation automation are being planned with new applications based on the concept of synchrophasors.

Basically, a phasor is a vector consisting of magnitude and angle that corresponds to a sinusoidal waveform at a given frequency. A synchrophasor is a phasor calculated from data samples from an analogical sinusoidal source using a standard time signal as the reference for the measurement. Synchronized phasors from remote sites have a defined common phase relationship, guaranteed by a common time reference like the GPS signal. Figure 40 shows the basic principles of a phasor measuring system.

The phasor data concentrator, usually located in the same substation of the phasor measuring unit (PMU), collects synchrophasors locally and distributes to remote super phasor data concentrators, for use by wide-area monitoring and automation systems, usually at control centers. This provides also the root source of data for many new applications being developed for control center automation and many other power system applications, like state estimation.

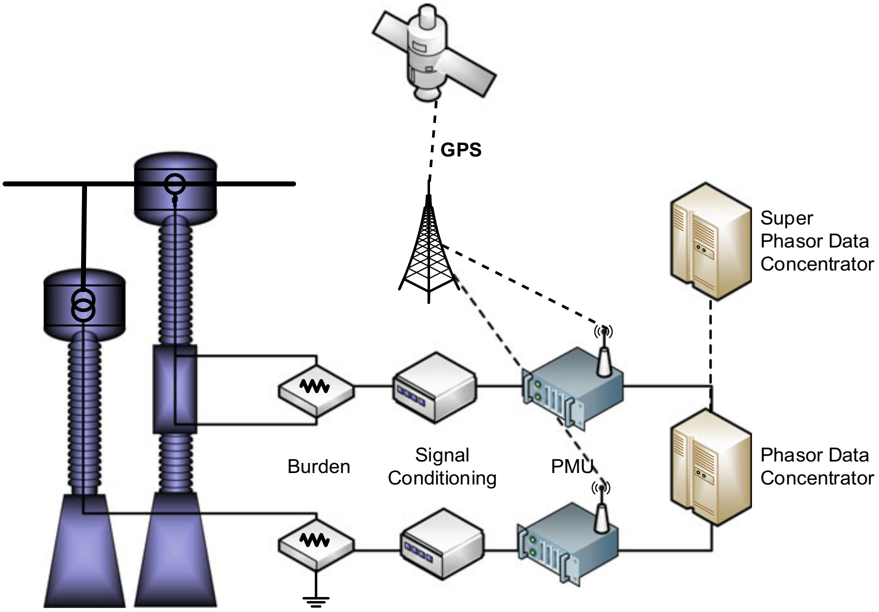


Fig. 40 Phasor measurement system. *Source* The Authors

5.6 *Trends in Control Center Automation*

Control center automation is the central focus of current development aiming to provide intelligence to the grid operation. Modern control centers are being deployed with many new characteristics such as:

- Clear separation of SCADA, EMS, and BMS
- IP-based distributed SCADA
- Middleware-based distributed EMS and BMS applications
- Ultrafast data acquisition system
- Hierarchical layers of services
- SOA adoption
- Access to cloud grid computing
- CIM compatibility
- Built-in security
- Platform independence
- Wide-area expanded applications
- Dynamic sharing of computational resources
- Distributed data acquisition, storage, and processing services.

In addition to managing the network, control centers are also the central repository of all grid-related data using the common information model (CIM) standard, to support other utility applications, like SCADA, EMS, operation, planning, asset management, maintenance, as shown pictorially in Fig. 41.

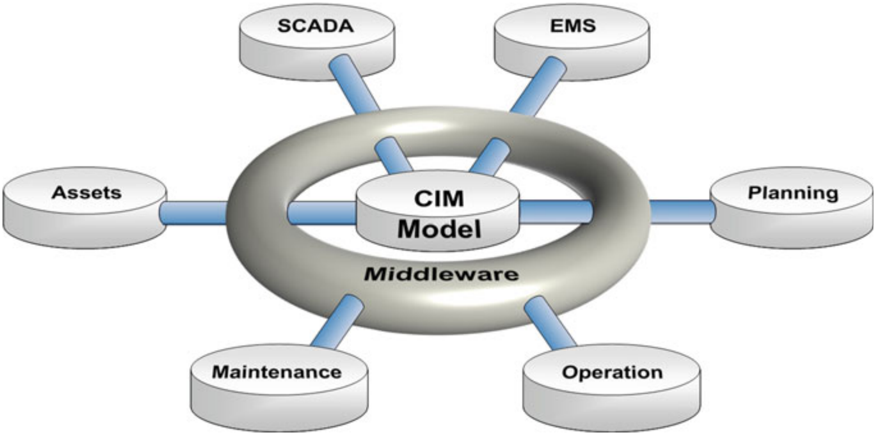


Fig. 41 Control center CIM model. *Source* Revista EletroEvolução, December, 2019

6 The Network of the Future

The success of the network of the future is dependent on the joint development and integration of all the previously described trends. Achieving these objectives represents a huge challenge for the entire power sector, and for each utility and agent of the energy sector, including consumers, producers, transmission, and distribution agents and regulators. This paragraph summarizes the main technical issues related to the network of the future, the need for standardization and interoperability, and the essential place of strategic planning to attain this future.

6.1 Technical Issues and Challenges

To address these challenges, CIGRE Technical Council has compiled the following list of ten issues that must be addressed in order to guarantee the full development of the network supply system of the future:

Issue 1—Active Distribution Networks

- Bidirectional power and data flows in distribution level
- Control and coordination of many small units
- Need for decentralized, intelligent control
- Massive implementation of smart metering and demand-side response
- Market and regulatory changes to manage efficiency, equity and cost recovery
- Distribution network architectures that include microgrids and virtual power plants.

Issue 2—Massive Exchange of Information

- Advanced metering with massive need for exchange of information
- New measured parameters, architectures of information, communication technologies, and algorithms
- Identification, requirements, and standardization of the data to be exchanged
- Disaster recovery and restoration plans
- Cybersecurity and access control.

Issue 3—Integration of HVDC/Power Electronics

- Impact on power quality, system control, security, and standardization
- Appropriate models for network performance analysis
- Harmonic distortion and filtering
- Designs and controls to provide benefits and performance enhancements to reliability
- Need new standards and grid codes
- Increased use of DC at end-use premises.

Issue 4—Massive Installation of Storage

- Need and impact on power system development and operation
- Construction: materials, installation and costs, environmental impact, efficiency of charge/discharge cycles, weight and size density, life-time estimation models
- Operation: modeling, management, sizing, co-operation with RES and DSM, islanding, peak reduction.

Issue 5—New Systems Operations/Controls

- New concepts for system operation, control and market/regulatory design
- Stochastic generation and modified loads due to DSM/storage
- Evolution of power system control at continental, country, regional, and local level
- Increased level of automation
- New competencies for system operators.

Issue 6—New Concepts for Protection

- To respond to the developing grid and different generation characteristics
- Wide-area protection systems (WAPS)
- Decreasing short circuit and flow reversal
- Coordination with fault ride through (FRT)
- Inadvertent and intentional islanding detection.

Issue 7—New Concepts in Planning

- New environmental constraints and solutions for active and reactive power flow control
- Risk-based planning with many uncertainties, addressing the interaction of transmission and distribution
- Comparison between new technological options
- Changing economic, market, and regulatory drivers.

Issue 8—New Tools for Technical Performance

- New customer, generator, and network characteristics
- Advanced tools, methods, and multi-agent techniques for the solution of dynamic problems, power balancing, harmonic performance, probabilistic, and risk-based planning
- Advanced modeling for loads, active and adaptive control strategies, and bridging the gap between three-phase and positive sequence modeling.

Issue 9—Increase of Underground Infrastructure

- Consequence on the technical performance and reliability of the network
- Technologies for uprating existing lines
- New submarine and underground cables
- Impact on stability, transients, overvoltages, and network management.

Issue 10—Need for Stakeholder Awareness

- Technical and commercial consequences, and engagement in the network of the future
- In the planning phase: demonstrate benefits, account for public views
- In the construction and operation phases: demonstrate compliance with environmental standards, and obtain support for the necessary actions.

These issues suggest that two models for network development in the future years are possible, and not necessarily exclusive:

- An increasing importance of large networks for bulk transmission capable of interconnecting load regions and large centralized including off-shore, as well as to provide more interconnections between the various countries and energy markets;
- The emergence of clusters of small, largely self-contained distribution networks, which include decentralized local generation, energy storage and active customer participation intelligently managed so that they are operated as active networks providing local active and reactive support.

The most likely shape of the energy supply systems of the future will include a mixture of the above two models, since additional bulk interconnections and active distribution networks are needed in order to reach the ambitious environmental, economic and security–reliability targets sought for.

6.2 Standardization and Interoperability

From the automation point of view, the greatest challenge in solving these issues will be how to guarantee the full interoperability of all these developments in a uniform and secure way. Interoperability is the ability of two or more devices or systems from the same vendor, or different vendors, to exchange information and use that information for correct co-operation. Figure 42 shows the concept that interoperability must be guaranteed not only at the physical component level, but also at the higher layers of the grid operation, mapped to the SGAM framework.

Standardization is the key requirement for any new technology to get full worldwide acceptance, considering the wide-area range of current solutions. Figure 43 shows an example of the automation architecture for a wholesale energy market, picturing the required interconnections from the physical meters up to the market agents, mapped to the SGAM framework.

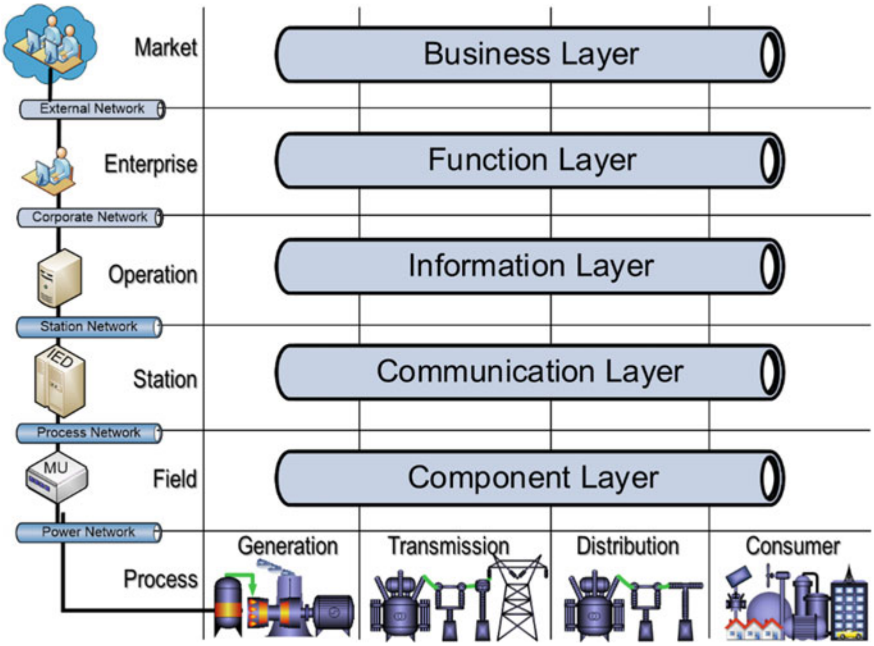


Fig. 42 Utility interoperability layers. *Source* The Authors

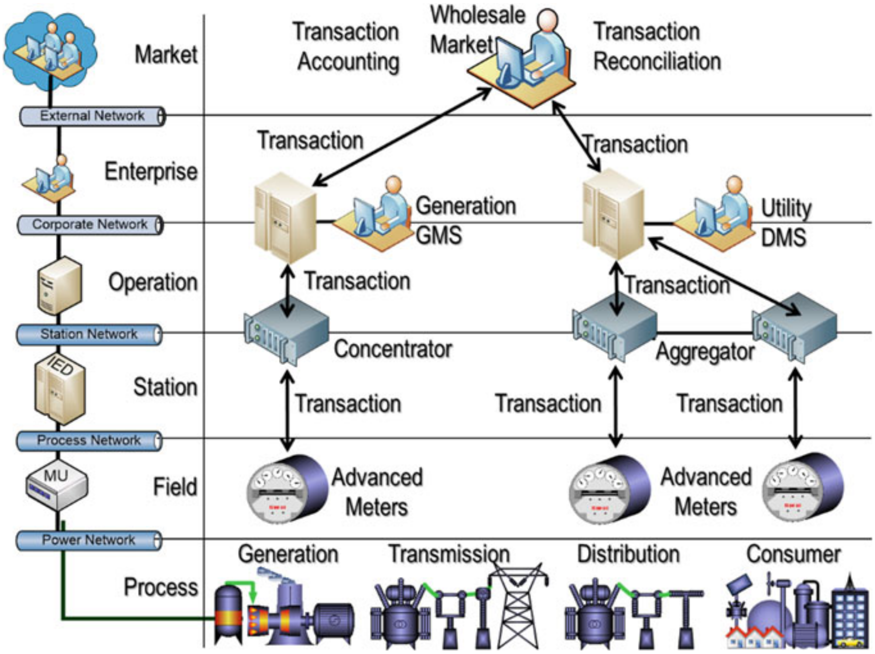


Fig. 43 Wholesale energy market. *Source* The Authors

6.3 Planning for the Network of the Future

As closing remarks for this chapter, the authors believe that a long-range strategic plan is an essential requisite for the survival and success of any utility or organization acting in the future energy sector. This plan should produce a consistent technological roadmap that:

- Defines the future state for all technological areas and markets
- Identifies the gaps in reaching the future state in each area
- Identifies other organizations working in each area and market
- Defines company's role and strategy in working in each area and market
- Identifies the company projects in each area and market.

The remaining chapters of this book are a good source of information about the specific and detailed technological changes expected to occur in the 16 subject areas covered by all 16 Study Committees of CIGRE. We hope you enjoy reading them as much as we!

Acknowledgements The authors want to express their gratitude to Tecnix Engineering and Architecture Ltd, for kindly supplying most of the pictures of this chapter, as excerpts from their training packages on Smart Grids.

The publication of this book would not be possible without the support from the Chairman of the Technical Council, Dr. Marcio Szechtman, the secretary of the Technical Council, Mr. Yves Maugain, Ms. Rannveig Loken, chair of CIGRE Study Committee (SC) B5 on Protection and Automation, and the enthusiasm and dedication of all the chapter authors, reviewers, and SC chairs.

References

1. Tiwari, G.N., Mishra, R.K.: Advanced Renewable Energy Sources. RSC Publishing, Cambridge, UK (2012)
2. CEN-CENELEC-ETSI: Smart Grid Reference Architecture, Smart Grid Coordination Group. European Commission, Brussels, Belgium (2012)
3. ISO: Organization and Digitization of Information About Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management Using Building Information Modelling. International Organization for Standardization, Genève, Switzerland (2018)
4. ISO 19101 a 19170: Geographic Information—Reference Model, International Organization for Standardization, Genève, Switzerland (2014)
5. IEC 61850: Communication Networks and Systems for Power Utility Automation, 2nd edn. International Electrotechnical Commission, Genève, Switzerland (2013)
6. IEC 61970: Energy Management System Application Program Interface. International Electrotechnical Commission, Genève, Switzerland (2005)
7. IEC 61968: Application Integration at Electric Utilities—System Interfaces for Distribution Management. International Electrotechnical Commission, Genève, Switzerland (2019)

Iony Patriota de Siqueira holds a D.Sc. and B.Sc. in electrical engineering, an M.Sc. (honors) in operations research, an MBA in information systems, and more than 40 years of experience in consulting, operation, and maintenance management for infrastructure sectors. He is an Honorary and Distinguished CIGRE Member and former Chairman of Study Committee on Protection and Automation, Chairman of Brazilian Technical Committee of IEC TC 57 and ABNT, an adviser for the Brazilian Maintenance Association, President and CEO of Tecnix Engineering and Architecture, Director of Brazilian Maintenance Institute, Permanent Member of the Brazilian National Engineering Academy, and a post-graduation visiting teacher at four universities. A recipient of CIGRE Technical Committee Award, Brazilian Engineering Premium, CIGRE-Brazil Best Paper Award, Vote of Praise from the Brazilian Chamber of Deputies and CIER Special Award. He has authored four books about Maintenance, Management Science, Power Plant Automation, and Critical Infrastructure Networks, and co-authored two books on Operations Research and Power System Resilience.

Nikos Hatziargyriou is professor in power systems at the Electrical and Computer Engineering School of the National Technical University of Athens (NTUA). He is Director of the Power Systems Division and founder of the “SmartRue” research unit at the Electric Energy Systems Laboratory. From April 2015 to September 2019, he was Chairman and until June 2018, CEO of the Hellenic Distribution Network Operator (HEDNO). From February 2007 until September 2012, he was executive Vice-Chair and Deputy CEO of the Public Power Corporation (PPC), responsible for the transmission and distribution divisions. He was chair and currently vice-chair of the EU Technology and Innovation Platform on Smart Networks for Energy Transition (ETIP-SNET) and former chair of the European Technology Platform on Smart Grids. He is honorary member of CIGRE and past Chair of CIGRE SC C6 “Distribution Systems and Distributed Generation.” He is Life Fellow Member of IEEE, past Chair of the Power System Dynamic Performance Committee (PSDPC) and currently Editor in Chief of the IEEE Trans on Power Systems. He has participated in more than 60 RD&D projects funded by the EU Commission, electric utilities and manufacturers for both fundamental research and practical applications. He is author of the book “Microgrids: Architectures and Control” and of more than 250 journal publications and 500 conference proceedings papers. He is included in the 2016, 2017, and 2019 Thomson Reuters lists of the top 1% most cited researchers.

Rotating Electrical Machines

**Nico Smit, Kay Chen, Ana Joswig, Alejandro Cannatella,
Eduardo José Guerra, Byeong hui Kang, and Traian Tunescu**

1 Introduction

Knowledge required to generate electricity is in existence since 1831. Nikola Tesla developed the AC generator into an industrial success during the nineteenth century. Basic generator design concepts have changed little since the nineteenth century, in contrast with significant technological advances taking place in material aspects, allowing generators and motors to handle higher voltage, more mechanical stress, higher current densities, higher temperatures and achieving better efficiencies.

As material technologies progressed, the size of generators increased, directly driven by the industrial revolution, requiring more electrical power to support and advance the exponential growth of global economies, which was successfully met by large robust and reliable turbo-generators and hydro-generators which in turn stimulated the development of advanced insulation systems, improved cooling methods and higher strength materials.

As industrial processes advanced and developed, higher mechanical motor torque was required to drive large mechanical industrial processes. This elevated the mechanical power requirements of electrical motors to higher levels, resulting in technological advances of both motors and generators to develop simultaneously.

The historic developments of motors focussed on achieving higher voltages and currents, various starting cage topologies to cater for higher starting torque and

---

On behalf of CIGRE Study Committee A1.

N. Smit (✉) · A. Cannatella · B. Kang · T. Tunescu
CIGRE, Paris, France
e-mail: Nico.Smit@mercury.co.nz

K. Chen · A. Joswig
Siemens, Mulheim, Germany

E. J. Guerra
IMPSA, Mendoza, Argentina

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_2

stronger materials required for high torque industrial loads, advanced cooling methods such as water cooling and forced air cooling. Another significant advancement in motors was achieved through the international standardisation of motor frame sizes and ratings which significantly contributed to the globalisation of motor manufacturing.

Historic developments of generators focused mainly on available fuel aspects:

- Air-cooled machines for gas turbine generator and hydro-generator applications;
- Hydrogen gas-cooled machines for coal-fuelled turbo-generator applications;
- Hydrogen gas cooling combined with water-cooling machines for turbo-generators in coal- and nuclear-fuelled applications.

The introduction of directly water-cooled as well as directly gas-cooled generator stator bars was a significant advancement in the design of large turbo-generators, allowing current densities to be increased from approximately 5 A/mm^2 for conventional air-cooled machines to up to 10 A/mm^2 for directly water-cooled stator windings. The direct cooling of stator winding copper conductors in combination with the use of hydrogen gas cooling to directly cool rotor windings resulted in revolutionary changes to the size, efficiency and capability of generator electrical output.

Significant achievements in the thermal conductivity of generator stator bar insulation material allowed the development of improved indirect hydrogen gas cooling of generator stator windings, resulting in less complex auxiliary systems for the removal of heat from high current density stator bars as the need for direct water cooling, with its associated adverse effects on copper conductors, is eliminated.

Advances in insulation material voltage withstand capability and improvements in manufacturing processes supported advances in capacity and also ensured more reliable and very high efficient generators and motors.

More recent developments are focused on the large-scale development and optimisation of generator and motor technologies for the support of renewable energy as well as to support changing grid requirements as a result of the introduction of larger-scale renewable energy. These developments are focusing on the following technologies:

- Small air-cooled wind turbine generators with developments mainly in:
    - Doubly-fed induction generators;
    - Permanent magnet generators.
- Air-cooled bulb turbine generators for run-of-river applications and tidal wave applications.
- Newer generation turbo-generators with the focus on being capable of withstanding harsh operating conditions such as severe load cycling and two-shifting. Two major developments in this field are:
    - Improvements in rotor copper coil extrusion techniques allowing legacy half-turn windings to be consolidated into a single turn winding or by consolidating

    the complete historically loose turn copper coil stack into a solid insulated coil. This eliminates copper dusting and slot liner wear which was a major concern for two-shifting units.
  - Development of air-cooled generators using demineralised water for the direct cooling of stator windings and air for the direct cooling of rotor windings. Water-cooled stator windings are commonly associated with very large generators requiring hydrogen gas for the cooling of rotor windings but with an ever-changing grid, water-cooled stator winding technology is now also applied to smaller air-cooled generators. This is done to ensure less strain on generator stator windings during severe load cycling conditions as water cooling maintain stator bars at a more constant temperature as opposed to indirect air or gas cooling.

- High efficiency motors support the drive towards more cost-effective energy utilisation which directly results in significant savings in future generation expansion which has a direct and significant reduction in greenhouse gasses.

Continued developments in electromechanical generator and motor technologies are essential to sustaining the energy generation and energy conversion process. Without the past technological advances in these magnificent machines, industrial developments would not have been possible, and today these magnificent machines are still the backbone of all economies. These machines will continue to play a significant role in all forms of renewable generation schemes due to its reliable, predictable and controllable nature, its high inertia support to grids, effective fast-acting voltage support when needed and its robust reactive power support capabilities. These machines continue to form the heart of the present electricity network and will continue to do so in future network topologies to reliably support renewable generation in the form of wind turbine generators, hydro-generators, concentrated solar power plant generators and bulb turbine generators. Electrical motors are presently the only effective means to convert electrical power into mechanical power, which is required in virtually every industrial process as well as in a magnitude of household appliances and will therefore continue to do so for generations to come.

It is therefore important to further develop and refine these crucial components in the electricity generation and consumption process to ensure it remains relevant by adapting to the evolving energy infrastructure.

2 State-of-the-Art Technologies

2.1 Technology

Present-day turbo- and hydro-generators have undergone significant developments since the inception of electrical machines. Although the basic principles have remained unchanged, significant advances were made in insulation material characteristics, cooling methods and material properties to allow the optimisation of designs which resulted in mega-sized machines with large power output, very high reliability and efficiency.

Some of the developments that contributed to the success of large motors and generators can be attributed to:

- Radial cooled thermal pumping gas-cooled rotors.
- Robust and optimised hybrid stator core end zone designs.
- Robust stator end-winding design for low vibrations and maximum reliability.
- Global Vacuum Pressure Impregnated Stator (GVPI).
- Insulation with enhanced thermal conductivity and electrical properties resulting in the possible elimination of water cooling in very large generator designs.
- Highly reliable water-cooling technology utilising hollow stainless-steel tubes embedded into copper conductor bundles which provides robustness to deal with fast ramping, transient over load and heavier duty cycles which will be required by future grids. The use of stainless-steel tubes also relaxes complex chemistry control issues.

Some of the more recent developments to further improve the ability of these magnificent machines to cope better with modern-day grid demands are as follows:

- High power density air-cooled generator technology with actively controlled pressurised air cooling as options for flexible operation in a wider power range, which also offers the elimination of H_2 gas for cooling which brings about safer and less complex operating and maintenance.
- Fast response brushless excitation systems eliminating the unreliability and high maintenance associated with static excitation systems requiring problematic carbon brushes to supply excitation current to generator rotors.
- Improvements in robotic inspection technologies which can result in less invasive maintenance inspections and potentially shorter shutdowns [1].
- Low maintenance permanent magnet synchronous generators (PMSG) for wind power generation.
- Doubly-fed induction machines applied to wind power generation and pumping storage systems.
- Maintenance and equipment health optimisation by means of artificial intelligence (AI).
- Reliability-oriented design.
- Online monitoring with real-time health assessment of generating and motor units.
- Optimised computerised maintenance management.

The following state-of-the-art technologies are presently in development:

- Preventive diagnostic systems for rotating machines using smart sensor and big data.

- Advanced calculation programs for optimisation of designs for rotating machines using artificial intelligence (AI) with the aid of advanced software embedded algorithms.
- The use of industrial diamond dust as a cost-effective replacement for mica flakes in the manufacturing of stator bar insulation and core lamination varnish.
- Use of water-cooling stator windings in large capacity permanent magnet generators.
- Use of superconductor materials in motors and wind turbine generators.

The long-term vision for rotating electrical machines such as synchronous generators, induction motors and DC motors is to remain relevant in the energy generation and consumption process but completely integrated into future technological advances associated with Fourth Industrial Revolution computer-based solutions. Closed-loop control systems as we presently know will not exist in a modern power generation process, being replaced with a highly intelligent self-learning monitoring and control process. This can significantly improve the life expectancy of rotating electrical machines as it can eliminate human error incidents. It will also act immediately to abnormal operating conditions, rectifying operating conditions faster than any human intervention can allow.

2.2 Methodology

Generator and motor design methods have evolved significantly from past elaborated hand calculations and iterations to current computer-based design models. The advances to computer-based calculations and modelling have significantly improved design and manufacturing repeatability as well as optimised designs with associated reduced manufacturing costs. Advanced modelling techniques are used to eliminate highly stressed areas in affected components, therefore significantly improving reliability and increasing life expectancy. The use of large capacity computing power has made these optimised designs possible. The use of new design and manufacturing methodology has unfortunately resulted in a lack of in-depth understanding of complex design principles.

Some of the modern systems and techniques used to assist design engineers with design optimisation and modelling are:

- The use of finite element modelling (FEM) applied to structural and electromagnetic analysis.
- Use of computational fluid dynamics (CFD) applied to thermal and ventilation phenomena.
- Long-term reliability analysis of thermal, hydro and wind power's electromechanical equipment.
- PROACT decision-making models for problem analysis and complex decision-making. The decision-making model 'PrOACT' is a mnemonic that stands for five key elements in the model:

  - Problem statement
  - Objectives
  - Alternatives
  - Consequences
  - Trade-offs.

- Optimisation of productivity in manufacturing processes using analytical software systems.
- Development of new materials which allow alternative design and manufacturing processes to be used.
- Big data, artificial intelligence (AI), self-learning algorithms, equivalent digital twin circuits, design of experiments (DOE) and response surface method (RSM) which can enhance the present computer-based modelling techniques to deliver an even more optimised perfectly repeatable design.
- Coordination of rated values between power export equipment in power stations.
- Clear understanding of power system needs using advanced power system modelling.

All above-listed techniques and systems can be used in multi-physics modelling with integrated finite element analysis (FEA) models linking mechanical structural integrity calculation, life cycle calculations, electrical loss and thermal calculation with computational fluid dynamics (CFD), all combined to perform optimisation for enhancing maximum power output and achieving optimum mechanical performance. The development of digital twin capability from these combined processes also allows the monitoring of machine operation post-design and manufacturing to further improve life cycle management.

2.3 Standardisation

Standardisation in industry has several benefits, both to manufacturers and for users of electrical equipment. Benefits to manufacturers include standardised designs, standardised manufacturing processes and standardised common materials supplied by sub-manufacturers. Skills can also be optimised as a larger pool of skills can be available between manufacturing industries with similar knowledge and experience. Standardisation can play a very important role in reducing costs and improving quality of designs as a larger pool of knowledge and experience can be used for optimising designs. Benefits from utilising economies of scale can also be realised, to both manufacturers and users of equipment.

Users of rotating electrical equipment benefits from large-scale standardisation as it eases interfacing new equipment with old equipment during refurbishment and replacement projects, which will have significant cost-saving opportunities as interfaced equipment can remain unmodified.

In the field of rotating electrical machines, significant achievements have been made to ensure standardised systems in the specification, manufacturing and testing of low voltage and medium voltage motors. One exception where standardisation is not possible is special application motors which might deviate from international standard designs. Standardisation of motors has already contributed significantly to costs savings to both manufacturers and users.

Within generator technologies, standardisation between manufacturers is rare, if existent at all. Each manufacturer optimises its design to achieve maximum performance versus cost for the specific technologies used in their designs. Due to the merger of various manufactures through time, designs have also merged between technologies, which eventually become incompatible with previous designs. This is bringing about significant project complications for users when midlife refurbishment and end of life replacements are required. Modifying existing plant to accommodate new design frame layouts, sizes and weight can add significant cost and time to a project.

Standardisation of electrical motors using IEC and IEEE standards has contributed significantly to achieving standard sized motors globally. The absence of frame size standards for generator technology has resulted in non-standard equipment globally. Although it might not be perfectly feasible to enforce standardisation of all aspects of generator designs, certain guidelines or standards can assist in achieving the same benefits that presently exist with electrical motor standardisation.

Some generators where frame size standardisation is already applied can be found in the field of wind turbine generators, small hydro-generators and small diesel generators, although different technologies can still have significant differences for the same rated power output, for instance, the differences between doubly-fed induction generators vs permanent magnet generators, or differences between brushed and brushless excitation systems. Significant differences also exist in the field of bulb turbine generators as the generator design depends heavily on the design of the total bulb construction in cases where the generator forms an integral part of the bulb.

In cases where it is not possible to standardise on aspects such as the generator frame, layout and weight, perhaps the standardisation between manufacturers on replacement spare components is possible, such as stator bar designs and its support components, seals, gaskets, bearings, hoses and consumables.

One complication with the process of standardisation is that standards guiding and enforcing standardisation are not always freely available to smaller manufacturers and users as these standards require some form of membership attached to annual fees, or once of purchase fees at a significant cost. It is understandable that costs are involved with updating standards and to keep it up to date, but the fact that costs are involved with the purchase of new standards results in the use of old standards during the specification process as not all users and manufacturers have access to the latest up-to-date standards.

A very important aspect to take cognisance of is the fact that the improvement of machine standards should be aligned with present and future market and grid developments. Presently, specific regional requirements from new grid codes are working against the benefits of standardisation as equipment purchased for different regions will be different with regard to reactive power capability, voltage envelope, etc. [2, 3], as required by these regional grid codes. Economic aspects are a very important factor to consider when purchasing non-standard equipment to comply with specific grid code requirements.

2.4 Education and Skills

The large-scale utilisation of technology to assist with modelling, design, optimisation, monitoring and predictions requires advanced skills. These skills are very different from past analytical skills and now require highly skilled personnel capable of developing new advanced modelling, design, manufacturing, condition monitoring and condition analysis tools. Skills of the future are required for improved team work, innovation, marketing, sustainability, econometrics, reliability engineering, finite element modelling, artificial intelligence systems requiring advanced programming, analysing and interpreting big data. Knowledge and intimate understanding of advanced sensors and monitoring systems within its applications are also a very important requirement.

To effectively implement advanced analytics, artificial intelligence and digital twin concepts for motors and generators, engineers require a clear and in-depth understanding of electrical machine equivalent circuits, thermal images and calculation of modification factors. These skills are quickly depleting but the effective use of present available expert engineering skills collaborating with modern software engineers can ensure that the present design capability remain embedded in present and future intelligent systems.

Although there will be a significant focus on upskilling engineers to be ready for the fourth industrial revolution, one aspect of rotating electrical machines will never change, which is the physical electromechanical nature of machines in which electrical technology will coexist with mechanical technology for the foreseeable future.

The present lack of interest in the state of the art of artisanship and mechanical specialisation is already affecting the health and reliability of large rotating machines. The Fourth Industrial Revolution has created various expectations in the younger generation, which is mainly focussed on acquiring soft skills, with a significant lack of focus on the interfacing architecture required between artificial systems and real-life applications.

Balance between hardware and software–electrical and mechanical must always exist to ensure a balanced approach to the Fourth Industrial Revolution; it cannot survive without proper coexistence of all arts of engineering. Skills in FME modelling as well as real-world hands-on experience in power plant operation or power equipment manufacturing/maintenance will remain very important. Therefore, good and solid theoretical education together with gaining strong practical experience in electric machines, power systems, mechanical structural integrity and heat transfers is fundamental and essential for engineers working in the power engineering sector.

A present phenomenon that greatly affects the future of rotating electrical machines is the migration of scarce skills from developing countries to developed countries, being offered better salaries, safer living conditions and a better future for their offspring. As a direct consequence, it leaves complex state-of-the-art equipment possibly poorly maintained. Although this phenomenon is presently affecting developing nations to a great extent, it is also an indication of what to expect in future for developed countries as there is a clear global deterioration in specialist skills as the interest to remain in a single career for life is diminishing. The present lack of experienced skills is already a major problem globally.

3 New Societal Requirements

Our modern world comes with modern expectations. These expectations need to be considered if the power electrical sector wants to fulfil the needs and expectations of modern society. Various aspects of these expectations are considered in this chapter.

3.1 Stakeholders

Society is directly affected by technologies used for power generation, be it due to the contribution of technologies to air pollution, noise pollution, visible pollution as well as the perception of pollution. It is important to identify relevant stakeholders when technologies and advances in technologies are considered. Various stakeholders play a significant role in power generation. Different cultures have different needs and expectations, and need fulfilment in different ways, which in turn need consideration in these new developments. The following stakeholders need consideration in the development of future technologies:

Country Needs from society in a developing country can be different from the needs of a society in a developed country. Focus on environment, health and preserving resources might have different meanings in the context of developing vs developed, and this must be considered when future power generation systems are planned and developed.

Government Voter base expectations and tax base expectations might influence the decisions governments make towards the development of new power generation projects. The choice of power generation technology directly influences the selection of generator technology, which again affects the need of specific skills. Very large complex water and hydrogen gas-cooled turbo-generators require adequate skills to maintain, manage and operate and require a completely different skills set than a photovoltaic plant or a wind farm. Skill and equipment availability for maintenance and repair purposes should play a significant role in the planning of new generator technologies. These decisions need to be considered when future generation technologies are planned and motivated for future governmental support and investment, together with solutions to fulfil the requirements of taxpayers.

People The end-users are always people, either in a family environment or in a corporate or industrial environment. People are directly affected by poor decisions. People have needs as well as rights and people expect these needs and rights to be fulfilled in a modern society, although not always possible with all existing technologies. Needs are also extremely diverse among people. Future technologies should attempt to fulfil a broad spectrum of needs as the voice of people becomes more powerful. Environmental rights are becoming a key influencer of future technologies as can be seen in the renewable energy drive. A large focus exists on compliance with legislation which places significant pressure on companies to comply and to also fulfil their corporate social responsibility towards society. Poor decision-making can adversely affect people if not considered carefully. Power plants are generally perceived as dirty and unhealthy. Both the fuel used in the process of generating electricity and the by-products from this conversion process is dirty. Coal transportation either by road, ship or rail always leaves a trail of black dust, contaminating the environment. Visible smoke from chimneys directly affects the health of people. Ash as well as the water used for conveying ash can have several health and environmental consequences, directly affecting the well-being of people.

R&D Research and development institutions have pressure on them to fulfil the needs of a modern connected society, and future developments must take these needs into consideration. R&D centres cannot consist solely of engineers anymore, but need to have a balance between engineers, psychologists, environmental experts, human behaviour experts, visionaries, health experts and need a close collaboration with key members from society.

Equipment Manufacturers With significant focus on health and environment, manufacturers of industrial equipment, which includes modern electromechanical equipment in the energy conversion process, need to be focussed on changing the perception that exists among the general population. This can be done by being completely transparent in their design and manufacturing process, allowing the general public access to their modern factories implemented with modern-day clean technologies. Where public cannot be allowed to enter factories due to dangers and the effect on production pressures, virtual tours in real time using 3D technology can be used or interesting short videos on social media. Up until now, factories were completely closed to the public due to safety reasons as well as internal intellectual property rules. This creates the impression that factories still operate with out-of-date polluting systems, whereas modern-day factories are operated environmentally friendly. By promoting a transparent manufacturing process, the perceptions of other stakeholders might change, and using modern social mediums can achieve this.

Energy Policy-Makers are the architects of the future power generation mix. If they have the correct mind-set as well as knowledge and are forward-thinking, they can establish an ultimate energy mix for the future. Unfortunately, too much political influence is affecting the work of these crucial stakeholders. By allowing the freedom to develop the perfect energy mix, a near-perfect balance between network stability, environmental affairs and state-of-the-art technology can be achieved.

3.2 Economy

The construction of new generating plant is a major capital expenditure. The significant costs involved with these projects can adversely affect the financial health of governments or private power generation entities if poor decisions are made. Profit margin in power generation is small, and any miss-interpretation of future business models can directly lead to the financial failure of a company or even a country. A deeper understanding of the desired value is therefore required in order to create value for customers, corporate clients, human talent, and suppliers and requires an in-depth study of social and environmental perspectives. The dependency on conventional project financial benefit calculations is no longer enough to direct the financial resources of organisations as renewable off-grid power generation solutions are becoming more financially viable for general consumers, making present grid consumption figures irrelevant for use in any business model for expanding grid fed electricity.

As fuel cost, labour cost and equipment cost keep on increasing, in many countries at a rate higher than inflation, the cost of electricity keeps on rising exponentially, getting to a point where general public cannot afford the cost of electricity anymore. This directly affects society. Society expects their basic needs to be met, with the expectation of reliable electricity at an affordable price.

3.3 Ecology/Environmental

As power generation projects have a direct influence on the environment, it is essential for practical tools to be developed and made available to society for evaluating the impact of projects on the environment and to quantify and compare different alternatives. The commitment of industry in its entirety is necessary to avoid the development of environmental damaging projects that can lead to serious environmental and social health problems. Decisions on power generation technologies can be very complex as its total life cycle impact need to be considered. A project might be environmentally friendly throughout its useful life but can have a devastating environmental impact when discarded.

There is presently a lack of available legislation to control and evaluate and guide the implementation of new generation technologies, considering the full life cycle impact of all available technologies. Legislation should in general promote electricity to be generated in a reliable and sustainable way with zero dangerous chemical waste and with optimised available land utilisation and minimised additional land acquisition.

3.4 Education, Skills and Work Culture

The introduction of new generation skills into the workforce of an industry characterised by high specialisation and mature technologies sets a new challenge to organisations. The main challenge being the time required to acquire the level of know-how and maturation to make decisions assertively. Industry should therefore think profoundly in how to change the work environment to attract and retain young talented people.

One initiative that can improve retention as well as speed up the built of skills is to promote educational mobility. Boosting global mobility of learners between institutions can help students to acquire new skills which can strengthen future employability and at the same time remain motivated in their role.

Multi-skilling will be an essential requirement in future. By encouraging modern engineers to be multi-skilled in different systems and by supporting their development in multi-skilled environments can keep modern engineers interested in their careers. Combined knowledge in electrical machines and power system dynamics is very important. Another facet is the use of artificial intelligence combined with existing knowledge of machines to create a self-learning machine model for machine design, condition monitoring, fault diagnostics, maintenance planning, etc.

3.5 Other

Rotating machines should and will play a new role to interconnect renewable generation into the electrical grid, providing to the grid not only electricity but also stability and other types of ancillary services. The unique capabilities of rotating machines (such as in synchronous compensator applications and other applications) will enable better utilisation of inverter interfaced renewables and therefore help to improve economics for future electricity generation scenarios. The grid is changing at a very fast pace and a balanced approach to phasing in renewable energy sources is essential. This is becoming more and more pressing and will require faster and more advanced engineering research. The impact of not delivering a well-balanced grid in time must also be made clear to society as failure to plan and improve the stability of the future grid, with the fast introduction of renewable energy sources, can have devastating consequences on society as it will result in frequent and extended power outages.

4 New Grid Requirements

4.1 Evolving Grid

The introduction of renewable energy into transmission grids has brought about significant changes to the whole transmission system, affecting all interconnected components. From a very stable controllable grid, mostly requiring fast interaction only during peak hours and unit trips, it has quickly evolved into a continuous fast response system. With various renewable energy sources feeding into the grid from different environmental regions, load demand must be constantly balanced with generation from all energy sources available at that point in time. The depletion of traditional synchronous machine inertia is also having a major effect on grid management as it is making grids very sensitive for fault conditions.

As more renewable energy sources are introduced into the grid, increased load, frequency and voltage variances can be expected throughout the day. During times of high feed-in of renewable power, base load units will have to operate at minimum load or even as spinning reserve, to enable fast ramp-up during sudden low feed-in of renewable power. This places extreme demands on conventional power plants, introducing mechanical and electrical stresses for which they were not designed for. Sudden frequency changes also have significant torque variations on motors, which could introduce failure mechanisms beyond their design capability. It is foreseen that the network of the future to be consisting of vastly more renewable energy sources. For countries with a large penetration of hydroelectricity, this will be of no concern; but countries relying heavily on conventional fuel for the generation of electricity, this can have a devastating impact on conventional equipment.

Various factors will have to be considered for this very fast-evolving grid, taking into consideration new stronger materials to withstand the mechanical effects on rotor shafts, copper conductors and stator winding insulation material. New concepts will have to be introduced to maintain winding temperatures constant during load cycled operation to reduce copper fatigue and insulation wear. The effects of new grid requirements will severely affect the reliability of generating equipment and directly affect its reliability. Modern operational requirements seem to be requiring availability targets as high as 95% with forced unavailability of 1%. Generators and motors are also required to have less frequent maintenance and maintenance to be easier to perform, also to be equipped with the capability of auto-diagnosis and predictive maintenance techniques from comprehensive monitoring systems.

Base load generators are in general not designed to operate in a continuous load cycling environment and can therefore have a detrimental impact on their reliability and life expectancy. New grid codes are also requiring generators to be able to operate for long durations at speeds below rated speed, while rated voltage should be maintained, resulting in possible over fluxing conditions. These new requirements must be considered when new machines are specified as these machines might still be in service 30 years into the future. Network conditions will have to be anticipated and already now included in specifications for new plant to allow successful operation throughout its design life.

4.2 Future Network

The future network will have definite and vast differences from the present network control philosophies and due to the complexity of instantaneously balancing future generation with future strict load stability requirements, a fully automated power delivery network will be required which monitors and control every consumer and node, ensuring an instantaneous two-way balance of electricity and information. This will require intelligent automated real-time interaction between centralised generators, distributed generators, consumers, prosumers as well as transmission and distribution control centres.

Modern grid codes will have to be developed considering this future network, requiring all connected systems to comply not only with electrical network requirements but also with advanced communication and control protocols. For the complete system to operate optimally, all systems will have to be perfectly harmonised using a common communication protocol. Presently, the transition from fossil-fuelled generation to renewable energy is taking place with very low focus on ensuring a sustainable power transmission system as real inertia is replaced with virtual inertia without fully understanding and appreciating the impact of it. Grid codes will have to play a significant role in managing this transition. From a grid stability point of view, taking into consideration the need for real inertia, an optimal balance is necessary between inverter fed generation and conventional generation. It is essential that this optimal balance is determined and guided through grid codes. Even with the most modern communication and control practices, grid stability cannot be ensured without the contribution of vast amounts of stored energy in the form of real inertia.

Present grid codes unfortunately have a very one-sided approach [2, 3], mostly focussing on the requirements for connected machine characteristics from a grid stability point of view, at a significant cost to generator manufacturers and users. Future grid codes need to approach grid stability with a much more analytical approach, taking into consideration the technical limitations of rotating machines, the effect of inverter fed generation on the stability of the system, the introduction of synchronous compensators in the future energy mix and real-time communication and control between all network interconnected systems. If grid codes are not completely harmonised between regions and between all network equipment from manufacturers to users, a significant risk of network failure will result. Presently, grid codes place wider operational requirements to generators which wish to connect to grids. This is done to strengthen networks in the absence of strong inertia-based generation. This trend is placing significant strain on conventional generation to comply with grid codes and requires additional development, design and manufacturing costs. As inverter fed energy is added to networks, requirements for conventional generators might become even more strict to utilise conventional generation to maintain grid stability. Grid codes will introduce, rather than mitigate, reliability concerns by introducing risky/harmful fault ride through capability requirement to turbo-generators. By specifying requirements either not clearly or too specifically strict, grid codes introduce the risk of significantly elevating the cost of generation capital expenditure projects.

4.3 A New Approach

A new way of thinking in managing a future modern grid will be required and might require limiting inverter fed generation to a predetermined level until new technology and/or vast battery storage is implemented to completely support inverter fed generation during fault transients. Grid codes play an important role in defining energy policy and payment mechanisms. Therefore, grid code developers should have it in mind to support R&D for the development of technologies useful and supportive of the future grid.

Study Committee A1 developed Technical Brochure 743, 'Guide on New Generator Grid Interaction Requirements' [3] to identify present shortcomings in international grid codes with reference to rotating electrical machine specifications.

5 New Technologies

5.1 Hardware and Materials

From a rotating electrical machine point of view, power electronics is associated with higher order destructive harmonics which most generator and motor insulation systems are not specifically designed to withstand. Higher order harmonics also introduce circulating surface currents on generator and motor rotors which lead to surface heating if damper circuits are not part of the original rotor design. With the increase in inverter fed renewable energy sources, conventional design generators and motors are at high risk of premature failure, if exposed to severe continuous harmonics. As inverters are a reality in modern power systems, all future power system connected devices must be designed to withstand the adverse effects of giga-scale power electronics. This needs to be taken into consideration in the designs of all generators and motors and will require international standards as well as grid codes to be updated to reflect this requirement. Presently, significant conflict exists between what grid codes require from electrical machines and what international standards dictate to manufacturers [2, 3]. This misalignment needs to be corrected to ensure a reliable future network.

As networks are becoming more erratic in their energy profile, all connected generating equipment needs to be able to withstand frequent and sudden load variations. These load variations result in significant thermo-mechanical stresses on long stator and rotor copper conductors and their insulating components. Conventional generators were mostly designed as base load units and cannot necessarily withstand frequent and extreme load variations. Most of these machines were built with state-of-the-art technology existing 30 years ago but do not necessarily have the ability to withstand the extreme anticipated requirements of a future network. This is a significant risk to the viability of a future network if not dealt with immediately in a practical manner, as extreme network variable energy profiles significantly affect the available life from these already over-stressed and mostly aged electrical components. One solution to relieve the impact on highly stressed electrical components is to introduce enhanced load-dependent cooling technologies. This can reduce the thermal–mechanical stresses during severe load swing requirements. Special generator design features such as water-cooled stator windings, variable hydrogen gas pressure or air cooling pressure control or modified stator core end regions can be significant contributors to adapt to flexible operating regimes. Some of these features can be introduced to many existing legacy fleet generators, but a large number of plants will require a systematic but urgent refurbishment and replacement strategy to reduce a growing forced outage risk.

Presently, legacy generating plant is subsidising wind and PV energy sources, to the detriment of these legacy machines. The introduction of large-scale PV and wind generation requires an equal investment in storage capacity as these sources of energy are rarely available during peak demand periods. Presently, legacy base load generating units are utilised in a load-following capacity to fill up the generation gaps left by PV and wind generation. These legacy machines are losing significant operational life as a result of the increased thermo-mechanical stresses on stator and rotor copper conductors and its insulation systems. If maintenance plans [4] are not changed to adapt to the much higher duty cycles on these machines, machines will fail prematurely with a significant and devastating impact on grid reliability. The cost of lost production as well as the cost of repairs or replacements of these failed machines will also significantly impact on the total cost of renewable generation as it is presently not accounted for in any price modelling.

During the process of plant refurbishment or replacements, attention should be paid to the introduction of additional capability of the renewed plant, such as the ability to operate in synchronous condenser mode and the ability to introduce some form of energy storage capability. This can significantly assist with future grid stability during highly variable PV and wind generation feed-in. It will be of utmost importance to develop new generating equipment which is not specifically focusing on supplying active power but also capable of supplying reactive power, frequency support, inertia, etc.

In general, over 45% of the global generated electric energy is consumed by electric motor systems. Energy-efficient electric motors present one of the largest opportunities for cost-effective electric savings and the action plans for the reduction of greenhouse gas emissions. In order to gain fast and efficient access to energy efficiency improvements of electric motor systems, regulations mandating the energy labelling of products for minimum energy performance standards (MEPS) have been widely applied to three-phase electric motors and the MEPS efficiency has resulted in higher efficiency levels such as IE3 premium efficiency motors with reference to the following efficiency classes as per IEC 60034-30:

Code IEC 60034-30	Efficiency class
IE1	Standard efficiency
IE2	High efficiency
IE3	Premium efficiency
IE4	Super premium efficiency
IE5	Ultra-premium efficiency

The world would save on the construction of approximately 108 nuclear reactors (108 GW) and about 378 TWh per year on electric energy consumption by a 3% improvement of motor efficiency by converting from efficiency class IE3 to efficiency class IE5 by 2030 [5, 6]. The present electric energy price for 378 TWh is about 30.2 billion US$ (at 8 US cents/kWh). Total worldwide installed power generation capacity and power generation would be approximately over 8000 GW and 28,000 TWh in 2030 [5, 7].

Significant efficiency gains are possible with improvements in materials, manufacturing processes and innovative motor designs. The following improvements were already accomplished with a continuous focus on improved efficiency gains in new designs:

Cage Induction Motors For small-, medium- and large-sized motors, the standard of IE4 is reachable and several innovative manufacturers already have prototypes or commercially available small-sized motors. There are also agreements among experts that the standard is feasible for all sizes if these motors are equipped with better core materials and an improved copper cage, hybrid (copper and aluminium) cage or with special slot designs. Experts have differing opinions on the feasibility of the ultra-premium efficiency class IE5 motor type with an overwhelming view that IE5 motors are not feasible as cage induction motors. There might be a possibility to reach the IE5 standard for large rating motors when equipped with more advanced core materials, copper cages, improvement of the stator winding filling factor and if nano-materials are considered for the reduction of winding losses. Nano-crystalline core materials and windings by carbon nano-tubes with higher conductivity show a possibility to significantly reduce iron and winding losses in the near future. For small and medium rating motors, it may not be possible without increasing the frame size of the motor, which will carry a significant modification cost impact for non-standardised motor replacement in future.

Synchronous Reluctance Motors with a Starting Cage For this motor type, the standard is feasible for small and medium sizes. There are already some existing prototypes, and some manufacturers already offer commercially available small size motors, which show the feasibility of the standard IE4. Unfortunately, power factors for these type motors are lower than for induction motors. Numerous technical issues such as reducing starting currents, mechanical noise and vibrations remain significant issues to overcome for medium- and large-sized motors. For small- and medium-rated motors, the standard IE5 is seen to be feasible by applying present technologies, for example, significantly thinner high-grade Si-steel, increased winding fill factor, better cooling by encapsulating the end-winding with a material of good thermal conductivity, etc. For large motors, it may not be possible to reach the standard without increasing the frame size of the motor.

Permanent Magnet Motors with a Starting Cage The consensus is that the standard of IE4 is achievable, and this is supported by a variety of manufacturers, whom also already have prototypes and even commercially available motors for the small and medium sizes up to 7.5 kW. For large rating motors, the standard is reachable, but there are some issues concerning the cost of permanent magnets as well as the feasibility of reducing starting currents, mechanical noise and vibrations. IE5 is clearly feasible for small- and medium-sized motors when equipped with improved core materials, multiple air gaps and increased quantities of permanent magnets as well as increasing the stator winding filling factor. Unfortunately for large motors, there are several issues concerning the cost of permanent magnets and reducing starting currents as well as mechanical noise and vibrations.

5.2 Software and New Tools

Rotating electrical machines in the form of motors and generators will still form part of global energy generation and consumption for the foreseeable future. It is therefore imperative that the latest technologies be used to improve its design, manufacturing, condition monitoring and maintenance practices to ensure that these components deliver the required reliability, efficiency and life expectancy demanded by future network conditions. Various modern design and plant management tools are presently available in the market and more are continuously being developed as computing power becomes faster and less expensive. The future of machine design, machine efficiency, and effective condition monitoring and maintenance practices lies in the effective utilisation of modern tools.

With the improvement in specialised online monitoring systems and field equipment in combination with advanced trending and condition assessment and analysis tools, a more complete health assessment of a generator and motor can be compiled. This information can be used to optimise planning for offline maintenance and inspection testing of generator and motor components. These modern condition assessment systems can also supply real-time operational analysis of components in service which can act as real time early warning should component condition deteriorate.

Self-learning systems can compare all monitored parameters in real time with learned historic data for each specific operating point and display any deviations in real time to the plant operator and maintenance personnel. As complex large rotating machines can have several hundreds of measured field data and accumulate data on several millions of different load points, fast and accurate real-time analysis is essential for effective real-time early warning systems.

Utilising artificial intelligence to predict plant behaviour from measured data at specific load points, in combination with external real-time historic input from machines operating internationally, machine behaviour can be analysed on a much larger scale with the aid of global operational experience to predict each machine's behaviour. For this to be achievable, a very large network of interconnected plant is required, each with a reliable condition monitoring system. Making use of this data in alarming and trip systems can significantly reduce the failure rate of machines. Analysed data can also be fed into maintenance management software which can be utilised to predict component deterioration for optimised maintenance and replacement strategies.

Digital twins can be developed from all learned real-time data, which can be used for real-time simulation of machine behaviour and the response thereof used to improve life cycle management, investigate the impact of grid dynamics on machines, design improvements and several other purposes.

Using operational data, field service data, equipment failure data and past design review information, processed and optimised with artificial intelligence and machine learning capabilities in the development of digital twins, practical improvements in new designs will be possible, e.g. improving the slot and tooth geometry for higher filling factors, less stray in the core, improved insulation life, etc.

5.3 Techniques, Methods and Tools

To improve condition monitoring capabilities on rotating equipment, new techniques and tools will have to be developed, or existing techniques improved to be effectively utilised on rotating electrical components. Presently, the rotors of motors and generators are mostly regarded as a black box with very little operational information available from the rotating parts, with shaft and frame vibrations in most cases the only information available. Utilising wireless technologies that have the capability to function in a strong magnetic field, high temperature and high vibration environment can in future be utilised to obtain field current and field voltage data, winding and rotor forging temperature and mechanical strain data. Advances in nano-sized surface mount self-energised non-intrusive sensor technologies can open a whole new world to operational and design engineers to learn the exact behaviour of certain components in certain operational extremities, which can further be used for optimisation of such designs.

Besides new technologies, new methodologies should also be developed to achieve optimised designs. It is of the utmost importance that a design process is started with human interaction from all relevant stakeholders, and it is essential that each stakeholder is accounted for during such a design initiation and review process. It is crucial that the requirements of the customer, power system specialists and equipment suppliers be considered when a design is carried out for new equipment.

By utilising new tools, methods and techniques, the following can possibly be achieved for motors:

- Higher filling factor for motor stator windings: Through the design of improved slot geometry combined with developing new production methods or by improving the production process, a higher filling factor can be reached. From a present filling factor of between 0.55 and 0.6, filling factors of up to 0.7 can be achieved. This would lead to a reduction of winding resistive losses from 100% to 79–86%.
- Maintaining magnetic core sheet quality through production processes: By improving the production techniques for core sheets through heat treatment and producing emboss-free and burr-free sheets, the quality in terms of magnetic flux density can be increased. Core sheets should be prefabricated to their desired geometry, annealed and thereafter insulated. This would guarantee the lowest losses and full utilisation of the cross-sectional surface. By reaching high-quality electrical steel throughout the production process with these mentioned methods, core losses can be reduced from $Bs = 1.9$ T and $W_{17/50} = 2.3$ W/kg to $Bs = 1.84$ T and $W_{17/50} = 2.0$ W/kg (100–87%).
- Eliminating circulating currents in the parallel strands of stator windings: Eliminating circulating currents would lead to loss reductions in the stator winding, with reductions possible from 100% down to 94–98% for a 60 Hz supply. However, for motors which are driven by inverters the loss reduction can be significantly higher due to the high switching frequencies in inverters.
- Casted copper cage: Using casted copper cages, resistivity can be reduced from 2.75 $\mu\Omega$ cm for aluminium to 1.73 $\mu\Omega$ cm for copper. This will improve the efficiency and reduce the rotor resistive losses by 37%.
- Potting, e.g. encapsulating the end-winding with a material of good thermal conductivity: This method will improve the heat transfer at the end-winding and reduce temperatures, which will lead to lower resistive losses in the end-winding and stator winding by 5%.
- Better fan efficiency: Improving the cooling fan aerodynamics by using bidirectional special aerodynamic fans, friction losses can be reduced up to 20%.
- Heat treatment of the stator and rotor pack: By heat treatment of the stator and rotor pack, losses could be reduced by 15%. The special heat treatment, i.e. using heat cycling to realign the stator and rotor pack magnetic field orientation, which got misaligned due to various manufacturing processes such as high temperature die-casting reduces losses by 5%. Further work might reduce stator and rotor pack losses by up to 15%.

5.4 Standardisation

IEC 60034-30-1, published in March 2014, significantly widens the product range for motors which was previously covered in the first edition of IEC 60034-30. The power range has been expanded (starting at 0.12 kW and ending at 1 MW). The super premium efficiency class motors (defined as IE4 in IEC 60034-30-1) are newly included, and ultra-premium efficiency class motors (defined as IE5 in IEC 60034-30-1) are envisaged to reduce the losses of IE4 motors further by up to 20%.

5.5 Other New Developments

Legacy base load units presently fulfil peak time demand and sustain grid stability during periods of high demand and during periods of low PV and wind generation feed-in, and this will also be the case for the foreseeable future. This should change as the energy landscape matures with the introduction of large-scale storage capacity. Although storage systems are presently very expensive and not always cost-effective due to high capital cost as well as high life cycle costs, further developments in storage capability can significantly reduce this cost. This is essential for the establishment of a clean future grid. Legacy rotating machines cannot subsidise PV and wind generation for much longer as the health of these plants deteriorates rapidly due to the negative impact of frequent intense load cycling and two shifting. A more environmentally friendly storage technology is essential for the sustainability of renewable energy. Batteries are presently the best solution although they are costly and do not have a clean environmental footprint throughout their life cycle.

Storage technologies such as storing energy in the form of hydrogen gas or molten salt, with the required corresponding energy reversal technologies, can be cleaner and much more effective than present-day battery storage. Storage technologies are also still evolving, and new developments might improve life cycle costs and environmental footprint, such as present developments in green hydrogen solutions.

Energy storage capabilities need to remain a significant focus point for the future. As energy storage becomes more cost-effective and environmentally friendly, the introduction of PV and wind generation can further increase without reliance on gas- and coal-fired generation. Legacy generating equipment will play a role as minimum base load generation and for grid support as synchronous compensators. All new generating equipment designs should consider a form of hybrid design, where generating equipment can be utilised in more than one mode or system. It should be capable of generating power as well as acting as synchronous compensators when not required for generation, a power plant should also have the functionality to store electrical, chemical or mechanical energy during high in-feed of renewable power, to be later converted again to electrical energy when renewable in-feed is low.

As motors are consuming approximately two-thirds of all generated electricity, it is essential to focus on the energy efficiency of these energy converters. Small improvements in their efficiency can have a magnificent impact on the future energy landscape. The timing for use of IE4 and IE5 efficiency class motors is highly influenced by the action of motor manufacturers, governments and by international actions against climate change.

There is a great possibility that IE4 and IE5 efficiency classes will be reached sooner than originally anticipated. Therefore, an international collaboration with motor manufacturers, material producers, production equipment providers, institutes and universities should be targeted to verify the technological feasibility of these efficiency classes. This will also save R&D costs and shorten the time table for mass production and setting the requirements as mandatory. A schedule should be communicated within governments globally to unify the time table for setting the requirements as mandatory. This motivates the manufacturers and researchers to prepare for the new standards and accelerate the process of developing new technologies.

Very soon, recyclable electric motors will play an important role. An ideal machine for recycling is a permanent magnet machine with a synthetic powder magnetic circuit and slot-less winding. After crushing powder materials, both powders and conductors can be separated and reused. The design and manufacture of recyclable electric machines are economically justified if costs of the final product do not significantly exceed the costs of a similar non-recyclable machine.

6 Future/Research Needs

6.1 Practical and Economic Aspects

Due to a strong present-day focus on global warming, sustainability of the ecosystem is a major driver in modern-day technological developments. Therefore, future needs are now more oriented to a sustainable energy balance; but at the same time, we need universal access to electricity to alleviate poverty globally. This can only be achieved by having cost-effective and sustainable energy for all. This task demands the capability to increase electricity production without increasing present greenhouse gas emissions. Present grid-tied energy sources are most probably not the ideal solution to achieve clean and affordable power. Hybrid systems which combine clean power, batteries and even diesel generation might become more feasible in meeting environmental targets. In order to increase the share of clean and renewable energy in the power system, batteries, gas turbines, smart solutions, distributed generation, and smart metering will be required. The gradual closing of coal power plants and reducing the use of liquid fuels to a minimum will be required to achieve the goals set out from an environmental point of view. To transform the present industrial focussed outlook into an eco-friendlier outlook will require centralised enforcement of new policies with accompanying strategic and careful planning and strong collaboration with public and private partnerships, including active participation of consumers.

To support an eco-friendly approach for electrical machines of the future, developments of equipment must have a very strong focus on efficiency and reliability. This will be required to harness as much energy as possible from available resources. These machines will also have to be smart, maintenance friendly and have the capability of auto diagnosis. It will have to be designed and manufactured for flexible operation as load following will be required due to the intermittence of natural resources such as wind, sun and water. To ensure a harmonious harnessing of available energy and effective conversion to useful electrical energy by making optimum use of machine capability and life expectancy, our comprehension of climate and short- and medium-term accuracy forecast will have to be improved significantly.

The role and subsequently the requirements for conventional generators and turbines are changing from historic base load electricity generation towards backup fast response power supply, contributing to stable grid frequency when and where required and grid support during grid faults. Depending on the requirements of specific grid configurations and generation mix topologies (including the requirements from future development plans), the most economical solution will most likely involve a combination of several technologies. Even with the growing renewables share worldwide, it can be stated that synchronous rotating equipment will remain the backbone of our energy systems, enabling the integration of large-scale renewable, frequency converter connected energy sources into the grid of the future.

6.2 Research and Developments

Investments in research and development must be focused on technologies that enhance the ecological friendly nature of energy conversion, breaking the strong reliance on fossil fuels. Climate change has proved not to be an apocalyptical fantasy but is part of our reality and demands prompt actions that must be reflected in innovation budgets. Research and development should also not only be focussed on equipment aspects but also human aspects, especially on programs that are specifically developed towards building the necessary skills of future generations of design and manufacturing engineers. These engineers will require specific skills and knowledge which standard universities do not always offer. Companies will have to invest in researching human behaviour in the work place to enhance and optimise skills and knowledge of modern engineers and engineering managers to become modern innovators.

As part of the technological evolution into utilising artificial intelligence to accomplish machine learning and self-diagnostics, research and development of reliable and effective online monitoring systems for rotating machines is necessary. These systems must still have the industrial robust aspects of past and present industrial revolutions but also have the sensitivity, accuracy and repeatability to measure data effectively for automated analysis and prognosis.

6.3 Education and Existing Knowledge

Millennials have different ideas of what good education is compared to traditional education. Their demands range from the use of multimedia education to shortening the time to acquire specialist knowledge. They have the need for quick high impact tutorials instead of long courses to gain the necessary knowledge for deployment in industry. Catering for these needs will revolutionise the education system but need to be done systematic and careful as a fast-uncontrolled transition of the total education system can have dire consequences to the future skills base. Conventional education systems have produced excellent engineers in all fields of engineering and therefore have a proven track record; any new education system will be a prototype as it will deviate from the known proven educational system, yet changes are necessary to fulfil the future skills need as well as to comply with the needs of future generations.

The present shortage of skilled and experienced design engineers poses a significant threat to future eco-friendly developments of rotating electrical machines as it requires a new way of thinking combined with established design principles of complex rotating electrical machines. To overcome this obstacle, generator and motor manufacturers could sponsor and guide engineering students through their studies and to employ them on successful completion of their studies. Companies should develop these young dynamic modern design engineers in the field of expertise required for the new direction in which rotating machines should be developed in. This will require a focussed development program during which they will be prepared and skilled with the necessary knowledge and tools. Such a focussed development program will have to expose these young engineers to various skills required for the successful transition from the historic industrial focussed design principles to the future ecological friendly and sustainable design principles and techniques.

Analysis of a variety of technologies used for electricity generation and grid ancillary services, which are available today, shows that each of these technologies has strong advantages in the specific field it is designed for, but no technology can provide all required services. Future systems will require effective integration of various technologies into specific energy conversion systems. One such an example is the requirement of fast and effective controllability of the energy conversion process, requiring future motors and generators to form an inherent unity with power electronics. This can contribute to achieving sufficient reliable and affordable energy.

Future engineering courses should develop competencies in the tools used at that point in time, and students must also gain exposure to tools being developed for future use. These students should be adequately trained to use all applicable design tools which they might encounter in their future line of work. Employees of design and manufacturing companies must take part in continuous development courses to ensure they stay competent in the use of the latest design and modelling tools. Possibilities also exist for engineers to collaborate interactively during the development of new products and the improvement of existing products. With the development of high-speed networks, design engineers from across the world can seamlessly engage in virtual interactive design and development rooms.

Due to the technological advances accompanying new developments, the users and maintainers of new equipment will also require new skills. This can already start in the design phase where users and maintainers can take part in the design of their purchased equipment in a virtual design office. The user can also make use of virtual interaction to perform quality control functions during the manufacturing and testing phase.

6.4 Other Future Needs

In future, energy generation systems might do away with electromechanical equipment for the energy conversion process and only make use of static systems to produce electricity. Presently, this is only employed in photovoltaic systems. Systems such as wind turbine generation, hydrogeneration and gas generation require large rotating equipment for the energy conversion process. As for the conversion of electrical energy into mechanical energy, this will remain an electromechanical function for the foreseeable future.

Very limited tools presently exist to perform effective condition monitoring of electrical machines, with many of these tools focussing on the mechanical aspects of rotating electrical machines. Further, the developments to accurately assess the online electrical health of generators and motors are essential to ensure reliable and accurate diagnosis of eminent failures.

Various systems are used to monitor and protect rotating equipment, with these systems mostly situated in different plant locations. The complete monitoring of rotating machines will require effective real-time interaction of these systems. Motors and generators are protected with various protection systems but monitor and operate in complete isolation from each other as rotor shaft vibration monitoring equipment, operational temperatures, shaft voltages and currents, winding vibrations, etc., are all mostly island systems. If all data measured and monitored from all these standalone systems are incorporated in a common data analysis system having machine learning characteristics, a complete present health condition model could be created. Any further operation resulting in deviations from the initial model will be alerted and further analysed, in real time compared with global machine data, historic and present operational data, in search for similar operational experiences, which can instantaneously inform the plant operator of developing faults and failure consequences as well as proposed corrective actions.

7 Future Issues

7.1 Desirable Futures

The early and accurate identification of developing faults will be a very desirable status to achieve. This information can be accurately fed into repair planning processes, with accurate and on-time management of unit shutdowns as all required spares can be purchased on time, with a very accurate bill of material as there will be a very low probability of scope creep.

Non-invasive generator maintenance and inspections can significantly save on outage duration, manpower requirements and human error incidents. For robotic inspections to achieve this state, additional development will be required to the inspection equipment itself as well as the design and construction of rotating machines to accommodate non-invasive inspections and repairs. A possibility in the distant future is to equip each large and critical machine with a permanent robotic inspection system with basic inspection and testing capabilities. This will allow quick verification of the internal machine condition without mechanical dismantling. The robot can be controlled remotely, and once the inspection is completely, be safely and securely parked in a docking station internal to the machine, ready for the next inspection. This state is presently not possible as generators and motors are designed for optimal cost and efficiency and not for robotic inspection and testing as a major design concern.

7.2 Potential Impacts

The significant and uncontrolled drive towards clean energy systems will result in a power system with clean energy dominance. Although this is desirable from an environmental perspective, it is not desirable from a grid stability perspective as it lacks the ability to sustain grid stability during faults and transients. Clean energy generation and storage are becoming cheaper and more economical and will soon surpass the cost-effectiveness of fossil- and nuclear-fuelled generation. This is a state that the world wants to achieve as soon as possible to save the world from the negative effects from global warming. As clean energy without storage is introduced into the network, the ability to keep a grid stable during fault events is negatively affected as it requires the backing of strong real inertia, which would not exist in a complete inverter connected renewable energy system. This can result in severe voltage and frequency fluctuations and subsequent blackouts.

Presently, the cost of energy storage is significant, which is resulting in the present inverter fed grid being built on unpredictable and uncontrollable sun and wind energy. The absence of storage in the present inverter fed renewable grid results in the absence of energy supply during high demand evening and morning peaks as well as from sunset to sunrise. These valleys of renewable inverter-fed supply are presently compensated for by fast ramping of conventional base load fossil-fuelled, gas-fuelled and, in some cases, even nuclear-fuelled generation.

Distributed generation technologies may bring multiple challenges to the generation business and poorly coordinated scattered construction sites could lead to poorly coordinated transmission system planning. It is therefore necessary to be proactive in anticipating the future effects of continuing the present trajectory and anticipate the effects of it. This is necessary to properly control and plan the network of the future, to have a proper mix of various energy sources to sustain demand 24/7 through all seasons with the necessary inertia and energy support to sustain a reliable network.

7.3 Risks and Consequences

In a scenario where clean energy is dominating the total energy mix, electromechanical conversion of energy will play a smaller role in the energy generation process. With the absence of any mechanical parts, maintenance is much easier to perform. Outdoor installation reduces civil works, making the initial investment cost significantly less than for conventional power plant construction. The energy price of solar power is presently similar to the price of wind power. Only large run-of-river hydro-projects can compete with wind and solar generation. The number of rivers capable of economically supporting future generation projects is limited and is not even feasible for most countries. The only feasible cost-effective expansion in power generation will be wind and solar, which will attract most of the investment. Presently, financial institutions are already not willing to finance any non-clean energy projects. As the network is supported by less conventional high inertia generation, the grid will be more susceptible to instability due to the impact of grid disturbances.

7.4 Educational Changes

To ensure adequate skills to face challenges of future electricity generation, a new thinking will be required to address these challenges. To address present and future skills and expertise shortages, the educational process will have to become more efficient and shorter. Young engineers will need to get in touch with new rotating machine technologies earlier and throughout their studies and be prepared to actively exchange experiences in this field. All specialists in this field should have easy and direct access to new developments regarding rotating electrical machines (specialised documentation, design data, simulated models, etc.).

Due to changes in the energy market, the educational interest in large rotating electrical machines (especially large synchronous generators) is rapidly decreasing. Universities and research institutes shift their focus to other technologies, and this will have a detrimental impact on the future network as a network of the future cannot exist without synchronous generators.

The interest from young electrical engineers is guided more towards power electronics systems due to the exciting developments in this field. This will result in a lack of new scholars specialising in rotating electrical machines. Schools, colleges and universities must be strongly reminded that even in a 100% renewable dominated energy sector, synchronous generator support is still needed.

7.5 Innovation

Innovation is strongly related to value. The comprehension of value from the customer's perspective is a way to lead change to a more prosperous industry. Innovation is likely to happen in automotivated and multidisciplinary teams. A different way to combine existing elements could result in a new product, or a new technique, method or process.

Specific focus on innovations in rotating electrical machine-related technologies is required to ensure a stable and reliable future network. This requires a very advanced innovative platform to achieve the following:

- Innovative fast response backup power plants compensating for fluctuating renewable generation.
- Contribution to grid frequency stabilisation by keeping minimum required rotating inertia on grids.
- Synchronous generators as short-circuit power sources if protection concepts are based on (short) circuit current detection.
- With new network requirements leaning towards flexible plant configurations for power production and/or grid stabilisation, it will also be necessary to develop new targets and priorities for synchronous generator designs as the present design and operating criteria are no longer applicable.
- Unstaffed remote-control operation of future power generation equipment must be reflected in more robust and reliable designs.

8 Conclusions

8.1 Directions

Rotating electrical machines will for the foreseeable future remain an important and essential member of the future energy network, both in the form of electrical energy generation and electrical energy conversion to mechanical energy. Advances in technologies used in rotating electrical machines will be required to support high load factors on these machines as they are the start and the end of every industrial process globally. To ensure the reliability and efficiency of these magnificent machines are further improved, further innovative developments are required, with specific focus on maintainability and reliability, keeping in mind the skills and technological interest of future designers, manufacturers and operational workforce.

The network of the future will require very robust electrical equipment which can handle any form of operation required. The network of the future will contain significant higher order harmonics, will require very fast response voltage and frequency support, will require instantaneous active power support and should still be able to achieve its design life reliably regardless of all these external challenges it is facing. The grid of the past was reliable and predictable due to the controllability of legacy generating technologies. A large base load network supported with pump storage and gas turbines was relatively easy to manage and control, as the unreliability was mainly influenced by poor maintenance and poor capital expenditure planning. The evolving network we are facing now has less controllable generation as it is now relying on environmental factors to supply energy, with conventional generation only being relied on for support. This is not sustainable as there is very little investment in conventional base load generation, and the plants presently utilised for this support are fast ageing as they were not designed with the intend to deliver fast action active power response.

To ensure that rotating electrical machines remain reliable and cost-efficient in the future network, certain innovations and developments are required:

- Design of smart machines with an auto-diagnostic capability will greatly enhance maintenance and repair planning. This will ensure that higher availability can be achieved, even in a harsh operational environment.
- The design of new machines needs to be more customer-centric, with active participation of plant operators, grid owners, design engineers, maintainers and innovation centres. Future machines will deviate from the present standard design methods as it will have to be tailored to every specific application and network configuration.
- Electrical machines will have a very close relationship with power electronic equipment. Presently, these two technologies have adverse effects on each other as power electronics do not like machine vibrations and rotating electrical machines cannot handle higher order switching harmonics well. Significant innovation is required in both rotating machines and power electronic equipment, harmonised with smart control systems to marry these two technologies to harsh operational requirements of the future network. The future applications of rotating electrical machines should be more than just active power generation.
- To improve life cycle cost of rotating electrical machines, new materials will have to be developed. Higher torsional forces on rotating shafts and couplings will require stronger steels. To reduce manufacturing costs will require optimisation of machine sizes, which will require better methods to dissipate heat losses. Higher thermo-mechanical stresses on copper and insulation material due to load cycling and two shifting will require more flexible yet stronger materials.
- As the future network, driven by numerous unharmonised grid codes, will require us to move away from standard design generators, manufacturers will have to be

geared towards flexible and fast manufacturing processes, with increased focus on reliability-oriented designs.

- Machine learning will need to play a significant role in gearing future designs towards new network requirements. Machines are presently designed taking historic information into account, such as past failures related to design defects, poor workmanship and repair complexities. Future designs will require a completely different approach as the network is fast changing and the impact of it unknown. Quick learning from present operational machines equipped with advanced monitoring systems is necessary to directly feed data into new design processes, immediately modelling the present operational stresses into a digital twin to evaluate the impact of new network topologies on designs, to effectively improve designs which will be fed through to the manufacturing process.
- The starting point of machine learning used for machine diagnostics or for design improvements starts with effective and reliable online monitoring. Sensor technologies require extreme robustness to operate in harsh environments found inside rotating electrical machines where sensors are exposed to oil, vibrations, temperature, high voltage, EMI, mechanical impact during maintenance work, etc. The reliability of any monitoring system relies on the continuous availability of field instruments. The value of monitoring is derived from the number of data points being monitored. In most motors and generators, only specific parameters such as temperatures and vibrations are monitored. This can still be greatly expanded to include a complete range of mechanical and electrical data, combined with operational data to develop an accurate image of the present health of a monitored machine.
- High-performing innovative employees are the foundation of a dynamic, productive and innovative industry. Technology managers in close collaboration with human resources personnel must attract, hire, develop and retain individuals who are high-performing continuous learners and innovators. This is a critical aspect required to face the challenges of the future. A great manager/leader is required to support this.

8.2 Priorities

- Industry must commit to projects which are socially and environmentally friendly.
- Compliance with standards and network requirements is essential, with an urgent need to harmonise grid codes and component standards.
- Corporate social responsibility.
- Develop the industry of rotating electrical machines into a highly innovative and technologically advanced arena attractive to young people.
- Value innovation.
- Commitment to continued and improved R&D.

- Develop sustainable production processes, product design and maintenance services which are beneficial for the environment, people and business.

Industry should stay open-minded and technology agnostic and enable product innovation. It is particularly important for institutions such as IEEE/CIGRE/EPRI to assist rotating electrical machines to transition into its new role. This requires the industry to have the right understanding of the technical challenges at hand and promote adequate attention and investment in the rotating electrical machines area.

8.3 *Other Aspects*

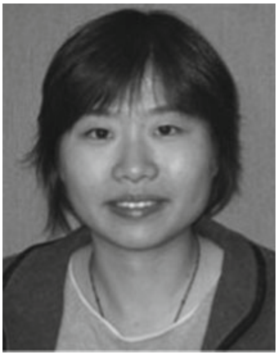
The bottom-line logic is to create value to customers, companies, human talent, suppliers, as well as to add to social value by the development of environmentally friendly rotating electrical machines.

The rotating electrical machine industry is facing a tremendous opportunity to be part of transforming the present situation into a better world for the next generation.

References

1. EPRI Report on Generator Robotic Inspection & Test Guide: Report # 3002013612 (2019)
2. IEEE Report on Coordination of Grid Codes and Generator Standards: Consequences of Diverse Grid Code Requirements on Synchronous Machine Design and Standards Technical Report: IEEE PES-TR69 (2019)
3. CIGRE Technical Brochure on Guide on new generator-grid interaction requirements: TB 743 (2018)
4. Klempner, G., Kerszenbaum I.: Operation and Maintenance of Large Turbo-Generators
5. Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems, International Energy Agency: Paul Waide, Conrad U. Brunner (2011)
6. World Energy Outlook 2011, International Energy Agency (2011)
7. Electric Motors: A Global Strategic Business Report MCP-1842, Global Industry Analysts, Inc. (January 2015)

Nico Smit graduated from the University of Pretoria in South Africa in 1998. He has more than 20 years of project, operating and maintenance experience on generating plant as an electrical engineer. He is serving as the CIGRE Rotating Electrical Machines Chairman since 2014.



Kay Chen received a BS degree in electrical engineering from the University of Alberta. After graduation, she worked at ATCO power, where her main responsibility is on generator operation and maintenance. Her projects includes generator rewinds, overhaul inspections, diagnostic monitoring and testing. Since 2011, she has been working for Siemens Energy in generator R&D. She is responsible for thermal/electrical design for the new Siemens portfolio of generator products. She also has been working on the test validations of the new generator designs. She started to serve as the chairperson for IEEE PES EMC WG8 on harmonisation between IEEE C50.13 and IEC600034/1 in 2007. She served as IEEE PES EMC generator subcommittee chair from 2010-2012. She has been serving as the chair for the IEEE PES EMC since 2017. Outside IEEE, she has been also actively participating in EPRI and CIGRE projects concerning generators.

Ana Joswig received the Dipl.-Ing degree in electrical engineering from the Technical University of Dortmund, Germany, in 2001 and Dr.-Ing degree in 2007. In this time, she worked for the University of Dortmund at the Institute for Electrical Machines, Drives and Power Electronics as member of research staff. In 2008, she joined the Siemens AG in Mülheim a.d. Ruhr. She is responsible for the functional design of turbo-generators with focus on electrical performance and thermal limits as well as for the interaction with the power grid and specialist for grid stability solutions.

Alejandro Cannatella received his electronic engineering degree from the Universidad Tecnológica Nacional (UTN), Mendoza, Argentina, in 1999. He also completed postgraduate studies on power system protection and power system stability at the Instituto de Energía Eléctrica (IEE), Universidad Nacional de San Juan (UNSJ). He is presently the lead for the electrical study team on hydro-generators for IMPSA. He is actively involved with CIGRE Working Groups and has authored and co-authored various technical papers in the field of rotating electrical machines and power systems.

Eduardo José Guerra received his Electromechanical Engineering degree from the Universidad Nacional de San Juan (UNSJ) in 1982. He spent the past thirty-seven years working in generation and transmission segments in the roles of engineer, procurement and construction, turnkey supplier, manufacturer of electromechanical equipment, independent power producer and consulting. Positions of direction, management and specialist were performed continuously during this time and twenty-two years of educational experience as professor in university-level and graduate-level classes. He is presently the Global Risk Manager for IMPSA (Mendoza, Argentina) where he is responsible for the risk management process of the company.

Byeong hui Kang is the General Manager of Rotating Machinery R&D design, manufacture and tests at Hyosung Heavy Industries in South Korea with 28 years' experience in the field of rotating electrical machines. He has a bachelor of engineering in mechanical engineering and masters of engineering in electrical engineering.

Traian Tunescu started his career in 1998 as an electrical engineer in the electrical repairs section of SH Portie de Fier in Romania. His career allowed him to gain significant experience across the whole spectrum of power plant electrical engineering, from component repairs and installation, supervising major hydro-generator plant modernisations to managing and coordination the operating regimes of hydropower systems as dispatcher in the hydro-centres dispatcher centre in Romania.

Power Transformers and Reactors

Simon Ryder

Abstract This chapter focuses on how changes in the electricity supply system will affect the life cycle of power transformers and reactors. This chapter gives a brief overview of the role of transformers in the development of the power system and on some of the developments in design, manufacturing and test. This chapter outlines some of the challenges facing power transformers and reactors and gives detailed consideration to each of the more important challenges. This chapter concludes with a summary of the work done by CIGRE and others to meet these challenges.

Keywords Distribution transformer · HVDC transformer · Phase-Shifting transformer · Power transformer · Shunt reactor · Voltage regulating distribution transformer · Wind-Turbine transformer

1 Introduction

This chapter will focus on how changes in the electricity supply system will affect the life cycle of power transformers and reactors. The CIGRE reference paper on the electricity supply system of the future provides some background information on these changes and the challenges they represent for the electricity supply system as a whole [1]. Challenges of special relevance for power transformers and reactors include the following:

- Bidirectional power and data flows at the distribution level
- Increased use of DC and power electronics at all voltage levels
- New and more advanced tools for modelling
- Increased environmental constraints
- Increased use of right-of-way capacity
- Offshore and subsea infrastructure

On behalf of CIGRE Study Committee A2.

S. Ryder (✉)
CIGRE, Paris, France
e-mail: sryder@doble.com

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_3

- A need for increase stakeholder engagement.

Underlying many of these challenges is the so-called energy transition, from a system based on conventional generation to one based on renewable energy resources and/or distributed generation [2].

This chapter will give a brief overview of the role of transformers in the development of the electricity supply system; it will then outline some of the challenges facing power transformers and reactors; and will then give more detailed consideration to each of these challenges.

2 Transformers and the Electricity Supply System

The electricity supply system has its origins in technological developments in the 1880s, especially the incandescent light bulb. Consumer demand for lightning using the new technology led to the development of small-scale power stations supplying local consumers. As consumer demand increased further, divisions emerged within the nascent electricity supply industry about how to meet increased demand. Some favoured continuing with small-scale power stations to supply local demand through DC distribution. Others favoured the development of larger-scale power stations to supply–demand over wide areas through AC distribution.

The first successful power transformer was developed in 1885 by engineers at the Ganz iron foundry in Hungary. The technology was rapidly adopted to allow the use of progressively larger-scale power stations supplying demand over progressively larger areas through AC transmission and distribution.

The so-called war of the currents was largely resolved in favour of AC by the time of the Chicago World Fair of 1893, which was powered by AC and also included an influential exhibit demonstrating the advantages of AC generation and distribution. Nevertheless, some large cities in the USA continued to have a public DC supply into the twenty-first century—New York until 2007 and San Francisco until 2012 [3].

The further possibilities of the AC model found a new outlet in the newly created Soviet Union after the Great War and the Revolution. According to Vladimir Lenin:

> Communism is Soviet power plus electrification of the whole country, since industry cannot be developed without electrification.

This summarised the so-called GOELRO plan for the reconstruction and economic development of the Soviet Union adopted in 1921. It involved the construction of 30 new power stations and an increase in the national electricity supply from 1.9 to 8.8 TWh [4]. The plan was essentially fulfilled by 1931, somewhat in advance of expectations. Its success provided the inspiration for subsequent five-year plans adopted by the Soviet Union and many other countries.

This model proved influential outside the Soviet Union, with a number of other countries adopting similar plans for economic development through the development of the electricity supply. Notable examples include:

- The Shannon hydroelectric scheme in Ireland (1929–34) [5]
- The creation of the Tennessee Valley Authority (1933) and the Bonneville Power Authority (1937) in the USA
- The Nationalisation of the electricity supply industry in France (1946), Great Britain (1948) [6] and Italy (1962) amongst others
- The Three Gorges hydroelectric scheme in China (2012) [7].

During this time, there was a large increase in both rated power and especially rated voltage of transformers. In particular, the highest-rated voltage of transformers increased from 10 kV when AC distribution was first introduced, to 110 kV by the time of the Great War, to 220 kV in its aftermath, to 400 kV in the 1950s, to 735 kV in the 1960s, and has now reached 1000 kV. The limit for the largest three-phase separate-winding transformer which it is normally considered to be technically feasible to construct is approximately 800 MVA (for a rated frequency of 50 Hz), and this was reached at the end of the 1960s.

During this time, there was a need to develop the improved design and calculation methods; improved manufacturing facilities and techniques; and improved test facilities and techniques. During this time, there was also a need to develop improved standards for transformers. The first IEC standard for transformers was published in 1955 [8] and has been continuously improved since. It has been widely adopted, although many national and regional standards also remain in use.

The first recorded use of computers in transformer design was in the mid-1950s, when computer calculations were applied to the calculation of short-circuit forces in power transformers. Early software adapted existing analytical methods, but with improvements in computers it has been possible to use numerical techniques and especially the finite element method. CIGRE working groups 12.04 and 12.19 have examined the subject of short-circuit withstand in transformers subject [9, 10], the latter informing the latest revision of the IEC standard for transformer short-circuit withstand capability [11].

Some typical magnetic field plots for transformers with different designs are shown in Fig. 1 (after [10]).

Other major application for computer software in transformer design includes electric field calculations, thermal modelling and transient voltage withstand capability. Electric field calculations are now largely made using the finite element method, in essentially the same way as magnetic field calculations. Application of the finite element has contributed greatly to the design of transformers for higher AC and DC voltages. Thermal modelling, and in particular the calculation of coolant flows and temperature distribution in windings, has become increasingly important in better optimising transformer designs. It was recently the subject of CIGRE working group A2.38 [12]. Calculation of transient voltage distribution was another important early application for computers in transformer design. As with short-circuit withstand capability, early software was essentially based on existing analytical methods. The need to improve modelling techniques led to the creation of CIGRE working groups A2/C4.39 [13, 14] and A2/C4.52, which is ongoing.

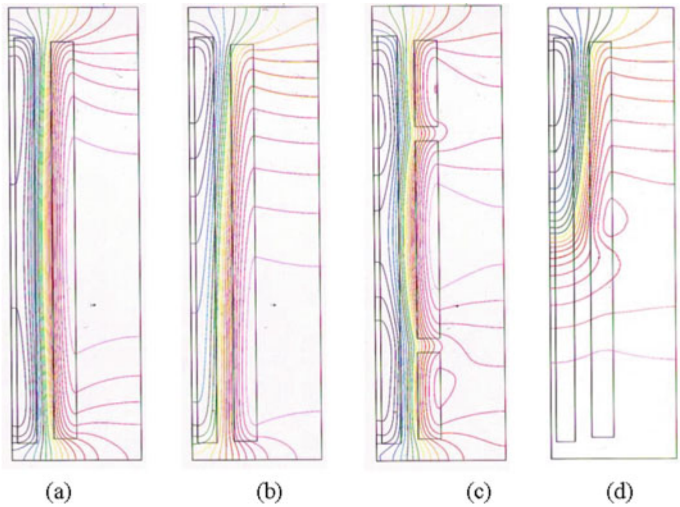


Fig. 1 Typical magnetic field plots for transformers with different designs. **a** HV in original position, maximum tap. **b** HV shifted 20 mm, maximum tap. **c** HV in original position, minimum tap. **d** HV in original position, maximum tap, split LV with only top half in operation

The results of a detailed calculation of coolant flows and temperature distribution in a transformer winding are shown in Fig. 2 (after [12]). The results of a detailed calculation of the voltages in a transformer winding during the lightning impulse test are shown in Fig. 3 (after [13]).

Emerging areas for the application of advanced computer software include tank design, and in particular the calculation of rupture strength [15], and calculation of sound levels, especially for shunt reactors [16].

As in many other industries, manufacturing facilities and techniques have been gradually improved. Consolidation of the manufacturing base has played a major role in this process, as production has been concentrated at fewer manufacturing plants each with better equipment. Major improvements in recent years have included the automation of core cutting, and more recently core stacking; the automation of winding, mainly for smaller transformers; use of hovercraft to move transformers during assembly; and the introduction of the vapour phase method for final dry out. Some information about manufacturing methods can be found in [17].

Test facilities techniques have also been greatly improved, especially for dielectric tests. For example, early versions of IEC standard 60076 focus largely on AC voltage withstand with lightning impulse as a type test only. Switching impulse testing and partial discharge measurements during AC withstand testing were first introduced in 1980 [18], initially as alternatives to AC withstand testing for transformers of 300 kV class and higher. Lightning impulse and partial discharge measurements are now routine for all transformers of 123 kV class and higher, and switching impulse tests for all transformers of 170 kV class and higher [19]. Two CIGRE working groups

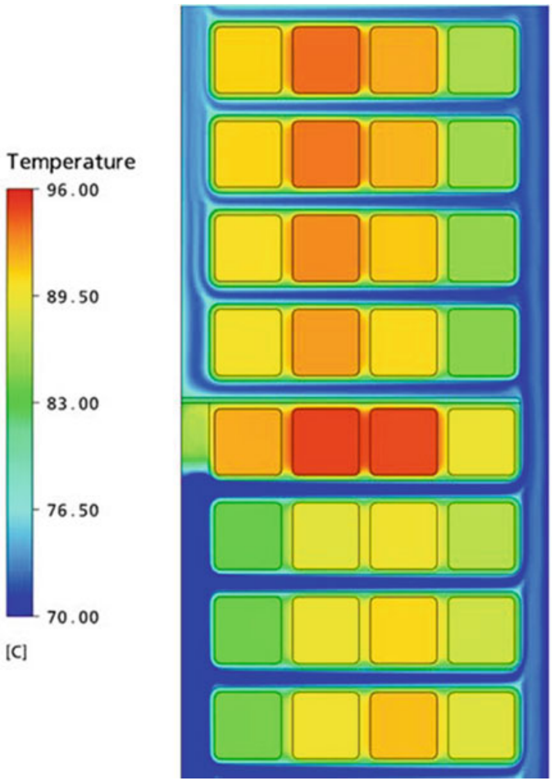


Fig. 2 Coolant flows and temperature distribution in a transformer winding

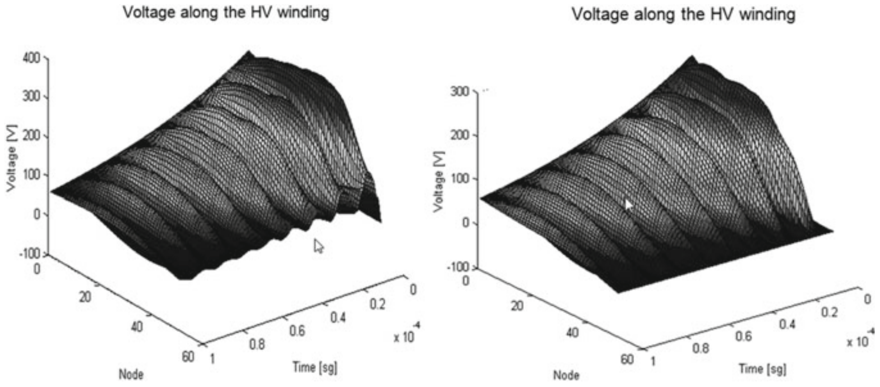


Fig. 3 Voltage distribution in transformer winding during lightning impulse test. **a** Maximum tap. **b** Minimum tap

are currently underway to improve dielectric test techniques further—A2/D1.51 on partial discharge testing and A2.64 on lightning impulse testing.

3 New Challenges—Power Transformers and the Energy Transition

As was mentioned above, underlying many of the new challenges is the so-called energy transition, from a system based on conventional generation to one based on renewable energy resources and/or distributed generation [2]. Note that whilst this would seem to imply a reduced role for long-distance transmission, this is not necessarily the case. In particular, there will likely be a need to integrate new renewable energy sources including geothermal; large-scale solar, especially in remote areas; large-scale wind, especially offshore and also onshore in remote locations; and perhaps also tidal. There may also be a continuing role for thermal large-scale power plants, including nuclear and also conversion of combustion plants to biomass.

The remoteness of many of the energy sources will likely mean an expansion of the transmission network, with power being transmitted over longer distances. Management of network losses will likely require the use of higher transmission voltages and also increased use of HVDC. Where these are overlaid onto existing transmission networks, there may also be a need for more phase-shifting transformers.

Integration of new renewable energy sources in remote and environmentally sensitive areas has increasingly involved installing new power transformers and reactors in environmentally sensitive areas, where the possible uncontrolled loss of oil, fire or explosion in the event of failure cannot be tolerated. New technologies have been developed and are now being implemented to reduce environmental risk, especially uncontrolled loss of oil and fire. Public concern over the potential risk of conventional oil-immersed transformers installed in dense urban areas and industrial centres is also increasing, and similar technologies are being applied [15].

Another major environmental impact of power transformer and especially reactors is audible sound. There is a need to minimise the impact of audible sound in environmentally sensitive areas and especially in dense urban areas. Transformer manufacturers, and their suppliers, have made great improvements in transformer audible sound levels in recent years [20, 21]. There is now a clear opportunity to consolidate these gains through improved specification and standardisation of new transformers. Further work may be needed to improve mitigation methods where lower sound levels than can reasonably be achieved by improvements in design and construction are required, or for existing transformers which no longer meet contemporary requirements.

A further major impact of power transformers and also reactors is losses. For many years, there has been pressure on users to reduce losses and on manufacturers to produce designs with lower losses in response. Many countries have now adopted statutory regulation of losses, now extending through the size range to include medium and large power transformers [e.g. 22]. There is now a need to balance requirements for low losses against other requirements which may conflict, e.g. low audible sound levels, low transport dimensions and mass, low installed mass [23].

Where the model of centralised generation from renewable sources applies, the economic and social importance of the power transformers and reactors in the transmission network will increase. Operators will need to improve their management of transformer through their lives, which will likely involve the application of new monitoring technology and also new analytical techniques [24–26].

In addition to integration of centralised renewable resources will likely also involve the integration of distributed renewable generation on a large scale via the distribution network. Small-scale solar and small-scale wind have the most obvious potential. There may be a role for other primary energy sources, depending on local conditions. As both solar generation and wind generation are inherently intermittent, there will be a need either to develop small-scale storage or else to rely on the distribution network for backup. The technology for small-scale storage is currently in its infancy, and so there will likely be a need for backup from the distribution network for the foreseeable future.

The need for backup via the distribution network is likely to be one of the main challenges in the integration of distributed generation on a large scale. In particular, there may be a need for backup generation, with some centralised generation and associated transmission capacity. This may require the adaptation of existing power plants and transmission networks. However, in some cases new transmission capacity may be required to connect areas with abundant distributed renewable energy resources and dense urban areas or industrial centres. This may include both use of HVDC and increased use of phase-shifting transformers.

Another challenge for the power system as a whole is loss in inertia, resulting in more frequency and voltage variation. This may have serious consequences for power transformers, as they generally have less margin on overexcitation and especially on over-voltage than other substation equipment. In some cases, new technologies may be required to increase inertia [27].

It can be seen that the new challenges identified above largely correspond to the new challenges from the CIGRE reference paper on the electricity supply system of the future [1] identified in the introduction as having special relevance for power transformers and reactors.

4 Responses to New Challenges

- Transformers for Solar Integration

Widespread integration of solar generation is quite a new challenge, and technologies for doing so are not especially mature. As most solar generation is in the form of photo-voltaic cells, which produce DC, these are integrated using inverters. Modern designs of inverter generate harmonics, including so-called supraharmonics in the

Fig. 4 Container substation, including transformer, for solar integration

kHz range [28]. There have been numerous reports of adverse effects of so-called supraharmonics on transformers [e.g. 29, 30], and there is now an urgent need to develop new transformer and perhaps inverter technologies to improve reliability.

A container substation including a standard dry-type transformer is shown in Fig. 4. These are widely used for the integration of smaller solar farms into the distribution network.

- Transformers for Wind Integration

Wind generation is a more mature technology than solar generation, and transformers for wind turbine applications are now the subject of an IEC standard [31]. This standard was partly aimed at improving the reliability of wind turbine transformers, which was initially rather disappointing. Some continuing challenges with reliability remain, especially with transient over-voltages, and were discussed during the CIGRE Paris session in 2018 [32].

In Europe, it has been found that the wind blows more reliably over coastal waters than over the land, and a large number of wind turbines have been installed in the Irish Sea, North Sea and Baltic Sea. In recent years, the size of the turbines and also the distance from shore have increased. It has been necessary to install large power transformers (>100 MVA) on offshore platforms to allow integration of wind generation at sea. The increasing length of the cable connections has led to increased demand for shunt reactors and the development of new shunt reactor technologies. Design of AC offshore platforms was considered in detail by CIGRE working group B3.26 [33], and specific aspects related to shunt reactors in more detail by CIGRE working group A2.48 [34].

Fig. 5 Walney 1 Offshore substation

A typical offshore platform used for integration of an offshore wind farm is shown in Fig. 5 (after [33]).

- Higher AC and DC Transmission Voltages

As was mentioned above, there will likely be a continuing need for a transmission network. In case of the centralised model, this will likely involve the expansion of the transmission network and use of higher voltages (AC and DC). In case of the decentralised model, the transmission network will be important as backup and also for supply of dense urban areas and industrial centres.

There will be a need to develop transmission transformer technologies to meet new requirements.

At the time of writing, the highest voltage AC networks in operation are at 1000 kV in China. There have also been networks operating at between 735 and 765 kV in a large number of countries since the 1960s. Such transmission voltages, and possibly slightly higher voltages in future, are likely to continue to be required to allow integration of renewable energy resources in remote areas.

A typical 1000 kV AC transformer is shown during works test in Fig. 6 (after [45]).

IEC formed a new technical committee (TC 122) to lead standardisation of EHV and UHV networks and substations. Transformers for EHV and UHV were a preferential subject at the CIGRE Paris session in 2016 [35]. IEC and CIGRE organise a regular colloquium on this subject, most recently at Hakodate (Japan) in March 2019 [36].

Use of DC for long-distance transmission is now a mature technology, with the first DC transmission lines (or cables) having entered service as long ago as the 1950s. The line voltages, and hence both the amount of power and the distance over which it can be transmitted, have steadily increased. At the time of writing, an 1100 kV

Fig. 6 Typical 1000 kV AC transformer on test

DC line is under construction in China. There also 800 kV DC lines in operation in China and in India.

Two recent developments have extended the possible use of DC transmission—VSC converters have reduced the technical challenges in constructing DC converter stations and the development of DC circuit breakers has allowed the possibility of multi-terminal DC networks [37]. Other recent developments include the use of DC transmission for connection of offshore wind generation and also the development of smaller-scale DC transmission to increase the capability of the distribution network to absorb distributed renewable generation. This was a preferential subject at the 2018 Paris session [38].

IEC have recently published an improved standard for HVDC transformers [39]. This was based in part on previous work by CIGRE Study Committees A2 and B4 [40–42].

- Increased use of phase-shifting transformers

Phase-shifting transformers are used to counteract loop flows in transmission networks and to enable better use of the network capacity. Even in case of centrally planned networks loop flows can arise, but integration of distributed renewable resources has made the problem worse in many areas. In some cases, it is preventing further integration of distributed renewable energy resources.

IEC have recently published an improved standard for phase-shifting transformers [43].

- Site Assembly

As was mentioned above, many renewable energy sources are in remote areas and transporting large power transformers and reactors to such areas may be very challenging owing to lack of suitable infrastructure. Similar challenges may exist in dense urban areas, where the local infrastructure is inadequate for heavy transport. Increased pressure to reduce losses is resulting in transformer designs with larger transport dimensions and mass and is increasing these challenges.

One possible method of meeting the challenges is the use of parallel transformers or the use of single-phase instead of three-phase transformers. These solutions are not easy to apply in all cases and can have undesirable consequences [23]. An emerging technology which has been developed to meet these challenges is site assembly. This has been widely applied in Japan since the 1980s and is now being widely used in other countries especially in China [44–46]. It is likely to be an important enabling technology for use of higher AC and DC voltages.

Site assembly of power transformers was a preferential subject at the 2018 Paris session [38]. A particular good summary of the state-of-the-art was given in [36]. Site assembly of power transformers is also the subject of ongoing working group A2.59.

A method for site assembly described in [46] is shown in Fig. 7.

- Reduced Environmental Impact—Oil

As was mentioned above, possible environmental impacts of uncontrolled loss of oil, fire or explosion in the event of a power transformer or reactor failure cannot be tolerated in environmentally sensitive areas or indeed in dense urban areas and

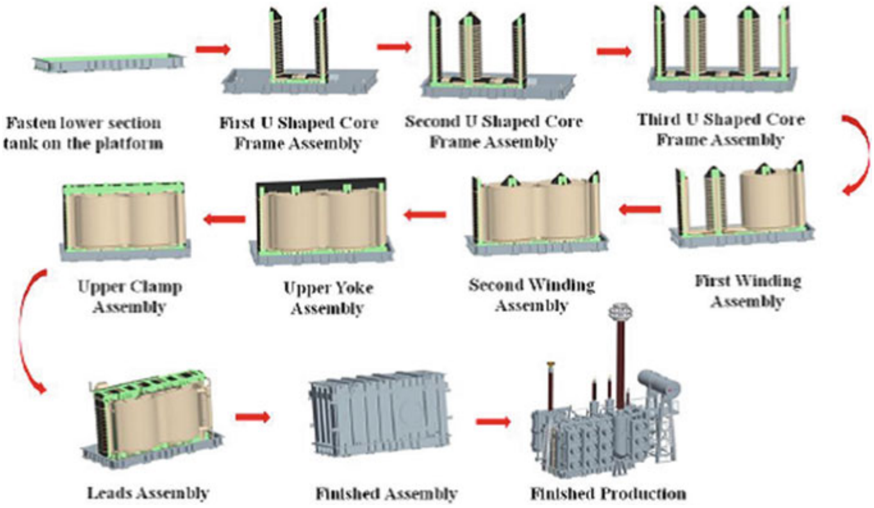


Fig. 7 Method for site assembly of large power transformer

industrial centres. The subject of power transformer fire safety was studied in detail by working group A2.33, which made a number of important recommendations [15]. Amongst the recommendations was that due consideration should be given to the use of alternative insulating media.

A large number of alternatives to conventional oil-immersed transformers have been developed. Dry-type transformers (usually with resin-encapsulated windings) are widely used in small sizes and have important advantages compared with conventional designs with regard to fire and explosion safety. However, they also have important disadvantages compared with conventional designs with regard to installed mass and dimensions; losses; and audible sound. There also seems to be a limit of approximately 30 MVA to the largest three-phase separate-winding transformer; it is normally technically feasible to use this technology. Another alternative is a gas-filled transformer. SF6 filled transformers have been used at transmission voltage in Japan since the 1970s and are also used in a number of other countries in the Asia-Pacific region. This technology has not yet found widespread acceptance outside the region and now faces an uncertain fortune given pressure to reduce SF6 use.

A number of alternative liquids have also been developed and were studied in detail by working group A2.35 [47]. Polychlorinated biphenyls at one time seemed to be a promising alternative but have now been withdrawn from use owing to environmental concerns. Silicone was widely used for some applications, but good fire performance was offset against poor biodegradability, poor dielectric properties, and poor heat transfer characteristics. The two most promising alternative liquids are now natural and synthetic esters. Both have now successfully been applied to transformers up to 420 kV class [48].

Further work is clearly needed in this area, and Study Committee D1 have established working group D1.70 to examine the functional properties of insulating liquids.

An early synthetic ester immersed 420 kV class transformer is shown in Fig. 8 (after [49]).

- Reduced Environmental Impact—Audible Sound

As was mentioned above, another major environmental impact of power transformer and especially reactors is audible sound. There is a need to minimise the impact of audible sound in environmentally sensitive areas and especially in dense urban areas. Transformer manufacturers, and their suppliers, have made great improvements in transformer audible sound levels in recent years. There is now a clear opportunity to consolidate these gains through improved specification and standardisation of new transformers. Audible sound levels for shunt reactors were studied by CIGRE working group A2.48 [34], who made recommendations concerning typical and minimum levels for specification purposes. CIGRE working group A2.54 was established to continue this work for power transformers. They published an interim report concerning typical and minimum no-load sound levels in 2019 [21]. They are currently working on typical and minimum load sound levels.

Fig. 8 Synthetic ester immersed transformer for 420 kV class

Where audible sound levels are required lower than can reasonably by improvements in design and construction, some form of external mitigation may be required. Similar considerations also apply to existing transformers which no longer meet contemporary requirements. Specific aspects related to shunt reactors were studied by CIGRE working group A2.48 [34]. It has been suggested that CIGRE Study Committee A2 should form a working group to examine audible sound level mitigation. It was decided in 2018 that such a working group would be formed once existing working group A2.54 was complete.

- Reduced Environmental Impact—Losses

As was mentioned above, a further major impact of power transformers and also reactors is losses. For many years, there has been pressure on users to reduce losses and on manufacturers to produce designs with lower losses in response. As was also mentioned above, there is a need to balance requirements for low losses against other requirements which may conflict, e.g. low audible sound levels, low transport dimension and mass, low installed mass [23].

In some cases, it may be possible to reduce losses without changing transport dimensions or mass. For example, no-load losses can be reduced by the selection of core laminations having lower specific losses [50, 51] and load losses can be reduced by the use of continuously transposed conductors [50, 51]. Improved design of insulation may allow reduced internal clearances and reduce both losses and transport dimensions and mass [52]. Once these improvements have been made;

further, reductions in losses can usually only be achieved by reducing flux and current densities, which will increase transport dimensions and mass and also installed mass.

Many countries have adopted statutory regulation of power transformer losses, now extending full the through size range to include medium and large power transformers [e.g. 22]. CIGRE working group A2.56 was established to provide users with some guidance on how best to specify and transformer losses. It is also expected that the working group will provide some useful guidance to countries planning to adopt new statutory regulations on different methods of doing so.

- Better Life Management

Where the model of centralised generation from renewable sources applies, the economic and social importance of the power transformers and reactors in the transmission network will increase. Where the model of decentralised generation applies, the economic and social importance of smaller power transformers in the distribution network will increase. Operators will need to improve their management of transformer through their lives, which will likely involve the application of new monitoring technology and also new analytical techniques.

Advances in transformer life management, especially in diagnostics, have been a frequent preferential subject at the CIGRE Paris session, most recently in 2018 [38]. They have also been the subject of a number of recent working groups [e.g. 53–55], culminating in working group A2.55 on transformer life extension.

The most important tool in transformer diagnostic testing has, for many years, been analysis of oil samples. It has the advantages of being non-invasive and having lower costs than most other available techniques. CIGRE working group A2.34 recommended making dissolved gas analysis at regular intervals and other oil tests, generally understood to include furan analysis and oil quality tests, at longer intervals [55]. Dissolved gas analysis has been in widespread use since the 1970s and is well-known for its ability to detect a wide range of different transformer faults. It has been extensively studied, most recently by CIGRE working group D1/A2.47, who have provided updated guidance on fault diagnosis [56]. Furan analysis is a slightly more recent development and is able to detect solid insulation ageing. It has also been extensively studied, most recently by CIGRE working group D1.01 (TF13) [57]. They provided some guidelines on its application, but noted that this was complex. The need to develop better techniques for detecting solid insulation ageing led to an interest in the possibility of using methanol and ethanol. This was recently studied by CIGRE working group A2/D1.46 [58].

In recent years, there has been rapid progress in transformer monitoring systems, both in the number of parameters which can be monitored and also in the accuracy and resolution of the results [24, 25]. This progress is likely to continue in the coming years. Transformer users need to be aware that the life of any modern transformer monitoring system is unlikely to be the same as that of the transformer being monitored. There will therefore be a need to renew and upgrade monitoring systems through the life of the transformer.

Possibly the biggest challenge to the successful application of transformer monitoring systems is the aggregation of results between different sensors and, at a substation or network level, different monitoring systems. Improvements in analytical techniques are clearly required. The application of modern analytical techniques to transformer data is in its infancy, and there is potential for rapid improvement [15].

- Variations in Distribution Voltage

Increased integration of distributed renewable energy resources, combined with the inherently intermittent nature, of the two main sources has led to bidirectional power flows on distribution networks in many areas. These have resulted in large variations in the distribution voltage in some areas with abundant resources. These variations in voltage have, in some cases, exceeded consumer and operator expectations, and even limits imposed by regulators or legislation.

In response, so-called voltage regulating distribution transformers have been developed. These are effectively distribution transformers with on-load tap-changers, although actual technologies used may be somewhat different from those used on medium and large power transformers. They allow better control of the distribution network voltage.

Until recently, this subject had been largely overlooked by CIGRE. A new working group under the leadership of Study Committee A3 is shortly to be established to study this area in more detail and provide recommendations concerning further action.

Meanwhile, voltage regulating distribution transformers have been the subject of intense study especially in Germany where the challenges of variable distribution voltages have been especially strong [59, 60]. There are now plans to develop an IEC standard for voltage regulating distribution transformers.

- Variations in System Frequency

A consequence of the loss of inertia owing to increased use of distributed energy sources, especially solar, is an increase in frequency variation. Transformers in accordance with IEC standards have only a limited capability for operation below-rated frequency [61], and standards or specifications may need to be revised if this is shown to be inadequate.

This issue will be partly addressed by the new working group under the leadership of Study Committee A3. Note that the problem of DC magnetisation of power transformers, which can give rise to similar phenomena, is already being studied by working group A2.57.

5 Conclusions

This chapter focused on how changes in the electricity supply system will affect the life cycle of power transformers and reactors. The CIGRE reference paper on the electricity supply system of the future provides some background information on these changes, and the challenges they represent for the electricity supply system as a whole [1]. Challenges of special relevance for power transformers and reactors include the following:

- Bidirectional power and data flows at the distribution level
- Increased use of DC and power electronics at all voltage levels
- New and more advanced tools for modelling
- Increased environmental constraints
- Increased use of right-of-way capacity
- Offshore and subsea infrastructure
- A need for increase stakeholder engagement.

Bidirectional power flows from increased integration of distributed renewable energy resources have led to large variations in distribution voltage in some areas with abundant resources. These variations in voltage have in some cases exceeded consumer and operator expectations, and even limits imposed by regulators or legislation. In response, so-called voltage regulating distribution transformers have been developed. These are effectively distribution transformers with on-load tap-changers, allowing better control of the distribution network voltage [59, 60].

In recent years, there has been rapid progress in transformer monitoring systems, both in the number of parameters which can be monitored and also in the accuracy and resolution of the results [24, 25]. This progress is likely to continue in the coming years. Possibly the biggest challenge to the successful application of transformer monitoring systems is the aggregation of results. Improvements in analytical techniques are clearly required. The application of modern analytical techniques to transformer data is in its infancy, and there is potential for rapid improvement [26].

Use of DC for long-distance transmission is now a mature technology, with the first DC transmission lines (or cables) having entered service as long ago as the 1950s. The line voltages, and hence both the amount of power and the distance over which it can be transmitted, have steadily increased reaching 1100 kV at the time of writing. Two recent developments have extended the possible use of DC transmission—VSC converters have reduced the technical challenges in constructing DC converter stations and the development of DC circuit breakers has allowed the possibility of multi-terminal DC networks [37]. Other recent developments include the use of DC transmission for connection of offshore wind generation and also the development of smaller-scale DC transmission to increase the capability of the distribution network to absorb distributed renewable generation. IEC have recently published an improved standard for HVDC transformers [39].

The large size of many modern HVDC transformers combined with the remoteness of many installation sites may make transport to site very challenging. An emerging technology which has been developed to meet these challenges is site assembly [44–46]. It is likely to be an important enabling technology for use of higher AC and DC voltages.

Phase-shifting transformers are used to counteract loop flows in transmission networks and to enable better use of the network capacity. Even in case of centrally planned networks loop flows can arise, but integration of distributed renewable resources has made the problem worse in many areas. IEC have recently published an improved standard for phase-shifting transformers [43].

Possible environmental impacts of uncontrolled loss of oil, fire or explosion in the event of a power transformer or reactor failure cannot be tolerated in environmentally sensitive areas and sometimes also elsewhere. A large number of alternatives to conventional oil-immersed transformers have been developed, of which the most promising seems to be transformers immersed in natural and synthetic esters [47]. Both have now successfully been applied to transformers up to 420 kV class [48]. Further work is clearly needed in this area, and Study Committee D1 have established working group D1.70 to examine the functional properties of insulating liquids.

Another major environmental impact of power transformer and especially reactors is audible sound. There is a need to minimise the impact of audible sound in environmentally sensitive areas and especially in dense urban areas. Transformer manufacturers, and their suppliers, have made great improvements in transformer audible sound levels in recent years. CIGRE working group A2.54 was established to consolidate this work, and in 2019 published an interim report concerning typical and minimum no-load sound levels in 2019 [21]. They are currently working on typical and minimum load sound levels. When this is complete, further work may be needed to improve mitigation methods where lower sound levels than can reasonably be achieved by improvements in design and construction are required, or for existing transformers which no longer meet contemporary requirements.

A further major impact of power transformers and also reactors is losses. For many years, there has been pressure on users to reduce losses and on manufacturers to produce designs with lower losses in response. Many countries have adopted statutory regulation of power transformer losses, now extending full the through size range to include medium and large power transformers [e.g. 22]. CIGRE working group A2.56 was established to provide users with some guidance on how best to specify and transformer losses. It is also expected that the working group will provide some useful guidance to countries planning to adopt new statutory regulations on different methods of doing so.

The conclusions of this chapter are further summarised in Table 1.

Table 1 Challenges for transformers and reactors in the power system of the future

System challenge	Transformer challenge	Responses
Bidirectional power flows	Variable distribution voltage	VRDT [59, 60] New JWG led by A3
	Variable system frequency	Better specifications WG A2.57 New JWG led by A3
Bidirectional data flows	Better monitoring systems	WG A2.27 [24] WG A2.44 [25]
	Better analytical techniques	[26]
Modelling tools		
Environmental constraints	Oil	Ester liquids WG A2.33 [15] WG A2.35 [47] WG D1.70
	Audible sound	Better specifications Better design and construction WG A2.54 [21]
	Losses	Better specifications Better design and construction WG A2.56
Increased use of right-of-way capacity	Higher DC voltages	Latest IEC standard [39] Site assembly WG A2.59 New JWG led by A2
	Higher AC voltages	Site assembly WG A2.59
	Phase-shifting transformers	Latest IEC standard [43]
Offshore infrastructure	Offshore transformers	WG B3.26 [33]
	Subsea transformers	
Stakeholder engagement		New Green Book(s) Support for Africa initiative

References

1. Hatziagyriou, N.: Electricity systems of the future. Electra **256**, (2011)
2. Vanzetta, J: Transition of the electricity system from conventional generation to a dispersed and/or RES system. Electra **275** (2014)
3. Fairely, P.: San Francisco's Secret dc Grid. IEEE Spectrum (2012)
4. GOELRO Plan: Adopted 21st December 1921
5. Bourgquist, W. et al.: The Electrification of the Irish Free State: The Shannon Scheme. Report of the experts appointed by the government (December 1924)
6. The Electricity Act (1947)
7. Fu, L. (ed.): The Three Gorges Project in China (2006)
8. IEC standard 60076: Power transformers, 1st edn. (1955)
9. Calculation of Short-Circuit Forces in Transformers. Final report of working group 12.04. Electra **76** (1980)

10. CIGRE Brochure 209: The Short-Circuit Performance of Transformers. Final report of working group 12.19 (August 2002)
11. IEC standard 60076-5: Power Transformers—Ability to Withstand Short-Circuit, 3rd edn. (February 2006)
12. CIGRE Brochure 659. Transformer Thermal Modelling. Final report of CIGRE working group A2.38 (June 2016)
13. CIGRE Brochure 577A: Electrical Transient Interaction Between Transformers and the Power System—Expertise. Final report of CIGRE working group A2/C4.39 (April 2014)
14. CIGRE Brochure 577B: Electrical Transient Interaction Between Transformers and the Power System—Case Studies. Final report of CIGRE working group A2/C4.39 (April 2014)
15. CIGRE Brochure 537: Guide to Transformer Fire Safety Practices. Final report of working group A2.33 (June 2013)
16. Bengtsson, C. et al.: Tank vibrations and sound levels of high voltage shunt reactors: advances in simulation methodologies. Paper PS1-11 presented at CIGRE Study Committee A2 Colloquium, Cracow (Poland) (October 2017)
17. CIGRE Brochure 530: Guide for Conducting Factory Capability Assessments for Power Transformers. Final report of CIGRE working group A2.36 (April 2013)
18. IEC standard 60076-3: Power Transformers—Insulation Levels and Dielectric Tests, 1st edn. (1980)
19. IEC standard 60076-3: Power Transformers—Insulation Levels, Dielectric Tests, and External Clearance in Air, 3rd edn. (July 2013)
20. NEMA Standard TR-1: Transformers, Step Voltage Regulators, and Reactors (2013)
21. Ploetner, C.: Power transformer audible sound requirements. Electra **302** (2019)
22. EU Commission Regulations no. 548/2014: Adopted 21st May 2014
23. Ryder, S., Zaleski, R.: Evaluation of alternative transformer designs to reduce transport dimensions and mass. Paper PS3-2 presented at CIGRE Study Committee A2 colloquium, Cracow (Poland) (October 2017)
24. CIGRE Brochure 343: Recommendations for Condition Monitoring and Condition Assessment Facilities for Transformers. Final report of working group A2.27 (April 2008)
25. CIGRE Brochure 630: Guide on Transformer Intelligent Condition Monitoring Systems. Final report of working group A2.44 (September 2015)
26. Cheim, L.: Machine Learning Tools in Support of Transformer Diagnostics. Paper A2-206, CIGRE 2018 Paris Session
27. Emin, Z., & de Graaf, S.: Effects of increasing power electronics based technology on power system stability: performance and operations. Electra **298** (2018)
28. CIGRE Brochure 719: Power Quality and EMC Issues with Future Electricity Networks. Final report of working group C4.24/CIRED (March 2018)
29. Murray, R. Transformers within photovoltaic generation plants: challenges and possible solutions. Paper 7.01 presented at CIGRE Regional Colloquium, Somerset West (South Africa) (November 2017)
30. Nyandeni, D. B.: Transformer oil degradation on PV Plants—a case study. Paper 7.03 presented at CIGRE Regional Colloquium, Somerset West (South Africa), November 2017
31. IEC/IEEE Standard 60076-16: Power Transformers—Transformers for wind turbine applications, 2nd edn. (September 2018)
32. Lapworth, J. et al.: Transformer internal resonant over-voltages, switching surges, and special tests. Paper A2-215, CIGRE 2018 Paris session
33. CIGRE Brochure 483: Guidelines for the design and construction of ac offshore substations for wind power plants. Final report of working group B3.26 (December 2011)
34. CIGRE Brochure 655: Technology and Utilisation of Oil-Immersed Shunt Reactors. Final report of working group A2.48 (May 2016)
35. Call for Papers, CIGRE 2016 Paris session
36. Call for Papers: CIGRE-IEC Conference on EHV and UHV (ac and dc), Hakodate (Japan) (April 2019)
37. Andersen, B.: The path towards HVDC Grids. Electra **275** (2014)

38. Call for Papers: CIGRE 2018 Paris session
39. IEC/IEEE Standard 60076-57-129: Power Transformers—Transformers for HVDC Applications, 1st edn. (September 2017)
40. Wahlstrom, B.: Voltage Tests on Transformers and Smoothing Reactors for HVDC Transmission. Final report of working group 12.02, Electra **46** (1976)
41. CIGRE Brochure 406: HVDC Converter Transformers: Design Review, Test Procedures, Ageing Evaluation, and Reliability in Service. Final report of CIGRE working group A2/B4.28 (February 2010)
42. CIGRE Brochure 406: HVDC Converter Transformers: Guidelines For Conducting Design Reviews for HVDC Converter Transformers. Final report of CIGRE working group A2/B4.28 (February 2010)
43. IEC/IEEE standard 60076-57-1202: Power Transformers—Liquid-Immersed Phase-Shifting Transformers, 1st edn. (May 2017)
44. Kobayashi, T. et al.: Quality control and site test for site assembled transformers. Paper PS 3-4, presented at CIGRE Study Committee A2 colloquium, Cracow (Poland) (October 2017)
45. Wang, X. et al.: Research and application of UHV AC transformers and shunt reactors. CIGRE paper A2-210, 2016 session
46. Wang, X. et al.: A study on key technology and demonstration of UHV AC and DC site-assembled transformers. Paper A2-306, CIGRE 2018 Paris session
47. CIGRE Brochure 436: Experiences in Service With New Insulating Liquids. Final report of working group A2.35 (October 2010)
48. M&I Materials press release, 23rd March 2015
49. Fritsche, R., Pukel, G. J.: Large power transformers using alternative liquids: experience in the range of 420 kV transmission level. Paper A2.208, CIGRE 2016 Paris session
50. Baer, R.: Transformer technology state-of-the-art and trends of future development. Electra **198**, 13–19 (2001)
51. CIGRE Brochure 642: Transformer Reliability Survey. Final report of working group A2-37 (December 2015)
52. Moser, H.P., et al.: Transformer board. Special print of Scienta Electrica (1979)
53. CIGRE Brochure 227: Life Management Techniques for Transformers. Final report of working group A2.18 (June 2003)
54. CIGRE Brochure 248: Guide on Economics of Transformer Management. Final report of working group A2.20 (June 2004)
55. CIGRE Brochure 445: Guide for Transformer Maintenance. Final report of working group A2.34 (February 2011)
56. CIGRE Brochure 771: Advances in DGA Interpretation. Final report of working group D1/A2.47 (July 2019)
57. CIGRE Brochure 494: Furanic Compounds for Diagnosis. Final report of working group D1.01 (TF13) (April 2012)
58. CIGRE Brochure 779: Field Experience with Transformer Solid Insulation Ageing Markers. Final report of working group A2/D1.46 (October 2019)
59. FNN Report: Voltage Regulating Distribution Transformer—Use in Grid Planning and Operation. VDE, Frankfurt (2016)
60. BEAMA Technical Report 4: Voltage Regulating Distribution Transformers (February 2019)
61. IEC standard 60076-1: Power Transformers—General, 3rd edn. (April 2011)

Simon Ryder was born in England in 1973. He studied Engineering Science at St. John's College, Oxford University, between 1992 and 1996. He worked for GEC Alsthom and later Alstom between 1997 and 2003, in transformer design, development, and eventually research. He is known for his work on the thermal characteristics of transformers and frequency response analysis (FRA). He joined Doble in 2003 initially working mainly on transformer life management. Since 2009, he has worked mainly on transformer procurement, especially supplier qualification and development. He is a senior member of IEEE-PES, a fellow of IET, and a Chartered Engineer. He was a member of CIGRE working groups A2.36 on transformer procurement and D1/A2.47 on advances in DGA interpretation; convenor of CIGRE working group A2.48 on shunt reactors; and a co-editor of the CIGRE Green Book on transformer procurement. He is also chairman of CIGRE Study Committee A2 on power transformers and reactors.

Transmission and Distribution Equipment

Nenad Uzelac, Hiroki Ito, René Peter Paul Smeets, Venanzio Ferraro, and Lorenzo Peretto

Keywords Circuit breaker · Switchgear · Instrument transformers

1 Introduction

Over the last 100 years, electricity has become the world's most flexible and reliable power system. Global demand continues to increase and, in many countries, the supply of electricity is strongly linked to gross domestic product (GDP) in the country. The infrastructure that enables the secure distribution of electrical power is based upon one specific device which must be extremely reliable: the circuit breaker (CB). The CB plays what is considered the most important role in the networks which is switching the power system current during both normal and abnormal conditions of the power systems.

The development of CBs has been closely linked with a remarkable growth of demand for higher voltage and larger short-circuit capacity of transmission systems. Since the late 1800 s, a diversity of interrupting technologies using oil, air, vacuum and SF_6 gas as interrupting media had been realized and contributed to large capacity power transmission constructions.

The oil CBs were first deployed in the power grid at the beginning of twentieth century and the oil was used due to its good interrupting performance [1]. In 1907, the first oil circuit breaker was patented by J. N. Kelman in the USA. The equipment was hardly more than a pair of contacts submersed in a tank filled with mineral oil. It was a time of discovery by experiments and most of the breaker design was done by trial and error in the power system itself.

On behalf of CIGRE Study Committee A3.

N. Uzelac (✉) · H. Ito · R. P. P. Smeets · V. Ferraro · L. Peretto
CIGRE, Paris, France
e-mail: nenad.uzelac@cigre.org

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_4

Half century later, in 1956, the basic patent on circuit breakers using SF_6 was issued to Lingal et al. [2]. This was a major shift in the breaker design—up to date, most high voltage circuit breakers use SF_6 as the interrupting and insulating medium.

Since then, the design, manufacturing, testing and field application of CBs continued to evolve following the requirements of the power industry. The air blast CBs with multi-break designs realized 765 kV transmission networks in 1965. Then SF_6 gas circuit breakers facilitated large capacity transmission and eventually realized UHV transmission in 2009. Simultaneously, vacuum CBs have been widely applied in medium voltage distribution networks, which are now available up to 145 kV ratings and with all indications that even higher voltage vacuum breakers will be coming to the market the coming years.

As a general trend, up to now, the interrupting capacity (efficiency) of the CBs has been increasing, resulting in the significant size reduction. This is illustrated in Fig. 1 that shows the technical evolution of unit interrupting capability of CBs with different technologies.

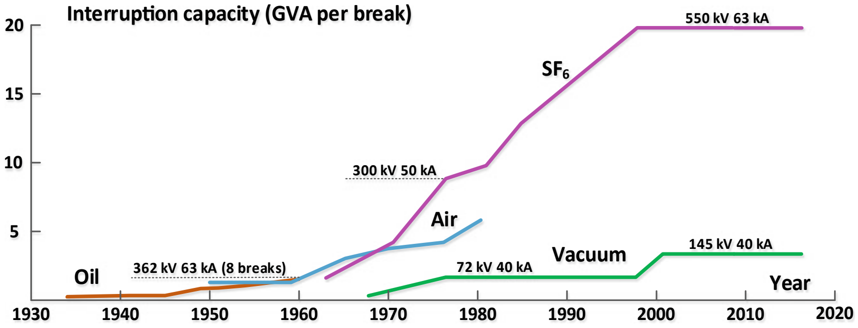


Fig. 1 Unit interrupting capability of CB with different technologies

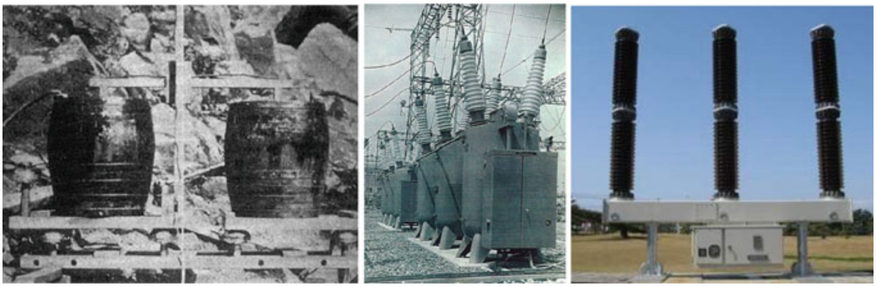


Fig. 2 Evolution of the CB designs: Kelman's oil CB built in 1901 (left), 168 kV bulk-oil, dead-tank oil CB, developed in 1959 (middle), 145 kV live tank Vacuum interrupter CB with Sf6, from 2010 (right)

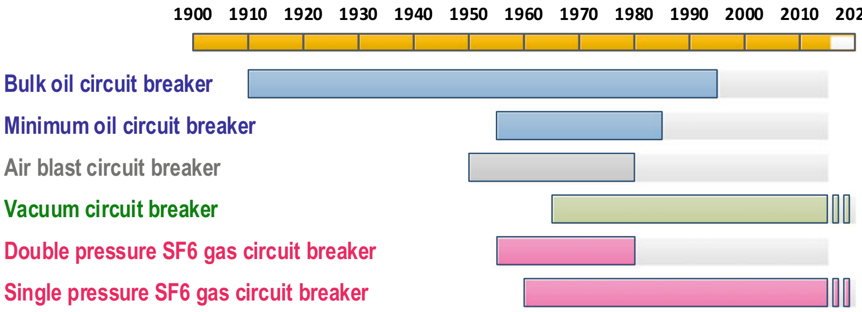


Fig. 3 Manufacturing period of circuit breakers with different technologies

Figure 2 illustrates the evolution of the CBs technology over the course of the last century, from using barrels filled with oil to utilization of the vacuum interrupters in the live tank design.

The general timeline of commercial production and use of these various types of circuit breakers is shown in Fig. 3.

One can see that some of the technologies like oil breakers are not being manufactured anymore, while others, like vacuum breakers and single pressure SF6 CBs, are still being produced and developed.

Moving forward, circuit breakers will continue to evolve in order to be able to meet the future requirements of the power grid that will be shaped by decarbonization, decentralization and digitalization drivers [3].

- **Decarbonization** is encouraged through international and national policies that promote reduction of carbon emissions and meet targets set out in the Paris Agreement.
- At the same time, several (supra)national, regional initiatives are launched to reduce the use and the emission of SF6 gas, an extremely potent greenhouse, in favor of alternatives with low or nil GWP. A key role is for electricity: forecasts are that by 2050, 45% of the world energy demand of will be electricity (at 200 EJ/yr), whereas this is 19% (75 EJ/yr) in 2016 [4]. Electricity displaces both coal and oil in the final energy demand mix.
- **Decentralization** of energy supply is required due to increased customer participation and increased demand. And as the energy industry pushes for renewable alternatives (wind, PV), the power grid is becoming more and more decentralized. This will lead to a more “chaotic” power flow with higher requirements on switchgear for protection and power system (re-)configuration.
- **Digitalization** as the grid becomes more decentralized, switching technology will be needed to ensure a consistent and reliable supply of electricity with a high degree of automation.

Taking these drivers into account, it is expected that two main power systems models will appear between 2020 and 2040, since they will be needed to reach ambitious decarbonization targets [3].

- **Bulk Model** it represents large transmission networks for interconnecting load regions with power generation regions like with offshore wind and for interconnecting different countries and energy markets. World power line capacity will increase from 2.5 PW-km in 2019 to over 7 PW-km by 2050. Forecasts are that by 2050 roughly 50% of these lines will be in the EHV (350–800 kV) class. Around 15% of bulk transport will be across HVDC connections, 85% is expected to be still HVAC [4].
- **Micro Model** it represents clusters of small distribution networks that are self-contained, consisting of distributed energy sources, storage and active customer participation.

In this chapter, we will look in how these trends influence the developments in HV switchgear, MV switchgear and instrument transformers.

2 Developments in HV Switchgear

System and component development is a matter of evolution. A revolution, however, has been caused by the maturation of power electronics. When Thyristors, IGBT's and GTO's became available at affordable prices, we can speak of a game changer in the previously steadily and quietly evolving power grid, when it comes to control. A major hurdle, however, are the losses of the semi-conduction junction in power electronics during normal current conduction. Therefore, hybrid solutions of switchgear having a galvanic, mechanical path for normal conduction and a power electronic switch for fault current interruption may emerge. In the foreseeable future, high-voltage switchgear is not going to replace arc-based mechanical switchgear, except for load switching [5].

Vacuum breakers will dominate the distribution systems and in the coming years will be more compact and may have a separate electromagnetic drive for each phase. A promising development is the self-actuating vacuum interrupter: no bellows, no moving external parts and no external operating mechanism. A 145 kV vacuum breaker is already available and the next steps will be a 245 kV double break and a 550 kV with 4 vacuum interrupters immersed in oil.

Short-circuit currents will increase and a substation equipped with fault current limiters (FCL) would be a widely appreciated development. A pilot with a 110 kV resistive FCL, however, has been stopped. A spin-off of ultra-fast drives for DC circuit breaker might be very fast AC switchgear that could be fault current limiting before the asymmetrical peak of fault current is reached.

As the application of high-temperature superconductivity in the power system comes within reach, various projects have been started worldwide. But will superconductivity be a game changer or will it only play a role in specific cases where the old and proven technology cannot be applied?

For long-distance transmission of bulk power, the choice will be made either for AC or for DC, and of course, the decision has to be made whether it will be done with overhead lines, underground cables or gas-insulated transmission lines. Overhead lines are the solutions with lowest investments, but with highest environmental impact. High voltage cables, under development up to 800 kV but common up to 600 kV, traditionally only in submarine applications, now become more and more prominent in onshore application, often as part of a line dominated grid. In that case, switchgear needs special attention. Gas-insulated lines are now applied up to 1100 kV. For meshed DC transmission grids, a DC breaker is in development and AC grids are in preparation for 1100 kV (commercial, China) and 1200 kV (pilot, India).

While the short-circuit power of the grids is gradually increasing, the interrupting capacity per break is now 550 kV voltage rating with 63 kA breaking capability, which enables to the design and construction of an 1100 kV double break circuit breaker. On the other hand, the general trend is to reduce the size and complexity of the interrupting devices. In several locations in HV systems, short-circuit levels up to 80 kA has been reached. SF_6 circuit breakers are under development to cope with this requirement.

SF_6 has excellent dielectric properties and is a great extinguishing medium. But outside the power engineering society, it is not appreciated because of its negative influence on the environment. This will be an ongoing discussion, so the only path to follow is to search for alternatives. The alternative gasses are already applied in several GIS pilot projects up to 170/245 kV, in GIL (420 kV) and in current transformers.

Figure 4 summarizes the manufacturing period of circuit breakers with different technologies along with technical subjects to be solved for wider applications. The subjects include the development of compact EHV vacuum interrupters, long-term reliability of circuit breakers with SF_6 alternatives and cost reduction of semiconductor circuit breakers.

2.1 HVDC Breaker

The interruption process for DC breakers is much more challenging that for AC breakers. AC breakers are interrupting the fault at a current zero, typically 2–3 cycles after the fault initiation.

In DC systems, there is no natural current zeros so the breaker must be able to create the artificial current zero, and with that needs to prevent the arc restrikes and also to dissipate the stored energy. In addition, DC breakers must be able to interrupt

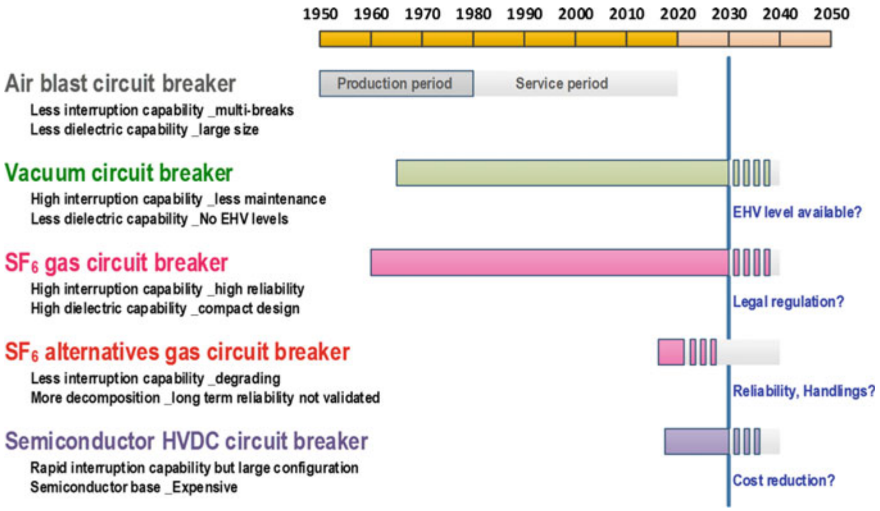


Fig. 4 Manufacturing period of circuit breakers with different technologies along with technical subjects to be solved for wider applications

the fault within a few milliseconds because of the fault current in DC system has much faster rate of rise because of the relatively low impedance in HVDC.

Figure 5 shows a photo of a prototype 500 kV, 25 kA hybrid mechanical and power electronic DC circuit breaker and its configurations. The hybrid HVDC circuit breaker consists of a main load branch and a main breaker branch. The main load

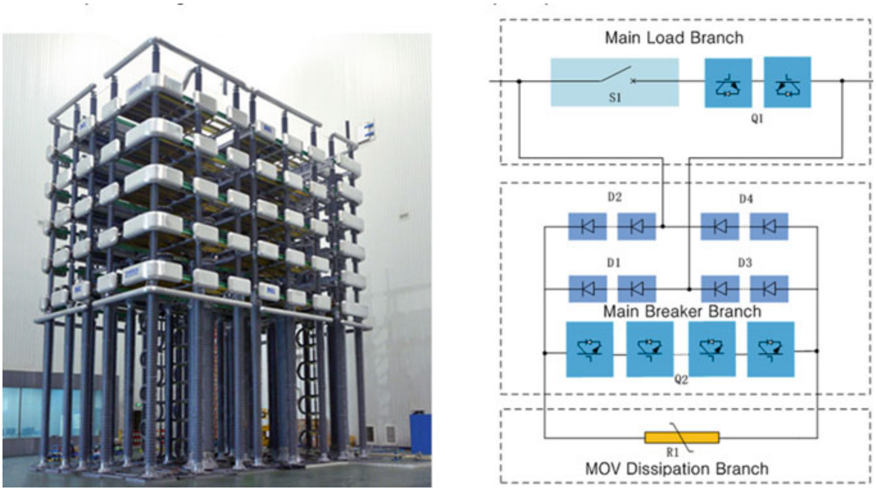
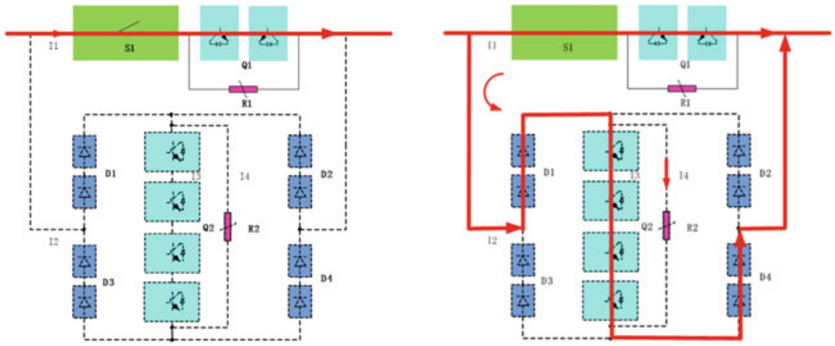
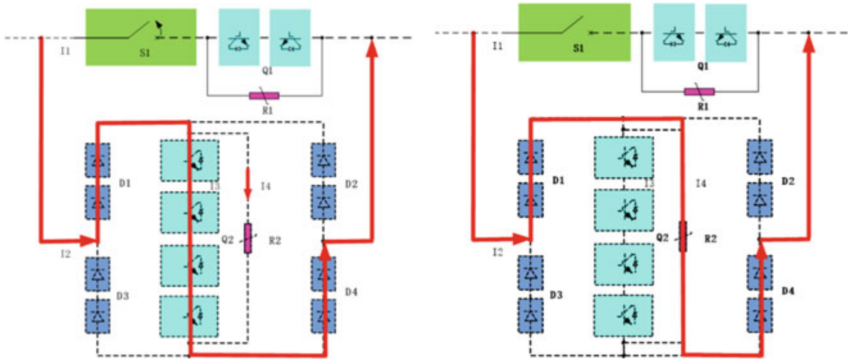


Fig. 5 500 kV DC circuit breaker (Hybrid mechanical and power electronic switch)—Courtesy of NR Electric, State Grid Corporation of China



Left: Nominal current carrying (load) condition **Right** : Current commutation from the load branch to the breaker branch



Left: Current commutation completion to the breaker branch **Right:** Current blocking by IGBT modules and energy dissipation by MOSA

Fig. 6 DC current interruption process of the 500 kV DC circuit breaker [6] (Courtesy of NR Electric, States Grid Corporation of China)

branch includes the fast mechanical switch (vacuum disconnector) and the IGBT commutation module. The main breaker branch is composed of the series-connected IGBT modules with several diodes and the energy dissipating MOSA connected in parallel. Figure 6 shows the DC current interruption process of the 500 kV DC circuit breaker.

Some of the applications and the new developments regarding HVDC breakers are discussed below.

2.1.1 HVDC Switchgear

Interruption of DC current is basically impossible because of the absence of a natural current zero crossing. Nevertheless, since the advent of HVDC systems over 60 years ago, the need arose of switching DC current, for commutation of current into a different path (transfer of current) either in a station busbar, line or neutral conductor or to bypass certain station equipment, e.g., a converter or part of a converter that is out of order. These switching functions are carried out by HVDC transfer switches.

Earthing operations, for safety or operational reasons, need to be carried by earthing switches and high-speed earthing switches.

When switching is performed under no-load (no current) conditions, disconnector switches are in common use. Though their function is to isolate, under energized (no load) conditions, small resistive leakage current needs to be interrupted.

Transfer, earthing and disconnector switches are very common in DC side switchyards in HVDC stations. HVDC switches can be either air insulated (most common) or gas insulated. Development is toward HVDC switches to be accommodated in systems up to ±1100 kV.

2.1.2 HVDC Circuit Breakers for Multi-terminal HVDC Grids

Almost all of the HVDC systems in use in the world are point-to-point systems, a single HVDC link connecting two HVDC stations nearby large-scale generation, e.g., a large hydropower plant or a large load center. In case of a fault, the total link needs to be de-energized, either by AC circuit breakers or by converter control (in LCC systems). During system restauration, there is no or limited energy flow. Especially in systems having submarine connections, repair times can be very long; a survey among European TSO reports an average repair time of 60 days [7]. Therefore, dedicated DC circuit breakers for DC fault current interruption at DC side are not necessary for point-to-point links.

With the need of connecting huge amounts of medium sized generators (commonly offshore windfarms) spread across a large surface, meshed HVDC grids or multi-terminal HVDC systems are being realized in small scale and conceived in a large scale, aimed to harvest hundreds of gigawatts in a few decades from now. The meshed or multi-terminal topology greatly enhances reliability, system stability and electricity trade across national boundaries.

A key requirement of such meshed HVDC grids is the possibility to de-energize faulted branches of the grid, without endangering the integrity of the system as a whole. The best candidate so far, apart from dedicated “full bridge” converter topologies, is the HVDC circuit breaker. This device needs to interrupt every possible DC fault current and to isolate the faulted section from the grid in a very short time.

Whereas HVDC switches are from technology point of view based on AC switching devices, having only slight modifications for typical HVDC arcing and insulation requirements, HVDC circuit breakers are totally different from AC breakers. HVDC circuit breakers consist of various components and are very complicated, large and expensive devices.

DC breakers at all voltage levels (LV—EHV) are based on the principle that generation of a counter voltage, exceeding the system voltage, suppresses the DC fault current to zero. During the fault current suppression process, the breaker needs to absorb the energy stored in the faulted DC grids, usually with a sizeable amount of MOSA. In HVDC applications, counter voltage generation is achieved though active interruption of the fault current in the main path of the breaker, after which the current is forced to commutate in a parallel path of high impedance, usually a capacitor bank. There, voltage is rapidly built up until it is limited by a MOSA bank that further conducts the fault current while system energy is absorbed. Several different technologies are in development, all using a combination of mechanical interrupters (vacuum, SF6) and an auxiliary circuit for current zero creation, either based on active current injection [8], power electronics [9], or HF oscillation excited by power electronics [10].

In 2017, CIGRE Technical Brochure 683 "Technical requirements and specifications of state-of-the-art HVDC Switching Equipment" was issued [11]. In this document, a large number of HVDC switchgear are summarized, explained and analyzed.

2.1.3 HVDC Multi-terminal Grids in China (±160, ±200 KV in Operation, ±500 KV to Come), ±525 North Sea HVDC Grid Under Study

HVDC circuit breakers are in service at the time of writing in two projects, one is the ±160 kV four terminal Nan'ao project (2013) [12] operated by China Southern Power Grid the other is the ±200 kV Zhoushan five terminal island link (2014) [13], from State Grid Company of China. Recently, HVDC circuit breakers were installed in both projects. In addition, the realization of the ±500 kV Zhangbei meshed HVDC grid [14], also a project in China, will initially include 16 HVDC breakers of five different designs. Several types of HVDC circuit breakers are under development, all for application in future meshed grids.

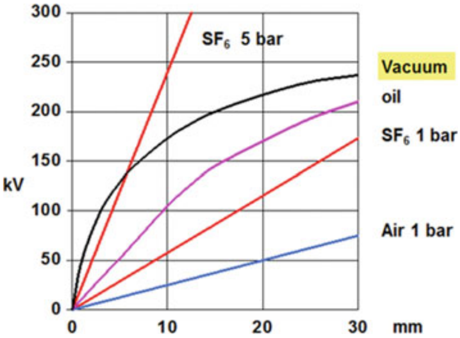
2.2 *Vacuum Interrupter at Transmission Level*

Excellent service experience of vacuum circuit breakers in MV power systems obviously resulted in exploration of possibilities to develop vacuum switchgears for transmission voltage levels. CIGRE investigated the service experience of HV vacuum circuit breakers and summarized the state-of-the art regarding the impact of the application of vacuum switchgear at voltages above 52 kV.

There are basically two ways to increase the dielectric strength of the vacuum gap to the value needed for insulation at transmission levels. One is to increase the contact distance in a two-contact configuration. However, the breakdown voltage U_b of vacuum gaps is not proportional to the gap length d (as it is in gases), but typically follows the relation:

$$U_b = \mathrm{A} \cdot d^{\alpha}$$

Fig. 7 Dielectric performance in Vacuum



where α is a parameter smaller than one and A is a constant. The explanation is that breakdown in vacuum is a surface effect, completely governed by the contact surface condition. In SF_6, breakdown is merely a volume effect that scales linearly with the gap length. The breakdown process is then mainly determined by the insulating medium and its pressure rather than by the contact configuration and condition.

Figure 7 shows an example of static breakdown voltage for different interrupting media under no load condition. The dielectric strength linearly increases with the contact gap in case of gas, however, that in a vacuum shows good dielectric strength with small gap (even 2–4 mm gap) but gradually saturates for a longer gap length.

The other way is to place two or more gaps in series (multi-break circuit breakers that typically ensure the uniform voltage distribution across all breaks during normal and switching system operation with grading capacitor), and in case of ideal voltage sharing between the gaps, the necessary withstand voltage level can be achieved with a total contact distance smaller than it would be with a single gap.

These two solutions co-exist in the market at voltages above 72.5 kV.

The first reported commercial development of transmission vacuum circuit breakers was in the UK in 1968 where eight vacuum interrupters were connected in series in a circuit breaker for 132 kV. The breaker has been in service for more than 40 years.

In the mid-1970 s, in the USA, a series arrangement of four vacuum interrupters per pole was used as retrofit kit for bulk oil circuit breakers up to a system voltage of 145 kV, and further plans were made for up to 14 break interrupters for 800 kV [15].

Simultaneously with this multi-gap/multi-break approach, Japanese researchers developed and commercialized single-break vacuum interrupter units up to 145/168 kV.

In 1986, two types of vacuum circuit breakers were published: a single-break 84 kV vacuum circuit breaker with a rated breaking current of 25 kA and a prototype vacuum circuit breaker for the 145 kV voltage level. Commercial single-break vacuum circuit breakers are available up to 145 kV and commercial double-break dead-tank-type vacuum circuit breakers are developed up to 168 kV (see Fig. 8) and 204 kV.

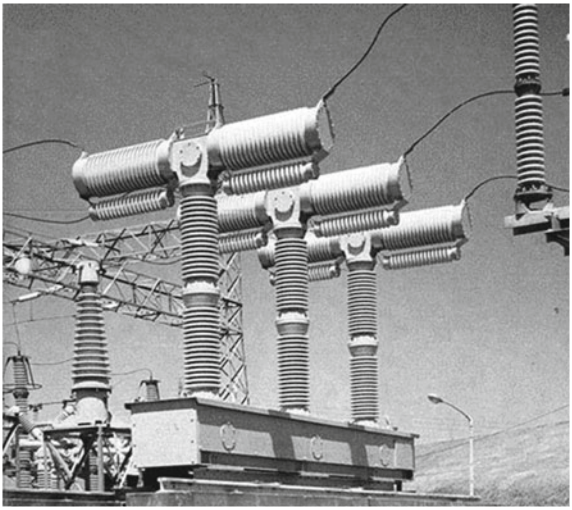


Fig. 8 168 kV, 40 kA Vacuum circuit breakers in 1972 (Courtesy of Meidensha)

In total, approximately, 8300 units of vacuum circuit breakers with rated voltages of 52 kV and above were delivered to the market by five manufacturers in Japan from the late 1970 s to 2010. Roughly, 50% were delivered to power utilities and 50% to industrial users. Cubicle-type GIS (C-GIS) represents 50% of the HV vacuum circuit breakers application, mainly by industrial users.

One of the reasons of the rather frequent use of HV vacuum circuit breakers in Japan is that utilities acknowledge the advantages of less maintenance (compared with SF_6 circuit breakers), the excellent frequent-switching performance, and suitability for rural distribution systems.

The reliability of HV vacuum circuit breakers appears to be comparable to SF_6 circuit breakers. A Japanese survey on the failure rate of HV vacuum and SF_6 circuit breakers installed in 72.5 kV transmission networks was conducted in cooperation with a Japanese utility. Mechanical failure of the operating mechanism was the main cause of major failures. There were no troubles caused by over voltages arising from HV vacuum circuit breakers. The quantity of failures, however, is too low to identify a trend regarding service years.

Most research and development efforts devoted to HV vacuum circuit breakers are concentrated in East Asia. Japanese companies showed the feasibility of mature products already twenty years ago, however, predominantly applied on their internal market where HV vacuum circuit breakers take a certain share in special applications.

Research and development work in Europe has been reported since the mid-1990s. Companies in Europe are now bringing HV vacuum circuit breakers on the market and have started pilot projects to gain experience in the field. In the modern generation of HV vacuum circuit breakers, SF_6 is tended to be avoided as outside insulation media of the vacuum interrupter, and instead, nitrogen or dry air is preferred. The most recent development was 145/170 kV vacuum interrupter that has been fully tested inside the air-insulated circuit breaker [16], including a dead-tank solution.

Fig. 9 Installation of Vacuum circuit breaker in 110 kV substation (courtesy of siemens)

When developing VIs for higher voltages, one must pay a closer look to its X-ray emissions [17]. Figure 9 shows the installation of the 110 kV breaker equipped with 145 kV VI in one substation.

Some manufacturers in the USA although having an early track record of HV vacuum circuit breaker development did not commercialize the HV vacuum circuit breaker technology. However, products for load switching, notably capacitor banks, with multi-break vacuum interrupters in series (up to 9 interrupter units per phase) emerged already long ago as HV switches up to rated voltages of 242 kV. Vacuum switchgear is occasionally seen as an option in HV disconnectors for increasing their switching capability.

Experimental (‘hybrid’) designs with SF_6 and vacuum interrupters in series have been reported as well. The idea is to use the very fast recovery of a vacuum interrupter to withstand the initial TRV (such as appears in short-line fault interruption), whereas an SF_6 interrupter with a reduced amount of SF_6 should withstand the peak value of the transient recovery voltage.

Moving forward, it is expected to develop single VIs for even higher voltage level classes. A mock-up of a 245 kV/63 kA VI has been already shown at CIGRE 2018 exhibition.

2.3 Circuit Breaker with SF6 Alternative Gases

SF6 has been an essential part of transmission and distribution equipment, included switchgear rated up to over 1000 kV. It has a proven track record and its technical advantages are well understood and documented both in industry and academia. Despite all the advantages, SF_6 has one major shortcoming—its environmental impact. Since Kyoto protocol in 1997, SF_6 has been on the watch list, but recently, there are number of regulatory activities that may result in banning the SF_6 for use in T&D products, including switchgear.

For example in USA, California Air Resource Board (CARB) is working on the SF_6 phase out plan that will likely start in 2025 [18]. Meanwhile, Europe has the goal to cut the F-gas emissions by two thirds by 2030 compared to 2014. In 2020, a new and tighter regulation is expected and SF_6 phase out plan might be part of it.

In addition to the regulative changes, both IEEE and IEC are investigating the impact of replacing SF_6 gas with alternatives on the switchgear standards [19].

At the same time, the technical community is in the process of evaluating the performance of alternative gases. On the following pages, some of the latest research is presented.

CIGRE SC A3 published a reference paper [20] on interrupting performance with SF_6 alternative gases including C5 Perfluoroketone (C5-PFK, F-Ketone, $CF_3C(O)CF(CF_3)_2$) [21] and Iso-C4 Perfluoronitrile, (C4-PFN, F-Nitriles, $(CF_3)_2$-CF-CN) [22]. The reference paper claims that there are no alternative interrupting media comparable to SF_6 covering the complete high voltage and breaking current ranges as needed by today's power systems with the same reliability and compactness as modern SF_6 circuit breakers.

SF_6 alternatives often lead to larger interrupters (often multi-breaks) with a higher gas pressure that requires the use of a larger driving energy of the operating mechanism. Therefore, the high GWP value 23,500 of SF_6 alone is not adequate to measure the environmental impact of electric power equipment based on SF_6 technology. The environmental impact of any specific application should be evaluated and compared using the life cycle assessment approach from its production to disposal as regulated by ISO 14,040.

There are still missing scientific data showing why a small amount of F-Ketone or F-Nitriles in CO_2 can significantly improve the interrupting capability. However, short-line fault (SLF) interruption performance (thermal interruption performance) with a mixture of F-Ketones with CO_2/O_2 (7-8 bar) is 80% compared to SF_6, which causes a 245 kV GIS to be de-rated to 170 kV. Interrupting performance with a mixture of F-Nitriles with CO_2 (7 bar) was cleared for 145 kV, which is unknown compared with SF_6.

In conclusion, the use of a 245 kV (50 kA for SF_6) GIS design using an operating mechanism with larger mechanical energy under higher gas pressures (7–10 bar for non-SF_6) can provide a 170 kV GIS (31.5–40 kA for non-SF_6).

2.3.1 Properties of SF_6 Alternative Gases and Mixtures

The properties of the selected alternative gases with reference to SF_6 are shown in Table 1. The GWP for the various gases is different: the C4-PFN has a much higher GWP than CO_2 or C5-PFK that are both around 1. All the gases of interest are not flammable, have no ozone depletion potential (ODP) and are non-toxic according to safety data sheets available from the chemical manufacturer [21, 22]. The dielectric

Table 1 Properties of pure gases compared to SF_6

	CAS number[c]	Boiling point/°C	GWP	ODP	Flammability	Toxicity LC50 (4h) ppmv	Toxicity TWA[a] ppmv	Dielectric strength/pu at 0.1 MPa
SF_s	2551-62-4	−64[b]	23,500	0	No		1000	1
CO_2	124-38-9	−78.5[b]	1	0	No	>300,000	5000	≈0.3
C5-PFK	756-12-7	26.5	<1	0	No	>20,000	225	≈2
C4-PFN	42532-60-5	−4.7	2100	0	No	12,000	65	≈2

[a] The occupational exposure limit is given by a time-weighted average (TWA), 8-hr

[b] Sublimation point

[c] A unique numerical identifier assigned to every chemical substance described in the open scientific literature

strength of pure C4-PFN and C5-PFK is nearly twice that of SF_6. CO_2 has a dielectric withstand comparable to air [23–24], significantly below that of SF_6.

The properties of gases and mixtures when used in switchgear are shown in Table 2. The concentration of admixtures of C4-PFN and C5-PFK with the buffer gas is given in the second column and is typically below 13% (mole). Note that for the use of C5-PFK in CO_2, additionally an oxygen admixture is used. Due to a reduced dielectric withstand of the mixtures compared to SF_6 at the same pressure, the minimum operating pressure needs to be slightly increased to about 0.7 … 0.8 MPa for C5-PFK and C4-PFN when using CO_2 as the buffer gas for HV application. For

Table 2 Properties/performances of gases and mixtures in MV and HV switchgear applications

	C_{ad}[a]	P_{min}/MPa[b]	T_{min}/°C[c]	GWP	Dielectric strength[d]	Toxicity LC50 ppmv
SF_6	–	0.43 … 0.6	−41 … −31	23,500	0.86 … 1	
CO_2	–	0.6 … 1	≤−48[f]	1	0.4 … 0.7	>3e5
CO_2/C5-PFK/O_2 (HV)	≈6/12	0.7	−5 … +5	1	≈0.86	>2e5
CO_2/C4-PFN (HV)	≈4 … 6	0.67…0.82	−25 … −10	327 … 690	0.87 … 0.96	>1e5
Air/C5-PFK (MV)	≈7 … 13	0.13	−25 … −15	0.6	≈0.85[e]	1e5
N_2/C4-PFN (MV)	≈20 … 40	0.13	−25 … −20	1300 … 1800	0.9 … 1.2	>2.5e4

[a] Concentration of admixture is in mole % referred to the gas mixture

[b] Typical lock-out pressure range

[c] Minimum operating temperature for P_{min}

[d] Dielectric strength compared to SF6 at 0.55 MPa. For the scaling of SF6 breakdown field, Ed with pressure correction in the form of $Ed = 84 \cdot p^{0.71}$ was used

[e] Compared to SF_6 at 0.13 MPa, measurements were for a mixture at −15 °C

[f] Calculations with Ref: https://www.nist.gov/srd/refprop

Air/C5-PFK mixtures in MV applications, 0.13 MPa can be kept and the dielectric withstand of SF_6 is approached. The high dielectric withstand of mixtures with relatively low admixture ratios of C4-PFN or C5-PFK can be explained by a synergy effect [25], i.e., a nonlinear increase of the dielectric strength with the admixture ratio, as is known in SF_6/N_2 mixtures. The GWP of mixtures with C5-PFK is negligible, at the cost of a higher minimum operating temperature. Low-temperature applications of e.g. -25 °C for HV can be covered by pure CO_2 or CO_2 + C4-PFN mixtures.

2.3.2 Interrupting Performance of SF_6 Alternative Gases and Gas Mixtures

The switching performance mainly focuses on thermal interrupting capability, corresponding to the short-line fault (SLF) testing duty and the capacitive switching capability. Preliminary information on the switching performance of pure CO_2 and CO_2 mixtures is collected in Table 3. The performance of SF_6 is given for comparison. With an enhanced operating pressure compared to SF_6, the cold dielectric strength, which is a measure of the performance in capacitive switching, can reach the same level as that of SF_6. In the scanned literature, only qualitative statements on the switching performance of C4-PFN and C5-PFK mixtures could be found. For CO_2, a few quantitative comparisons exist. Very roughly, for pure CO_2 at an increased fill pressure of about 1 MPa, about 2/3 of both the dielectric and thermal interruption performance of SF6 might be expected. With the admixture of C4-PFN and C5-PFK into CO_2, the dielectric performance can be close to SF6. The SLF switching performance for the mixtures of CO_2/O_2/C5-PFK is reported to be 20% below that of SF6 [25]. For an adapted circuit breaker (CB) with CO_2/C4-PFN, a SLF performance similar to that of SF6 is stated [26]. There are, however, also direct comparisons of pure CO_2 with CO_2/C4-PFN and CO_2/C5-PFK mixtures using identical geometry and pressure, which show similar thermal interruption performance of CO_2 with and without mixtures. IEC test duties L90 (SLF) and T100 (100% terminal fault) with the new mixtures have been passed with some design modifications [27] or certain

Table 3 Switching performance of gases and mixtures compared to SF_6 at increased operating pressures in HV applications

	Operating pressure (MPa)	Dielectric strength/pu	SLF performance compared to SF6/pu[a]	Dielectric recovery speed/pu
SF_s	0.6	1	1	1
CO_2	0.8 … 1	0.5 … 0.7	0.5 … 0.83	>0.5
CO_2+C5-PFK/O^2	0.7 … 0.8	Close to SF_6	0.8 … 0.87	Close to SF_6
CO_2/C4-PFN	0.67 … 0.82	Close to SF_6	0.83…(1)[b]	Close to SF_6

[a] At same pressure build up

[b] Same performance as SF_6 is stated but it is not clear if this was under same conditions

de-rating [25], suggesting that the switching performance of the new mixtures is not significantly lower than that of SF_6. This has also been shown to be valid for the bus transfer switching duty of disconnector switches, e.g., [28, 29].

Formation of critical by-products under repetitive switching in a small volume is discussed in [24]. Considerably more experience seems to be needed on the post arcing toxicity of the potential SF_6 substitute gases. Additional reported issues are: material compatibility [16] (e.g., effects on sealing and grease), gas tightness and gas handling procedures. Therefore, existing HV equipment cannot be filled with the new gases without design or material changes. Internal arc tests were done with all mixtures and no critical issues are reported, [26, 30, 31].

With the C5-PFK mixtures for HV (GIS with 8 bays for 170 kV, 31.5 kA, based on a 245 kV, 50 kA design) and MV (primary switchgear, 50 panels, 22 kV, nominal current: 1600 A for feeder, 2000 A for busbars), pilot installations have been in operation successfully since 2015 in Switzerland [30, 32] and Germany. Pilot installations with the CO_2/C4-PFN mixture are planned in several European countries 0, such as a 145 kV indoor GIS in Switzerland, 245 kV outdoor current transformers in Germany and outdoor 420 GIL in the UK [26, 28].

As the latest SF6 alternative, research and test results were published on a breaker filled with a CO_2/O_2 mixture [33]. The concept of a variable pressure scheme is introduced in terms of insulation coordination across multiple ratings with the low-end pressure scheme bounded by switching and interrupting performance and the high-end pressure scheme bounded by saturation temperature limits which were not practical even with SF_6.

2.4 Offshore Switchgear Applications

As offshore wind turbines continue to grow in size and power output, wind farm developers and operators are preparing to switch over to 66 kilovolt (kV) technology rather than the current 33 kV technology. The wind turbines being developed will be 12 MW reaching heights of 250 m. The higher operating voltage offers benefits like reducing the number of required substations as well as reducing the length of cables that need to be installed.

HV switchgear installed in these turbines will need to be compact and to have minimized maintenance costs (Fig. 10). Circuit breakers will have to be able to switch higher capacitive currents in a very long AC cables. Also, it is possible that current zero will be missing due to large reactive compensation onshore.

Fig. 10 Compact 66 kV switchgear for offshore applications. Courtasy of GE

3 Developments in MV Switchgear

Distribution grids are going through a radical step change, driven by various trends. One is that power flows are changing from rather stable, predictable and unidirectional toward variable, volatile and bidirectional. Another trend is the increased pressure by stakeholders to achieve a higher availability of electric power, i.e., a reduction of power interruptions. Additionally, load currents, short-circuit currents and system voltages are on the rise due to developments both at load side and generation side of the power systems, as well as by increasing demands on power quality [34].

To satisfy those requirements, advanced switching equipment (circuit breakers, reclosers, fault interrupters) that work with more complex protection and tele-control systems are used instead of fuses and switches.

In addition, switching generators on and off and clearing faults nearby power plants require functionalities that are outside general-purpose circuit breaker specifications. Users should be aware of the special requirements to be put forward for generator circuit breakers. One of the aspects to be considered is the dielectric withstand strength across open contacts to facilitate the separation of two parts of the power system (or a generator) running non-synchronously.

Furthermore, a larger societal pressure to limit spatial, visual and environmental impact of distribution switchgear forces the power industry to look for compact and/or underground equipment independent of the ambient (e.g., submersible). Small spaces lead to potential safety and health issues that need to be solved in an adequate and transparent way. Internal arc withstands capability is a growing concern where equipment gets more compact. Also, because of bidirectional power flows, distributed generation introduces new and more complicated safety issues, during network repair, restoration and modification.

Last but not least, utilities are facing a significant resource challenge. From a human perspective, there are a disproportionate number of utility experts leaving the workforce comparing to those who are ready to enter. This results in having less qualified labor which needs the power system to operate simpler and safe. Utilities will depend more on “plug and play,” “fool-proof,” “maintenance-free” and “longer life” switchgear, equipment with advanced sensors and tele-controlled intelligence. From a financial perspective, utilities are faced with the pressures to reduce operational and maintenance costs. To illustrate the trends in the MV grid, consider the following examples.

3.1 Distribution Switchgear

There is a clear trend moving from fuses and switches toward circuit breakers and reclosers with protection relays. The main reasons are:

- better coordination between protection relays, resulting in shorter fault clearing times
- better selectivity, the ability to perform auto-reclosing with short interruption times
- the possibility to faster or even automatic restoration when tele-control is available.

Additionally, dispersed generation will influence load flow/fault current directions and patterns in such a way that at many nodes, fuses with switches may no longer be applied. Another argument for circuit breakers instead of fuses is to avoid touching high voltage parts like fuses when removing them to isolate parts of the system.

In Fig. 10, the relationship is illustrated between certain developments in the distribution grids, their consequences, necessary countermeasures and the impact of the measures on switchgear assemblies. When the facilities mentioned in the last paragraph are available, the functionality of the switchgear can be augmented. By telecommunication, it could be possible to collect system analogue inputs to improve operational efficiency (e.g., volt/var optimization), load flow calculations and theft detection support. But it is also possible to provide engineering access for remote device management, including firmware and setting management, as well as remote protection profile changes for work on the power system and for temporary system conditions such as adverse weather. Functions as controlled switching, islanding (system separation), synchro-check and synchronization can be implemented.

3.2 Remotely Controlled Switchgear

When the power supply can be controlled and restored by control center operators or by the atomized systems, the gain in a reduction of system average interruption duration index (SAIDI) will be enormous. The following conditions must be considered for the control center:

- Information about the fault location should be available (from indicators, protection relays)
- The status of all involved switchgear should be available (including alarms)
- Information about maintenance and other activities, including information about earthed parts of the network should be accurate
- Operational information about dispersed generation should be timely and accurate
- The relevant switchgear should be controllable
- Power flow should be visible.

When applied in a smart way, tele-control by SCADA is very beneficial. For instance, the increase in costs to add SCADA to every recloser may well be below the benefits received, which depend upon the utility geography, predominantly lines or cables, field resources (technician manhours) and the expected benefits, such as improved reliability, customer inclusion, safety, efficiency, security and environmental impact. Figure 11 shows the customer interruption benefits (for one utility) as function of the number of SCADA connected reclosers. Clearly diminishing returns in terms of customer interruptions is visible by a further increase of the number of SCADA connected reclosers, levelling out around 1500 with 900,000 customer interruptions saved, i.e., average 600 customer interruptions saved per recloser.

Another example is on the benefits of remote switching and taking safety measures, such as non-reclosing settings. The benefits are improved partial circuit restoration times, reduced field coordination (phone calls) and increased crew utilization.

As the electronic equipment for telecommunication, monitoring, protection and control (IED) is installed near primary equipment, it should be designed and tested for working in the harsh electromagnetic environment. One example is showed in Fig. 12. The circuit breaker and switches in the ring main unit (RMU) were controlled by a dedicated remote-communication system (installed on the left-hand side). Auxiliary supply was derived from the low voltage side of the MV/LV-transformer in the RMU.

3.3 Automatic Restauration

A next development will be automatic system restoration, where local and essential information is collected, and decisions are made to autonomously operate within seconds or tenths of seconds. The well-known auto-reclosing functionality is a simple predecessor of such developments. As switching will be performed rather fast, the

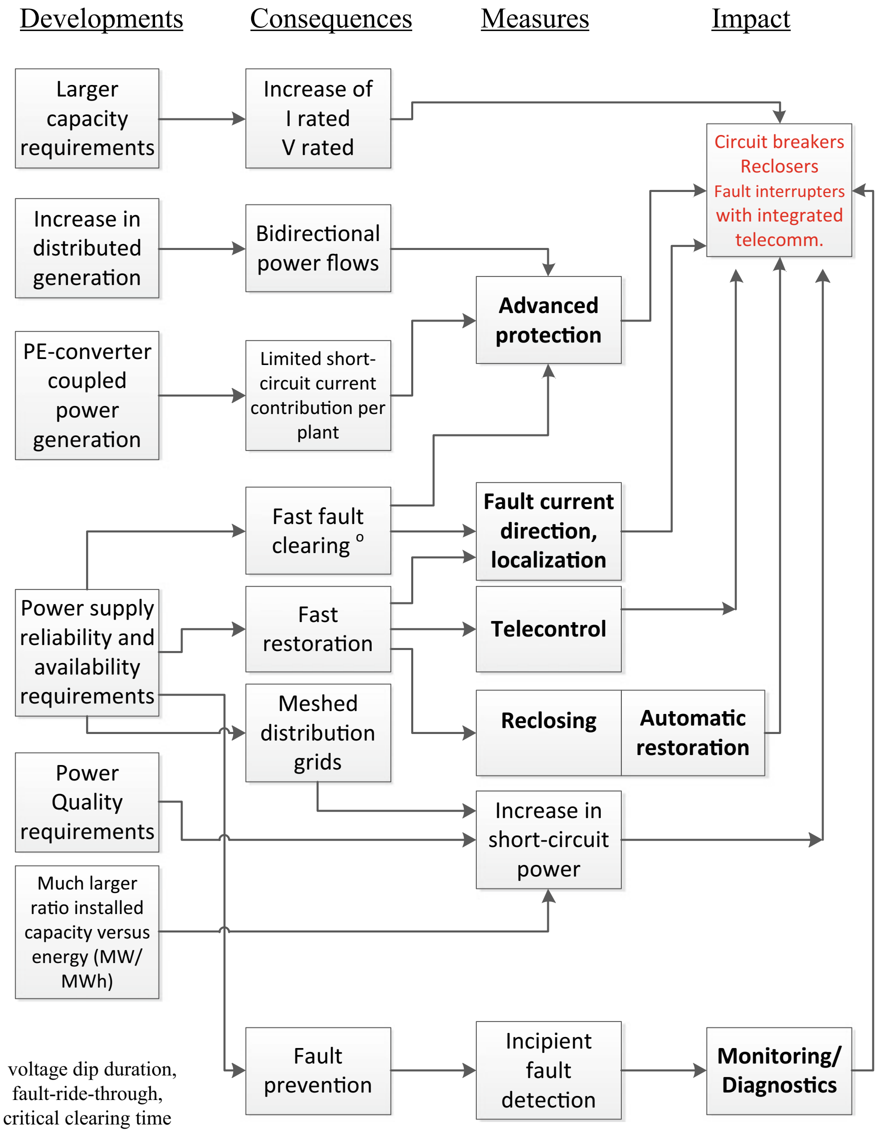


Fig. 11 Distribution system relationship diagram

risk of reconnection of still running generators and motors must be considered. Possibly, synchro-check apparatus will have to be applied to prevent large damage to running plants. Note that breaking out-of-phase currents is not a specified test duty for reclosers or fault interrupters machines connected through power electronic converters show different behavior and may be switched off and on automatically,

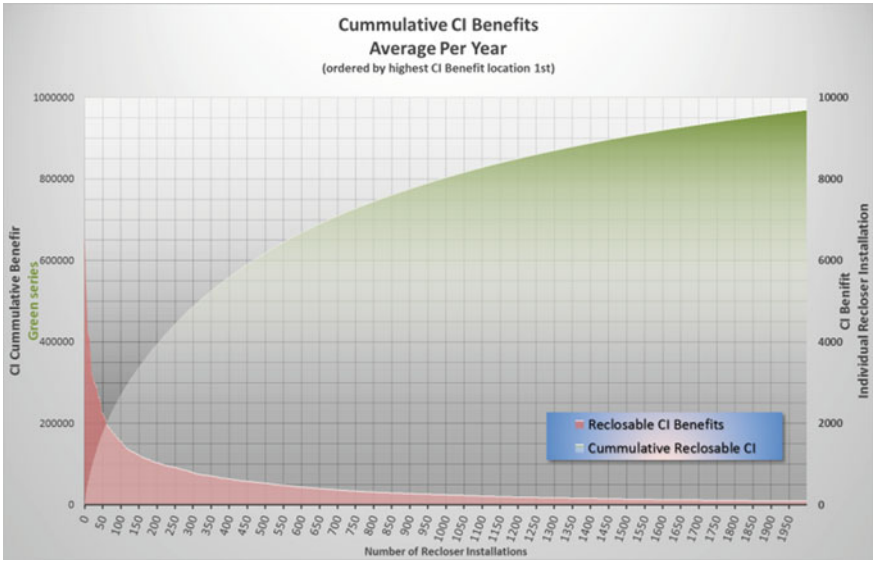


Fig. 12 Customer Interruptions saved as function of number of SCADA-connected reclosers

but this must be verified carefully. Figure 13 shows an example of an Inteligent electronic device (IED) used for protection and restoration (Fig. 14).

Fig. 13 Tested tele-controlled 12 kV RMU with telecommunication and control box (courtesy of Eaton)

Fig. 14 Protection and restoration IED

3.4 Islanding

Islanding is a condition in which a distributed generator like solar panel or wind turbine continues to generate power and feed the grid, even though the electricity power from the electrical utility is no longer present. Each part of the grid is running at its own frequency, which has its own challenges both for protection and switching equipment. New products and new standards will be needed to fully satisfy the requirements of the emerging "two-way power flow" grid. To name some of the issues that will need to be considered.

It is expected that in the near future, the power plants connected to a distribution grid will have to stay connected and consequently may keep the electric island energized. Fault-ride-through requirements, microgrids, no-break installations and industrial grids result in an increased possibility of system separation in distribution grids. Regardless, facilities should be installed to accommodate the synchronization of the island before coupling it back to the main grid. False synchronization causes large stresses for the rotating equipment and potentially failing current zeroes at breaking the out-of-phase current[1] [35–36]. In [36], apart from the conditions for generator circuit breakers, information about out-of-phase conditions in transmission networks has been given, but for general-purpose distribution circuit breakers no information is available (about out-of-phase angles, depressed voltages, protection and control interactions, etc.). An example of a simulated out-of-phase current at false synchronization is presented in Fig. 8 [35].

Another peculiarity to be mentioned is the dielectric strength across open contacts when a medium voltage circuit breaker has to split a distribution grid or to separate a generator from the grid. The voltage stress across the open contacts is larger than the voltage specified for general-purpose breakers and users are assumed to apply a disconnector to withstand the continuous operating voltage difference between the two parts of the network. It is expected that, at the distribution level, the application of disconnectors for this purpose will not become common practice. The IEEE series 1547 [37] has put forward dielectric requirements for the interconnecting (paralleling) switch. For instance, such a switch has to withstand continuously 220% of the rated voltage across open contacts.

3.5 Fault Currents

The fault currents are both increasing and decreasing due to the new grid developments. Both cases are explained below.

First, the network developments (larger loads, more dispersed generation, power quality issues) result in higher short-circuit powers and the need for higher rated voltage levels. This in turn prompts the need for system voltage conversion (e.g., 24 kV instead of 12 kV), a larger current carrying capacity and more redundancy together with intelligent circuit breakers.

Thus, short-circuit current levels are increasing. This is not so much caused by distributed generation, but by the enforced network structure (parallel circuits, lower impedances). At the same time, network losses are reduced, leading to a higher X/R ratio and thus larger DC-time constants in the short-circuit currents, especially close to transformers (see Fig. 15). Consequently, a larger peak value of the fault current can be expected as well as a more severe major loop switching.

Second, the contribution of non-synchronous generators to fault currents is completely different, as the short-circuit current will be limited by the capability of the

---

[1] Note that these stresses occur with synchronously connected machines, but not with rotating equipment connected by power electronic converters. Islanding with only non-synchronous generators cannot be expected to occur without special facilities which are able to force an AC-voltage into the isolated part of the network.

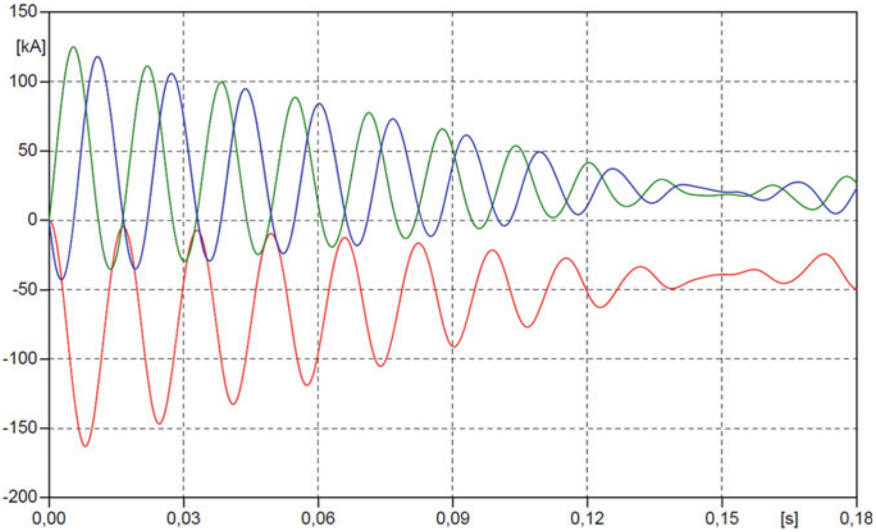


Fig. 15 Prospective fault current considering the moment of inertia of the synchronous machine and resulting from synchronizing under out-of-phase conditions (out-of-phase angle φ0 = 90°)

power electronic converter and its controller. In Fig. 16, examples are given of the waveforms of short-circuit currents supplied by a windmill and a windmill farm. The peak values of the currents are small compared to those of synchronous and asynchronous generators and their duration limited. Non-synchronous generators behave like current sources, and therefore, the contribution is independent from the distance to the fault. In addition, to supply a comparable amount of energy as conventional power plants, the installed capacity must be an order of magnitude larger. Such effects compensate to a certain degree the reduced contribution per non-synchronous generator.

Connecting new distributed generation to the network increases the local fault current level. Thus, the network's fault rating limits the amount of distributed generation

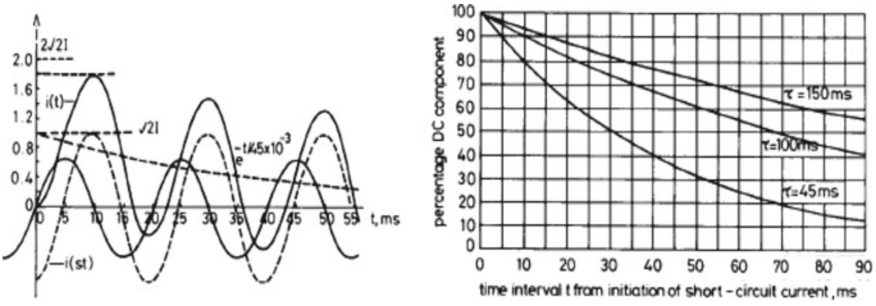


Fig. 16 DC-offset of a 50 Hz short-circuit current, large τ typically for transformer fed faults [14]

that can be connected. This is largely because most distributed generating capacity connecting in dense urban areas uses rotating machinery, e.g., piston engine-based combined heat and power installations and diesel standby generators, which have the highest impact on fault current levels. Novel ultra-fast current limiting circuit breakers are under development, capable to limit and interrupt fault current in a time below 1 ms. This is achieved by applying a parallel combination of an extremely fast mechanical switch in the main path, power electronics to interrupt and MOSA to absorb the energy [38].

3.6 Environment, Resilience and Safety

In urban environments, it is often difficult to find space for new switchgear locations or extend existing facilities. The difficulty comes both from a shortage of space and from societal resistance against this kind of installations. To overcome such problems, solutions have been found in pole-mounted switchgear, compact RMU's, special housings, integration in other infrastructure and even in underground switchgear. Examples are given in Fig. 17.

There is a trend to a further reduction of the visual and spatial impact, resulting in higher costs and a push to find more intelligent solutions. This trend reflects the inherent value of the permits to occupy certain routes (right of way) and certain locations which form essentially utilities' "raison d'être." There is also a pressure to look for less obvious solutions, like underground RMUs, in cellars, inside bridgeheads, on higher floors (for instance above shops), in parking spaces of multi-store buildings or in poles. One of the problems faced is to get access to the equipment, especially with unplanned switching actions. While manually operated switchgear may be placed below grade, the hazards associated with operating in confined spaces become problematic. Remotely controlled (SCADA), automatic and maintenance-free switchgear may help to solve the direct access problems to a large extent.

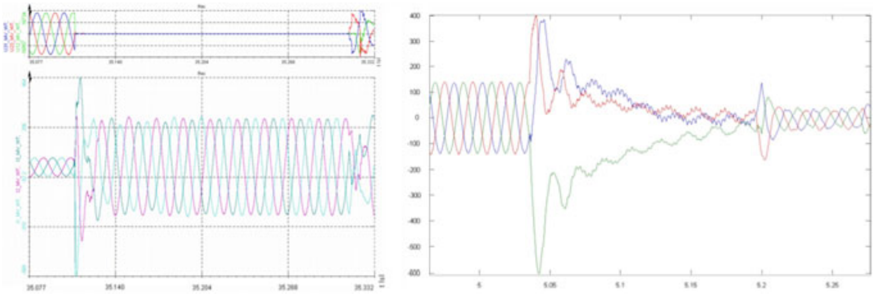


Fig. 17 Fault current measurement at MV-side, 100% voltage dip: (left) a 2 MW full converter DG at 30% load, peak 3.16 pu, (right) a 3 MW DFIG at 100% load, peak 4.7 pu

Fig. 18 12 kV RMUs adapted to their environment and automated underground 25 kV switchgear

Fig. 19 38 kV, Smart, submersible Vacuum fault interrupter with reclosing capability

Some of the spatial solutions conflict with another societal pressure: resilience. That is the preparedness for catastrophic events like cyberattacks, floods, fires and explosions. Floods may arise from sea (tsunami, broken sea-defense), rising rivers or heavy rainfall. Submersible equipment is deemed to be required for underground solutions, where flood is a risk to be mitigated. In general, there is a trend to request equipment insensitive to ambient conditions like humidity and pollution (Figs. 18 and 19).

3.7 Compact, Multifunctional Switchgear

When designing more compact switchgear (smaller dimensions, combined functions, three-position switch, three-function circuit breaker, and embedded sensors), safety aspects need special attention., e.g., under normal operational conditions are the dielectric distances large enough? And how will this be under abnormal conditions, for instance when the mechanical integrity is at stake? Can the enclosure be touched safely? Even when flooded by dirty or salty water? (An example is showed in Fig. 20) [39, 40].

Fig. 20 27 kV, smart submersible SF_6 switch (courtasy of G&W electric co) [39]

As trouble continues to happen in the system, utilities need fast and efficient means of isolating the circuit to conduct their repairs. While IEDs can contribute to better system performance, the practical aspects of restoring faulted sections still require the creation of safe working zones.

Leakage of SF_6-gas or an alternative such as CO_2 takes away oxygen, how hazardous are its decomposition products in practice? Is the safety guaranteed? SF_6-gas has a very high global warming potential compared to CO_2: what is the leakage rate? Can the equipment burn and what toxic gases may be expected at a fire? Is the long-term aging and material compatibility properly understood when using alternative gases?

Is the switchgear assembly arc resistant and are internal arc tests performed? What are the consequences of an internal arc for the substation itself and for the people regarding health and safety when repairing the switchgear to be put in service again?

The answers of such and other questions are becoming more and more important to stakeholders, rightfully so considering the pace of changing power grid. In the future, we can expect further development of standards and products to address those emerging requirements, like the submersibility and visibility of the disconnect switch contacts (Fig. 21).

4 Developments in Instrument Transformers

An instrument transformer (IT) is defined, according to IEC 61869 Standard Series [1], as “a transformer intended to transmit an information signal to measuring instruments, meters and protective or control devices.” A transformer is “an electric energy converter without moving parts that change voltages and currents associated with electric energy without change of frequency” [1]. This chapter intends to provide

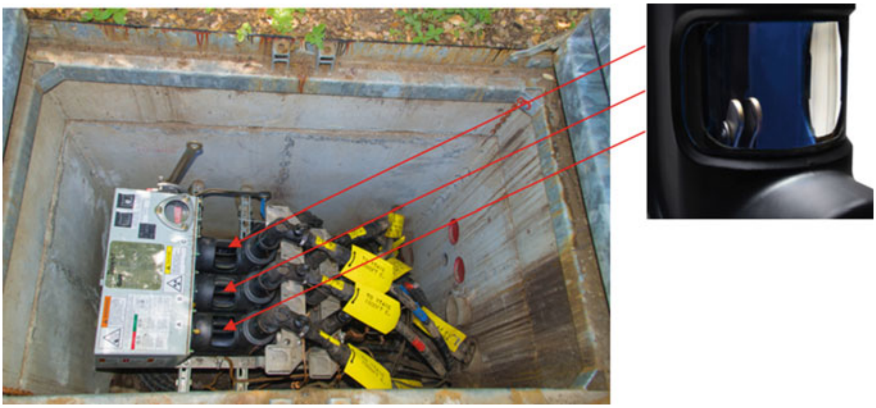


Fig. 21 Submersible vacuum interrupter solid dielectric switch with built in disconnect providing visible gap, courtasy of G&W electric [40]

an overview of the new technologies which are nowadays used for facing new measurement challenges, in particular due to the deep penetration of renewable energy sources (RES).

4.1 Inductive Instrument Transformers

4.1.1 Basic Principles

The transformer is a static electric machine and can be represented as in Fig. 22. It consists of a magnetic core, typically obtained by joining several thin metallic layers, and of two copper windings: the primary and the secondary. Its working principle is based on Faraday's' law, Lenz's law and conservation of energy law.

4.1.2 Current Transformers

A current transformer (CT) is used in series to the main circuit. The primary current I_P is proportionally scaled to the secondary one I_S, which is typically closed on a resistive burden B. The CT burden is almost a short-circuit and in most of the applications it has one point connected to ground. The quantities of interest from a metrology standpoint are the ratio between the primary and secondary terminal voltages N and the phase angle between them γ.

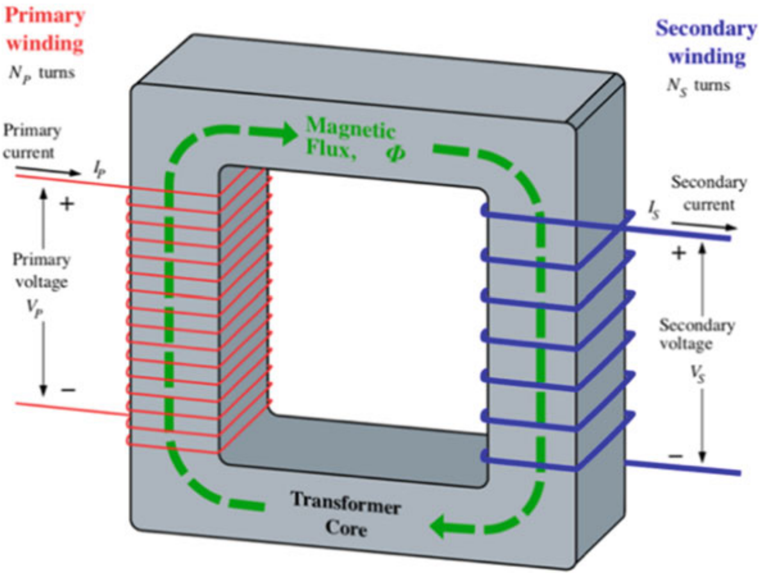


Fig. 22 Main components of a generic Inductive Instrument transformer

Fig. 23 From left to right: wound-type, bar-type, ring-type CT

Current Transformers Types

There are different types of CTs. According to their applications: wound-type, bar-type, and toroidal-type as shown in Fig. 23.

The bar-type differs from the wound-type by the fact that the primary “bar,” which is integral part of the CT, is the only primary winding available, hence constitutes a single turn configuration. As for the ring-type, it differs from the others in the primary stage; the primary conductor, representing then the primary winding, has to be inserted into the hole of the CT. In terms of rated currents, the bar-type and ring-type are used to carry high currents, whereas the wound-type is the mostly used for low ratios and lower-rated current values.

Fig. 24 From left to right: wound-type and capacitive-voltage-type VT

4.1.3 Voltage Transformers

A voltage transformers (VT) is much similar to a power transformer. The VT primary voltage varies in a very limited range compared to the CTs, which can experience a variety of different currents depending on the load demand of a particular time-slot. Hence, the flux inside the core of a VT can be considered as almost constant, whereas the one of the CTs cannot. Moreover, a VT works under near open-circuit conditions, with relatively high burdens (instrumentation) connected to the secondary terminals. The quantities of interest in a VT are the ratio between the primary and secondary terminal voltages N and the phase angle between them γ.

Voltage Transformers Types

According to the working principle of the transformer, there are mainly two different typologies of VTs: wound-type (on the left) and capacity voltage- type (on the right) transformers (collected in Fig. 24).

In case of wound-type voltage transformer, two sets of windings are used to scale the voltage to match with the measuring/protective instruments inputs.

The capacitive-voltage transformer (CVT) is basically a VT connected to the power line through a series of two capacitors (C_1 and C_2 in Fig. 25); the VT is connected to the C_2 terminals, whereas the power line voltage is applied to the series of the two capacitors. This way it is possible to both reduce extra-high voltages by guaranteeing the safety properties of a standard VT and to guarantee the amount of apparent power (burden) requested to the CVT (even some tens of VA).

Fig. 25 Schematic of a capacitive-voltage transformer

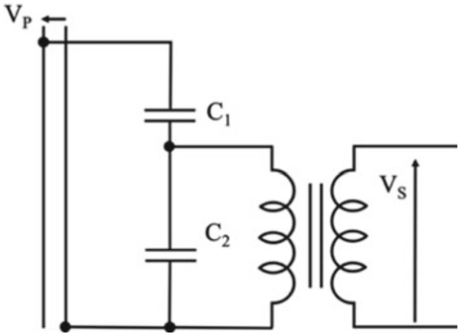
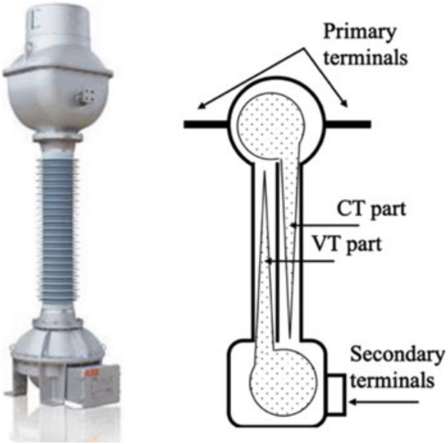


Fig. 26 Picture (left) and simple schematic (right) of a combined transformer



Combined Transformers

An instrument that includes the features of VTs and CTs is the combined transformer. By definition, it is an "instrument transformer consisting of a current and a voltage transformer in the same enclosure"; hence, it does not introduce novelties from a technological point of view but only in the application of different technologies. It is largely adopted in high voltage (HV) primary stations, but it can be found even in medium voltage (MV) applications. They are typically installed in places with limited free space. In addition, the cost of combined transformers is lower than for single transformers. Figure 26 includes a picture (left) and a simple schematic diagram (right) of the combined transformer.

The upper part of the transformer is dedicated to the primary terminals. The main central part of the instrument provides the main connections for the two measured quantities: there is proper physical separation between the voltage and the current. This is also the main drawback of the combined solution: the two parts are separately insulated and contained inside the external insulation. Therefore, parasitic capacitances arise and are subjected to an electric field distributed in the height of the combined transformer. Finally, the lower part of the transformer contains the secondary voltage and current terminals, including the ground connection.

4.2 Low-Power Instrument Transformers

4.2.1 Introduction

A new generation of ITs has been developed and spread in the last few decades. Initially, they have been referred to as non-conventional ITs; while after their standardization [2], they are referred to as low-power instrument transformers (LPITs). The general aspects of LPITs are regulated by Standard IEC 61869-6, defining these devices as: "arrangement, consisting of one or more current or voltage transformer(s) which may be connected to transmitting systems and secondary converters, all intended to transmit a low-power analogue or digital output signal to measuring instruments, meters and protective or control devices or similar apparatus." In addition to this definition, it is essential to clarify the meaning of "low-power." The Standard states that an IT can be considered low-power if its output is typically lower than 1 VA. So, it is clear that the Standard has not been strict in defining the LPITs; therefore, the classification of ITs is not as straightforward as it seems, there is some degree of freedom to the manufacturer and user of such devices.

The LPITs structure is shown in Fig. 27 in the block diagram, where the upper block-chain describes the general components of a passive LPIT, while the bottom blocks only apply to active LPITs. However, the block diagram, defined in, does not constitute a fixed schematic to build a LPIT but a general one which could vary depending on the considered device.

Figure 27 highlights that the basic principle of the LPITs is not common to all of them, but it varies depending on each technology for manufacturing them. The following section discusses two kinds of LPITs in detail; the typical technologies

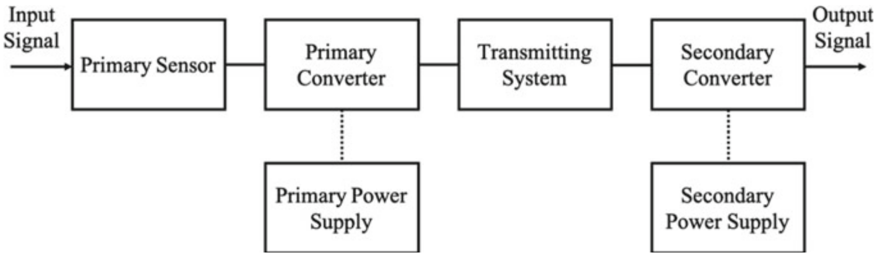


Fig. 27 General block diagram of a single-phase LPIT

adopted for LPITs are: resistive, capacitive and resistive/capacitive dividers for low-power voltage transformers (LPVTs), and Rogowski coils and inductive transformers with shunts, for the low-power current transformers (LPCTs).

4.2.2 LPCT Proportional: Iron Core

Basic Principles

The iron-core-coil-based low-power current transformer represents a development of the classical current transformer.

The LPCT consists of an inductive current transformer with primary winding, small core and a secondary winding with minimized losses which is connected to a shunt resistor Rsh.

This resistor is an integral component of the LPCT and of great importance for the operation and stability of the transformer. Therefore, the LPCT in principle provides an output voltage.

The shunt resistor Rsh is designed in a way that the power consumption for the transformer is nearly zero. The secondary current Is causes a voltage drop Us across the shunt resistor which is proportional to the primary current in amplitude and phase. Figure 28 shows the schematic diagram of an LPCT with iron core [3].

Advantages and Disadvantages

Because of the low input power requirement of modern intelligent electronic devices (IED), the LPCT can be dimensioned for high impedances Rb. Therefore, its saturation is improved in case of very high primary currents enlarging in this way the measuring range.

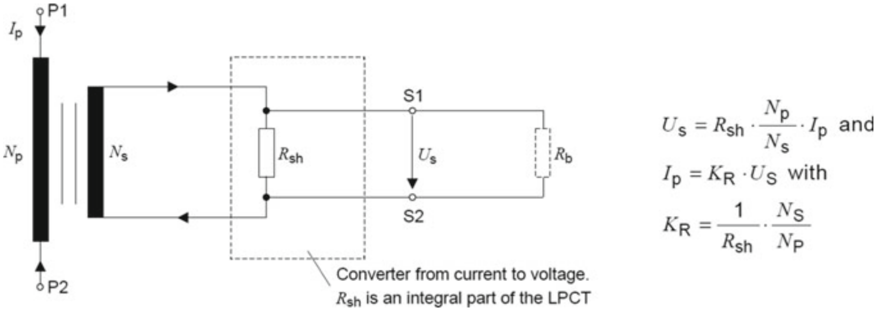
Due to the large measuring range and its linearity, the same LPCT is normally used for metering and protective purposes. Moreover, an LPCT results far smaller and more compact than a CT.

On the contrary, an LPCT with iron core suffers of nonlinearity close to the saturation region.

4.2.3 LPCT Derivative: Rogowski-Based CT

Basic Principles

The Rogowski coil is a measurement device used to measure alternating currents. It consists of an iron-free toroidal core, typically made of air or other insulating materials, on which a solenoid is wound. Then, the conductor carrying the current to be measured is inserted in the Rogowski coil as shown in Fig. 29; where S and R are cross-section and radius, respectively.



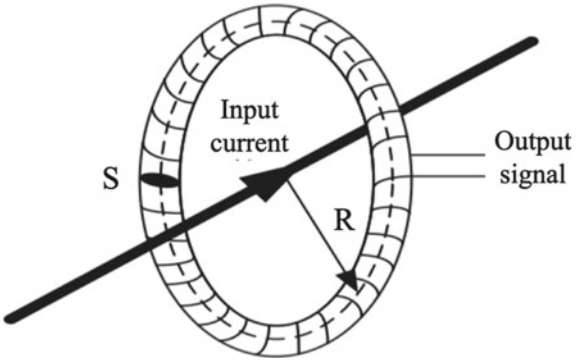
$$U_S = R_{sh} \cdot \frac{N_p}{N_s} \cdot I_p \text{ and}$$
$$I_p = K_R \cdot U_S \text{ with}$$
$$K_R = \frac{1}{R_{sh}} \cdot \frac{N_S}{N_P}$$

Key

IP	primary current
RFe	equivalent iron loss resistor
Lm	equivalent magnetizing inductance
Rt	total resistance of secondary winding and wiring
Rsh	shunt resistor (converter from current to voltage)
CC	equivalent capacitance of the cable
US(t)	secondary voltage
Rb	burden in ohms
P1, P2	primary terminals
S1, S2	secondary terminals

Fig. 28 Schematic diagram of an LPCT with Iron core

Fig. 29 Basic structure of a Rogowski-based coil



The working principle of a Rogowski coil is based on Ampere's law: the current $i_P(t)$ flowing through the primary conductor generates a varying magnetic field with induction B, which induces a voltage $u_s(t)$ at the solenoidal terminals, proportional to the mutual inductance M between the primary and secondary conductors. Such phenomenon can be expressed as:

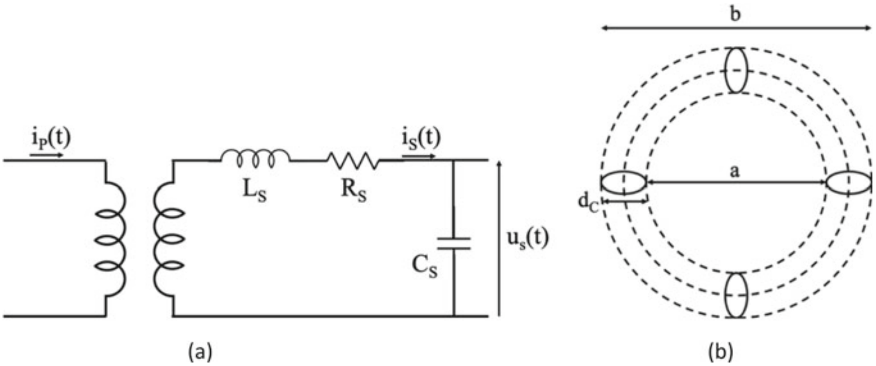


Fig. 30 **a** Rogowski coil equivalent single-phase circuit **b** Geometrical parameters clarification picture

$$u_s(t) = -M\frac{di_P(t)}{dt}. \tag{1}$$

Equation (1) shows that the Rogowski coil output is not a current proportional to the primary one, but a voltage proportional to the derivative of $i_P(t)$. Therefore, in its basic configuration, the device does not feature a current-to-current relation. To obtain such a relation, an integrating block is required; however, for the sake of simplicity and to avoid any external components, typical off-the-shelf Rogowski coils do not include any integrator.

Based on these principles, it is possible to obtain an equivalent circuit of the Rogowski coil, valid for low frequencies (including the power frequencies, 50 and 60 Hz). According to Fig. 30a, the main components of a Rogowski coil are:

- An ideal transformer, which provides the nominal ratio of the device;
- an inductor L_S:

$$L_S = \frac{\mu_0 N^2 d_c}{2\pi}\log\frac{b}{a},$$

- a resistor R_S:

$$R_S = \rho\frac{l_w}{\pi r^2},$$

- a coupling capacitor C_S

$$C_S = \frac{4\pi^2\varepsilon_0(b+a)}{\log\frac{b+a}{a-a}},$$

Fig. 31 Picture of a medium voltage (left) and a ring-type (right) LPCT

where ρ, ε_0 and μ_0 are the wire electrical resistivity, vacuum permittivity and permeability, respectively. As for the geometrical parameters, N is the number of turns, b and a are the outer and inner diameters of the toroid, r is the wire radius, d_c is the single loop diameter and l_w is the length of the coil. For the sake of clarity, the meaning of the geometrical parameters is clarified in Fig. 30b.

It must be noted from the above equations that precise manufacturing information is required to obtain the Rogowski parameters; hence, obtaining such parameters is not straightforward for off-the-shelf devices.

Advantages and Disadvantages

The Rogowski coil, being iron-free, does not suffer from the nonlinearities of a typical CT; therefore, the Rogowski coil can be considered linear in its entire working range. Such a range is theoretically infinite, and significantly higher than the one of an CT.

Continuing with the geometrical features, a Rogowski coil is far smaller and more compact than a classical CT.

These coils also offer advantages regarding the measurements provided: they operate in a wide range of frequencies (from fractions of Hz to almost GHz) and they provide accurate answers to short transient input signals.

However, Rogowski coils also have some drawbacks which make them unsuitable for certain applications. For example, the need of an integrating circuit in addition to the Rogowski coil makes it necessary to have power supply close to the Rogowski application, and that is not always possible for physical or safety reasons. Furthermore, Rogowski coils are very sensitive to the physical and electrical environment (i.e., primary conductor position, electric fields, temperature, etc.); hence, a preliminary study on the location of the Rogowski coil is necessary to avoid collecting invalid measurements.

Figure 31 shows two LPCTs, one for medium voltage (left), and one for cable applications (right).

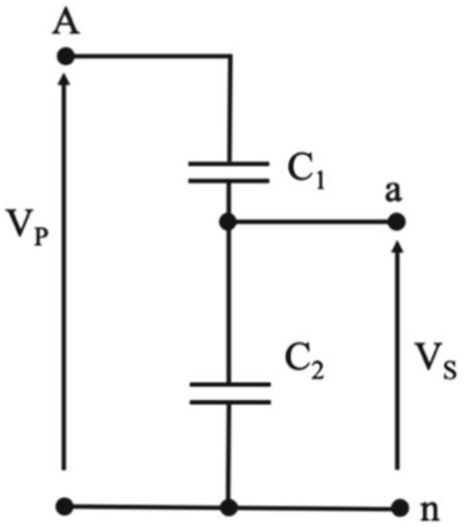


Fig. 32 Voltage divider schematic

4.2.4 Low-Power Voltage Transformers: Resistive or Capacitive Dividers

Basic Principles

It is a passive LPVT and does not require any external power supply, which results in huge flexibility for in-field installation. As voltage divider, it consists of a series of two impedance Z_1 and Z_2 as in Fig. 32; V_P and V_S are the input and output voltages of the voltage divider. In addition, the picture shows the terminal markings as A, a, and n for the high-voltage primary terminal, high-voltage secondary terminal and reference terminal, respectively.

When the voltage V_P is applied, the two impedances are subjected to the same charge Q but not to the same voltage. The relationship between the charge and the capacitor value C is described by the relation $V = Q/C$. Hence, the higher the value Z is the lower the voltage at its terminals will be. Therefore, the input/output expression of the voltage divider is summarized by:

$$V_S = V_P \frac{Z_1}{Z_1 + Z_2}$$

In other words, in order to reduce the input voltage, it is just necessary to have two impedances with $Z_1 < Z_2$.

Such a simple technology is spread and standardized [4], in alternating current applications, along all voltage levels, from the low to the extra-high voltage. Figure 33 shows two voltage dividers, one for medium voltage (left), and one for high voltage (right).

Fig. 33 Picture of a medium voltage (left) and a high voltage (right) LPVT

Resistive Divider (RDs)

The two impedances Z_1 and Z_2 are resistors.

The impedance Z_1 connected to the network can be constituted by one single resistor or more connected in series.

Capacitive Divider (CDs)

The two impedances Z_1 and Z_2 are capacitors.

In some CDs, one of the capacitors is obtained directly using the insulating material which establishes the cage of the overall CD.

Advantages and Disadvantages

The voltage dividers are not affected by ferroresonance and problems to LV wiring, i.e. short circuit, that can cause the failure of an inductive voltage transformer.

The RD can ensure a high level of accuracy and stability in the range of temperature.

Compared to a RD, a CD does not suffer from the heat dissipation due to the resistors. Hence, the voltage applied (e.g., power frequency tests, cable tests…) is not a limiting parameter of a CD.

In terms of frequency, the CD is not subjected to any variation in its behavior. CD has a behavior considered linear in a wide range of frequencies.

There are two relevant disadvantages:

First, CDs cannot be used in direct current application, due to the nature of their capacitors.

Second, it is complicated to obtain a CD with reduced ratio error but thanks to its linearity it is possible to achieve very accurate classes (e.g., 0.2 or 0.5) with the use of the correction factor.

Fig. 34 Optical voltage transformer

4.2.5 Optical Voltage Transformer

Basic Principles

The optical-type voltage transformer (OVT) is based on the well-known Pockels' effect. Figure 34 shows a picture of a commercial OVT. OVTs are mainly composed by the Pockels' cells manufactured with electro-optic materials to sense the electric field, a shielding layer to prevent perturbation or disturbances, and the fiber-optic secondary circuit to send the information gathered by the cells. With such a configuration, the varying electric field of the primary source induces a modulating index in the electro-optic material, which in turn will send a "light" information.

Advantages and Disadvantages

The advantage of the OVT is represented by its high immunity versus external electric and magnetic fields at rated frequency as well as vs. electromagnetic interferences (EMC). The OVT also is very light in weight and compact in size. Moreover, if well calibrated and compensated, it can feature high accuracy (down to far less than 1%) and linearity over a wide temperature as well as frequency ranges, starting from DC up to even MHz. Furthermore, the OVT features intrinsic safety properties due to the use of fiber optics or similar optical elements which guarantees insulation between primary and secondary circuits.

The disadvantage is its cost and complexity of the circuit for conditioning the electric signals inside the sensor and for making proportional the output signal with respect to the primary voltage.

4.3 Electronic IT (EIT)

There is a growing usage of IT with active components inside. It means that in order to provide an output signal, they must take power from outside the sensor or from inside (from the primary side). In the latter case, they are referred to as *self-powered*.

Typically, EIT is LPIT with active components, which provide the output signals. Inductive-type ITs with active components inside are less common. The electronic circuitry in an EIT can be located both inside the housing of the IT or outside. The reference Standards for EIT are the IEC 60044-7 for electronic voltage transformers and IEC 60044-8 for electronic current transformers [41, 42]. Very soon, they will be replaced by the new Standards IEC 61869-7 and IEC 61869-8 for electronic voltage and current transformers, respectively. In case of external location of the active part, normally, it is designed to collect analog signals coming from the passive LPIT of the three phases and converts tall of hem into analog or digital output signals. In this case, the electronic unit is referred to as *Merging Unit*. Figure 35 shows the block diagram of a Merging Unit with digital output [43].

There are some advantages associated to an EIT: it can have a high fan-out; hence, the output cable can be of large lengths (even hundreds of meters) and be applied to many IEDs on the same time. Moreover, it can be adjusted in transformation ratio. It means that a custom or specific ratio can be set in factory. Also, as seen, the output can be either analog or digital. IEC 61869-9 IEC Standard specifies the 61850-9-2 protocol requirements for EIT with digital output (Fig. 35).

Optical IT (mainly used in for HV networks) normally have an electronic unit for signals conditioning and conversion with analog/digital output. Another important advantage is given by the very large bandwidth that can be obtained with EIT (even tens of MHz).

There are some disadvantages: the reliability is expected to be lower than "passive" IT due to the presence of active components; an auxiliary power supply must

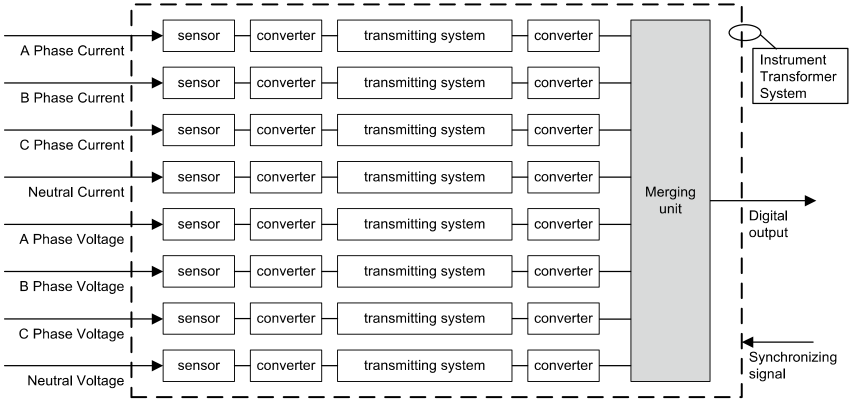


Fig. 35 Schematic block diagram of a Merging Unit with digital output

Fig. 36 Optical voltage transformer

be provided for the operation of the internal circuitry; they can lack of robustness versus voltage/current transients, burst, swings, EMC, etc. In case of outdoor applications, the electronic circuit must be designed in order to take into account possible ground loops, atmospheric events (lightning, overvoltages) and harsh operating temperatures.

4.3.1 Optical Voltage Transformer

Basic Principles

The optical-type voltage transformer (OVT) is based on the well-known Pockels' effect. Figure 36 shows a picture of a commercial OVT. OVTs are mainly composed by the Pockels' cells manufactured with electro-optic materials to sense the electric field, a shielding layer to prevent perturbation or disturbances, and the fiber-optic secondary circuit to send the information gathered by the cells. With such a configuration, the varying electric field of the primary source induces a modulating index in the electro-optic material, which in turn will send a "light" information.

Advantages and Disadvantages

The advantage of the OVT is represented by its high immunity vs. external electric and magnetic fields at rated frequency as well as versus electromagnetic interferences (EMC). The OVT also is very light in weight and compact in size. Moreover, if well calibrated and compensated, it can feature high accuracy (down to far less than 1%)

and linearity over a wide temperature as well as frequency ranges, starting from DC up to even MHz. Furthermore, the OVT features intrinsic safety properties due to the use of fiber optics or similar optical elements which guarantees insulation between primary and secondary circuits.

The disadvantage is its cost and complexity of the circuit for conditioning the electric signals inside the sensor and for making proportional the output signal with respect to the primary voltage.

4.4 IT for HVDC

The reference IEC Standards for DC-IT are the IEC 61869-14 [44, 45]. In Fig. 37, the generic block diagram of a DC-IT is shown.

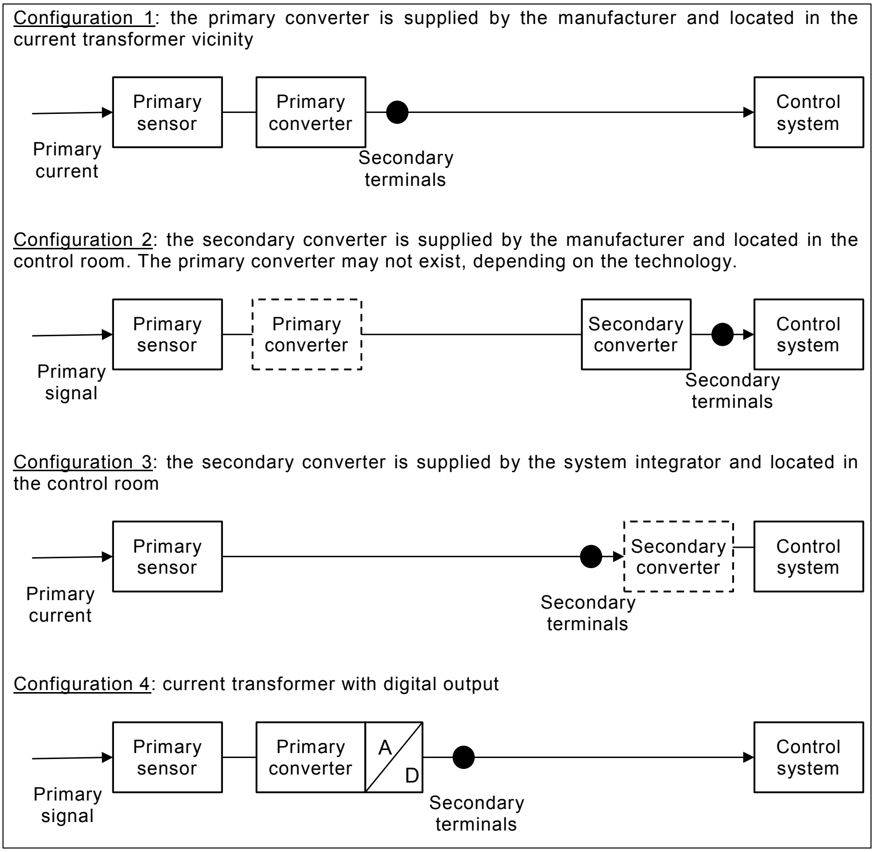


Fig. 37 Generic block diagram of a DC-IT

DC Voltage-Current measurements accuracy is directly related to the safety, stability and economic operation of DC transmission system. With the increase of the load capacity of DC networks accuracy and response time characteristics of DC-IT have become a challenging key-element.

The main DC Voltage sensor technologies relate the (i) DC voltage conversion into DC current, and then the DC current is measured by using inductive CT; (ii) the high voltage is converted into low voltage by resistance/resistance-capacitance dividers; (iii) the optical technology (Pockels effect).

As for the DC Current sensor technologies, they are mainly based on inductive DC current technologies or optical technologies (Faraday effect).

Issues and disadvantages can be listed for all existing technologies.

For inductive technologies: inner Losses, heavy in weight, limited bandwidth (few kHz), accuracy temperature-dependent (mainly for CT); slow response time; immunity.

For resistive technology: accuracy temperature-dependent; insulation issues (impulse voltages, etc.); complex architecture for insulation requirements; accuracy change in time due to material instability; immunity.

For optical technology: free-charges presence; accuracy dependent on boundaries charges; complexity increases for solving free-charges issue (conversion into AC signal, etc.); immunity.

In Fig. 38, a picture of a DC Current IT for 362 kV rated voltage is shown.

Also, the difference of operating and ambient temperatures between the top and the bottom of the sensors affects the accuracy (particularly for HV IT).

There are some very important type of tests to be performed for DC-IT. In particular the polarity reversal test profile (90 min at negative polarity; 90 min at positive polarity; 45 min at negative polarity; reduce the voltage to zero), and the response time (25, 50, 100, 250, 500 μs according to the Standard IEC 61869-14 to be tested according to Fig. 39).

4.5 New Applications of IT

Nowadays, instrument transformers are even more used for different applications than traditional protection and measurement (tariff) ones. The main constrain is that one single IT shall perform correctly for all applications required. For instance, they are widely used for power quality evaluation, for diagnostic of electric assets, for power network state estimation, etc. All such applications require that ITs feature more enhanced characteristics than inductive ones, like larger bandwidth (up to tens of MHz), very large dynamics in amplitude (from few volts or amps up to kV and kA), very high accuracy (in the order of 0.1% for PMU applications).

The use of non-conventional physical principles, as seen above, has led to introduce new requirements and procedures for connecting IT to IED (protection relays, energy meters, etc.). In particular, the use of LPVT based on correction factor required to be entered it into the IED, allowing then it to operate with the actual transformation

Fig. 38 DC Current IT for 362 kV rated voltage

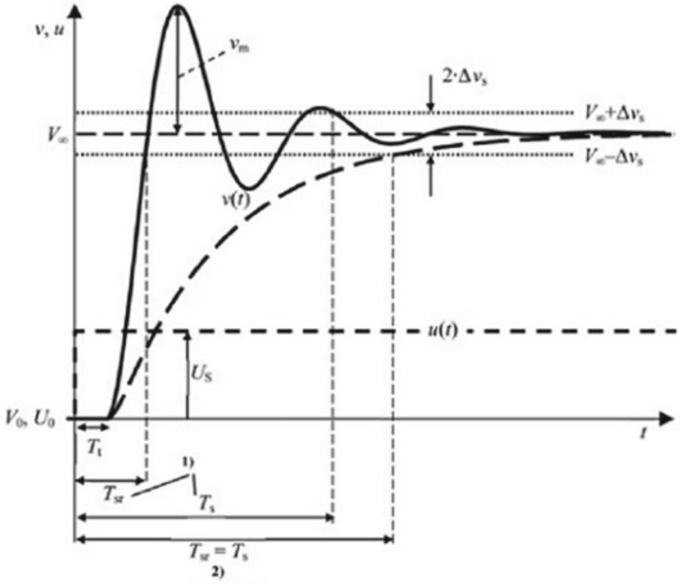


Fig. 39 Pattern of the response time according to the Standard IEC 61869-14

ratio of the LPIT; in case of use of Rogowski coil, a 90° shift of the phase of the output voltage must be considered by the IED in case an integrator is not used. All such changes and news have been promptly taken into consideration by IEC TC38 and addressed in the new Standard Series IEC 61869. In the following, some of the most important changes and applications associated to IT.

4.5.1 Designation of Accuracy Class When Using the Corrected Transformation Ratio and Ratio Correction Factor

The advantage of defining accuracy class using the individual ratio correction factor instead of the traditional rated transformation ratio (Kr) is that a higher accuracy class can be designated for a passive LPIT.

Designation of the accuracy class in IEC 61869-6 is based on rated transformation ratio. To clarify this, a ratio error was defined, which is an error that an instrument transformer introduces into the measurement of a current and voltage and which arises from the fact that the transformation ratio of individual instrument transformers is not equal to the rated transformation ratio. Traditional metering and protection devices were not designed flexibly enough to accept the transformation ratio of individual instrument transformers. Therefore, a rated transformation ratio was used that represented a whole group of instrument transformers classified with the same accuracy class. Because the transformation ratio was slightly different for each instrument transformer, the accuracy class had to be designated so to cover all instrument transformers of the same class, resulting in reduced accuracy class designation. Today's technology makes it possible to effectively use the individual transformation ratio of passive LPIT in protection, metering and control devices. This is possible by using the ratio correction factor CFI combined with the rated transformation ratio or by using the corrected transformation ratio Kcor I.

Designation of accuracy class based on the ratio correction factor and corrected transformation ratio is next explained based on actual accuracy tests performed on passive LPCT of the same design. However, this method can be applied to any type of instrument transformers.

The ratio correction factor CFI is defined by the formula:

$$CF_1 = \frac{1}{1 - \frac{x}{100}}$$

where x is error in per unit between the rated transformation ratio and actual transformation ratio at rated current. The corrected transformation ratio is defined by the formula:

$$K_{\mathrm{cor}} = \mathrm{CFI} \cdot Kr$$

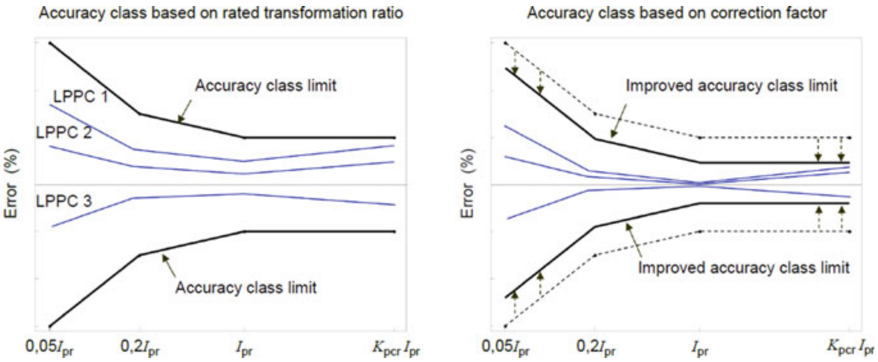


Fig. 40 Accuracy class designation improved based on individual ratio correction factor CFI

In actual applications, protective relays can be designed to separately accept the rated transformation ratio (Kr) and the ratio correction factor CFI or the corrected transformation ratio K_{cor} as one number that combines both Kr and CFI.

Figure 40 illustrates the accuracy class designation improvement for three passive LPCT using the ratio correction factor CFI.

4.5.2 Frequency Response Specifications

There is a need of measuring frequency components of voltage and current in a wider frequency range with respect to the past. This is mainly due to the presence of distributed generation and with the deep penetration of Inverters connected to the feeders, whose switching frequency and its relevant harmonics can range from few kHz up to hundreds of kHz.

4.5.3 Power Quality Measurement

The need of monitoring such high-frequency components for their mitigation is crucial for assuring service continuity and network reliability as also specified in reference Standards [46–48]. The detrimental effects of high-frequency pollution are well known like resonances in sections of the networks, aging of assets, tripping of Relays, instability of rated frequency, etc. Only LPITs can assure the reading of such high-frequency components with a proper accuracy. Typical frequency bandwidths requested for LPVT and LPCT for power quality evaluation and monitoring are from DC of few tens of Hz (for railway applications) up to 150 kHz.

Partial Discharge Measurements

As well-known partial discharges (PD) measurements are today one of the most famous and used methods for monitoring the health of electrical assets and for predictive maintenance.

Such phenomena can be sensed by both voltage and current sensors which shall feature a frequency range of tens of MHz. Normally capacitive LPVT and high-frequency windows-type inductive current transformers (HFCT) are used for such an application. The future the challenge (requested by DSO and TSOs) is to use, the same LPVT and LPCT used for protection and energy/power measurements also for PD measurements.

4.5.4 Sensors for Phasor Measurement Units (PMU)

Power network state estimation is recognized to bring many important advantages, like an optimum control of the power flow in the network, fault location, technical and non-technical losses monitoring, etc. The total vector error (TVE) is often considered as the main index to evaluate the performance of the synchrophasor measurements [48]. It is easy to see that the amplitude errors can originate both from sensor and from the PMU device itself. Phase angle errors are due to sensors phase error, to synchronization errors and to other errors coming from the PMU circuits and algorithms.

As an example, it can be shown that in case a 0.5 accuracy class voltage sensor is assumed to represent the only source of uncertainty in the measurement chain, the TVE would be equal to 1.03% which falls outside the limit specified by the relevant Standard on PMU (1%) measurements characteristics. It arises that the contribution of the IT to the overall uncertainty in PMU measurements is dominant with respect to all other uncertainty contributions. For performing correct synchrophasor measurements an accuracy class of 0.1–0.2 is required to the IT.

4.5.5 Sensors Embedded into Existing Components

One of the main advantages of LPIT is represented by the capability to be embedded into existing components. For instance, an LPCT can be housed around the output bushing in a GIS; a resistive or capacitive-voltage dividers can be embedded into post-insulators in air-insulated switchgear or inside the bushing or on the backside of a plug-in connector in GIS systems; combined voltage and current LPITs can be embedded into MV cable terminations. Figure 41 shows an example of cable termination with embedded an LPVT and an LPIT. Embedding LPIT into existing components allows to save space, to make easily retrofitting in all substations with no IT and to increase the safety inside the substation. On the contrary, the certification and testing procedure of LPIT embedded into equipment requires that the whole equipment is tested. It can happen that Standards for the equipment require different

Fig. 41 Cable termination with combined LPIT embedded—on the left for air-insulated substation; on the right for gas-insulated substation

test level of requirements than those of IT. This matter is still under discussion among standardization bodies (IEEE and IEC).

5 Summary

The power grid is changing at the accelerated pace due to disruptive drivers distribution, decarbonization and digitalization. The massive installation of intermittent distributed renewable sources as well as energy storage will continue at accelerated pace, including the exponential increase of the offshore wind generation that is forecasted to reach 100 s of gigawatts of power by 2040. Moving forward, the next generation of digitization in energy will be crucial for enabling growth in renewable energy and driving more efficiency across the energy value chain from generation to consumption. This will result in less clear boundaries between transmission and distribution and further advancements of T&D equipment including switchgear and instrument transformers.

References

1. Ito, H., et al.: CIGRE Green Book: switching Equipment. Springer (2018)
2. Lingal, H.J., Brawne, T.E., Storm, A.P.: An investigation of the arc quenching behavior of Sulphur hexafluoride. Trans. AIEE. **72**, 242–246 (1953)
3. Di Silvestre, M.L., et al.: How Decarbonization, Digitalization and Decentralization are changing key power infrastructures. Renew. Sustain. Energy Rev. **93**, 483–498 (2018)
4. DNV GL Energy Transition Outlook 2018: Power Supply and Use. (https://eto.dnvgl.com/) (2018)

5. Bianco, A., Bertolotto, P., Riva, M., Backman, M.: Switching technology evolution: the solid state contribution to the capacitive switching control. In: 23rd CIRED Conference Paper 778 (2015)
6. The EU Horizons 2020 project Promotion (“Progress on Meshed HVDC Offshore Transmission Networks”) seeks to develop meshed offshore HVDC grids on the basis of cost-effective and reliable technological innovation. https://www.promotion-offshore.net/
7. Lindblad, P.: Reliability on existing HVDC links feedback. CIGRE Sci. Eng. **11**, 96–103 (2018)
8. Tokoyoda, S., Inagaki, T., Kamimae, R., Tahata, K., Kamei, K., Minagawa, T., Yoshida, D., Ito, H.: Development of EHV DC circuit breaker with current injection. In: CIGRE-IEC 2019 Conference on EHV and UHV (AC & DC), Hakodate, Japan (2019)
9. Häfner, J., Jacobson, B.: Proactive Hybrid HVDC Breakers—A Key Innovation for Reliable HVDC Grids, in CIGRE Symposium. Italy, Bologna (2011)
10. Ängquist, L., Nee, S., Modeer, T., Baudoin, A., Norrga, S., Belda, N.A.” Design and test of VSC assisted resonant current (VARC) DC circuit breaker. In: 15th IET International Conference on AC and DC Power Transmission (ACDC 2019), pp. 1–6. Coventry, UK (2019)
11. CIGRE Technical Brochure 683: Technical Requirements and Specifications of State-of-the-art HVDC Switching Equipment (2017)
12. Zhang, Z., Li, X., Chen, M., et al.: Research and development of 160 kV ultra-fast mechanical HVDC circuit breaker. Power Syst. Technol. **42**(7), 23312338 (2018)
13. Zhou, J., Li, H., Xie, R., Liu, L., Nie, W., Song, K., Huo, F., Liang Dapeng, D.: Research of DC circuit breaker applied on Zhoushan multi-terminal VSC-HVDC project. IN: 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), pp. 1636–1640. Xi’an (2016)
14. Tang, G., Wang, G., He, Z., Pang, H., Zhou, X., Shan, Y., Li, Q.: Research on key technology and equipment for Zhangbei 500 kV DC grid. In: 2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia), pp. 2343–2351. Niigata, Japan (2018)
15. CIGRE Technical Brochures 589: The Impact of the Application of Vacuum Switchgear at Transmission Voltages by WG A3.27. (2014, July)
16. Teichmann, J., et al.: 145/170 kV vacuum circuit breakers and clean-air instrument transformers—product performance and first installations in AIS substations. In: Conference of A3-311, CIGRE (2018, August)
17. S. Giere et al. X-Radiation Emission of High-Voltage Vacuum Interrupters: Dose Rate Control under Testing and Operating Conditions, 2018, 28th International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV)
18. Janssen, A., Steentjes, N.: Some peculiarities of the fault current contribution by dispersed generation. In: IEEE Powertech Conference Eindhoven. The Netherlands (2015). Report 455770
19. California Air Resource Board: 2019 Discussion Draft of Potential Changes to the Regulation for Reducing Sulfur Hexafluoride Emissions from Gas Insulated Switchgear. https://ww2.arb.ca.gov/sites/default/files/2019-08/sf6-gis-discussion-draft-20190815.pdf (2019, August)
20. IEEE Technical Brochure TR-64: Impact of Alternate Gases on IEEE Switchgear Standards (2018, August)
21. Seeger, M., et al.: Recent development and interrupting performance with SF_6 alternative gases Electra No. 291,.26–29 (2017, April)
22. M™ Novec™ 5110 Dielectric Fluid, Technical Data Sheet (2015)
23. M™ Novec™ 4710 Dielectric Fluid, Technical Data Sheet, (2015)
24. Niemeyer, L.: A Systematic Search for Insulation Gases and Their Environmental Evaluation. Gaseous Dielectr. **VIII**, 459–464 (1998)
25. Juhre, K., Kynast, E., et al.: High Pressure N_2, N_2/CO_2 and CO_2 Gas Insulation in Comparison to SF_6 in GIS Applications. In: 14th International Symposium High Voltage Engineering (ISH), Paper C-01, pp. 1–6 (2005)
26. Simka, P., et al.: Dielectric Strength of C5 Perfluoroketone. In: Proceedings of 19th International Symposium on High Voltage Engineering. Pilsen, Czech Republic (2015)

27. Kieffel, Y., et al.: Green gas to replace SF_6 in electrical grids. IEEE Power Energy Mag. **14**(2), 32–39 (2016)
28. Owens, J.G.: Greenhouse Gas Emission Reductions through Use of a Sustainable Alternative to SF_6. EIC (2016)
29. Hammer, T.: Decomposition of low GWP gaseous dielectrics caused by partial discharges. In: 21st International Conference on Gas Discharges and Their Applications. Nagoya, Japan (2016)
30. Gautschi, D.: Application of a Fluoronitrile Gas in GIS and GIL as an Environmental Friendly Alternative to SF6. CIGRE, B3-106 (2016)
31. Tehlar, D., et al.: Ketone Based Alternative Insulation Medium in a 170 kV Pilot Installation. CIGRE SC A3 & B3 Colloquium. Nagoya, Japan (2015)
32. Hyrenbach et al.: Alternative Gas Insulation in Medium Voltage Switchgear. CIRED (2015)
33. Söderström, P., et al.: Suitability Evaluation of Improved High Voltage Circuit Breaker Design with Drastically Reduced Environmental Impact. CIGRE (2012)
34. Schiffbauer, D., Majima, A., Uchii, T., et al.: High Voltage F-gas Free Switchgear applying CO_2/O_2 Sequestration with a variable Pressure Scheme. In: CIGRE-IEC 2019 Conference on EHV and UHV (AC&DC). Hakodate, Japan (2019)
35. Jansen, A., Uzelac, N., Found, P., Schoonenberg, G., Liandon, M.R.: Evolution of functional requirements for MV switchgear. CIGRE 2018 Conference
36. Janssen, A.L.J., et al.: Circuit breaker requirements for out-of-phase switching. In: CIGRE SC A3, B4 &D1 International Colloquium 2017, Winnipeg, Report A3-044
37. CIGRE Technical Brochure 716: System Conditions for and Probability of Out-of-Phase—Background, Recommendation, Developments of Instable Power Systems, CIGRE JWG A3/B5/C4.37 (2018)
38. IEEE 1547 Series of interconnection standards for distributed resources with electric power system
39. https://www.modernpowersystems.com/features/featurenovel-fault-limiting-circuit-breakers-for-dense-urban-grids-5748048/
40. Kerr, B., Ache, J., Lynn, S., Uzelac, N.: Smart switchgear for extreme installation environments. In: Conference Paper 1100, CIRED (2019)
41. IEC 60044-7: Instrument Transformers—Part 7: Electronic Voltage Transformers
42. IEC 60044-8: Instrument Transformers—Part 8: Electronic Current Transformers
43. IEC 61869-9: Instrument Transformers—Part 9: Digital Interface for Instrument Transformers
44. IEC 61869-15: Instrument Transformers—Part 15: Additional Requirements for Voltage Transformers for DC Applications
45. IEC 61869-14: Instrument Transformers—Part 14: Additional Requirements for Current Transformers for DC Applications
46. IEEE Std. 519: Recommended Practices and Requirements for Harmonic Control in Electric Power Systems
47. IEC 61000-4-30: Testing and Measurement Techniques—Power Quality Measurement Methods
48. IEEE C37.118: IEEE Standard for Synchrophasors for Power Systems
49. Mantilla, J.D., et al.: Environmentally Friendly Perfluoroketones-based Mixture as Switching Medium in High Voltage Circuit Breakers. CIGRE A3-348 (2016)
50. IEC/IEEE 62271-37-013. ed. 1.0. 2015-10, High-voltage Switchgear and Control Gear, Part 37-013: Alternating-current Generator Circuit-breakers
51. IEC 62586-1 Ed.1: Power Quality Measurement in Power Supply Systems—Part 1: Power Quality Instruments (PQI)
52. Darko, K.,Beierlein, A., Micic, S.: Improving system safety and reliability with solid dielectric switchgear. In: Conference Paper 2058, CIRED (2019)
53. IEC 61869-1: Instrument Transformers—Part 1: General Requirements
54. IEC 61869-6: Instrument Transformers—Part 6: Additional General Requirements for Low-power Instrument Transformers

55. IEC 61869-10: Instrument Transformers—Part 10: Additional Requirements for Low-power Passive Current Transformers
56. IEC 61869-11: Instrument Transformers—Part 11: Additional Requirements for Low Power Passive Voltage Transformers
57. IEC 61850-9-2: Communication Networks and Systems for Power Utility Automation—Part 9-2: Specific Communication Service Mapping (SCSM)—Sampled Values Over ISO/IEC 8802-3
58. Milosevic, A., Kartalovic, N., Milosavljevic, S., Uzelac, N., Gambin, R.J., Niemczyk, M.: Field testing on solid dielectric MV switch. In: Conference Paper 2260, CIRED (2019)

Nenad Uzelac graduated from the School of Electrical Engineering in Belgrade, Serbia, in 1995, with a major in electrical power engineering and completed Master of Science in product development at Northwestern University, Evanston, USA, in 2004. In 1999, he joined G&W Electric Company as an R&D Engineer, and in 2005, he became R&D Manager for developing new MV switchgear including reclosers and fault interrupters. Starting in 2015, he became responsible for G&W Global Research, tasked to develop new technologies. His research interests include AC and DC switching, materials and insulation technologies, condition monitoring and diagnostics, sensors, and arc fault studies. He was a convener of CIGRE A3.24 WG on “Tools for simulation of internal arc on MV and HV switchgear” and CIGRE A3.32 WG “Non-intrusive methods for condition assessment of distribution and transmission switchgear.” Currently, he is a chair of CIGRE A3 study committee on T&D Equipment. He is also a senior member of IEEE and a chair of IEEE Switchgear Technology and Innovation subcommittee.

Hiroki Ito joined Mitsubishi Electric Corporation in 1984. From 1989 to 1991, he worked as a researcher in the Coordinated Science Laboratory at University of Illinois, USA. After returning to Mitsubishi Electric Corporation, he was engaged in the research and development on DC and AC gas circuit breakers. In 1994, he received his Ph.D. degree from Tokyo Institute of Technology. He was a director of internationally accredited high voltage and high-power laboratories of Mitsubishi Electric Corporation from 2005 to 2012. He is currently a senior technical advisor of Energy and Industrial Systems Group, Mitsubishi Electric Corporation. He joined CIGRE Working Groups 13/A3.07 “Controlled Switching.” He was the convener of CIGRE Working Group A3.22 “Technical requirements for UHV substation equipment” and A3.28 “EHV and UHV switching phenomena.” He was the chairman of CIGRE Study Committee A3 dealing with transmission and distribution equipment from 2012 to 2018. He was awarded as the CIGRE honorary member in 2018.

René Peter Paul Smeets received a Ph.D. degree for research work on switchgear in 1987. Until 1995, he was an assistant professor at Eindhoven University. During 1991, he worked with Toshiba Corporation in Japan. In 1995, he joined KEMA, the Netherlands. At present, he is with KEMA Laboratories of DNV GL, as a service area and innovation leader. In 2001, he was appointed part-time professor at Eindhoven University, the Netherlands, in the field of high-power switching and testing technology. In 2013, he became adjunct professor at Xi'an Jiaotong University, China. Dr. Smeets is convener/member of working groups and study/advisory committees of CIGRE in the field of emerging high-voltage equipment such as high-voltage vacuum, HVDC switchgear and SF6 alternatives. He was convener of CIGRE A3.27 (high-voltage vacuum switchgear), was secretary of CIGRE WG A3B4.34 (HVDC switchgear), and at present, he is convener of CIGRE WG A3.41 (impact of SF6 alternatives on switching). He is convener of two maintenance teams in IEC on high-voltage switchgear. Dr. Smeets published and edited three books and authored over 300 international papers on testing and switching in power systems. In 2008, he was elected Fellow of IEEE, and since 2008, he is chairman of the "Current Zero Club," a scientific study committee on current interruption. He received seven international awards, among which two from CIGRE.

Venanzio Ferraro is a chairman of the Italian Electrotechnical Committee TC38 for Instrument transformers. (formerly CEI). He participated in number of IEC and CIGRE working groups related to instrument transformers and currently is a member of CIGRE A3.43 Working Group "Tools for lifecycle management of T&D switchgear based on data from condition monitoring systems." Since 2018 he is an innovation leader in Schneider Electric focusing on Identification and validation of innovative technologies, start-ups and partners for innovation in connected and smart medium voltage products. Prior to that, he was an R&D manager in Schneider Electric responsible for developing new products, systems and software in the field of medium voltage product automation. is a chairman of the Italian Electrotechnical Committee TC38 for Instrument transformers (formerly CEI). He participated in number of IEC and CIGRE working groups related to instrument transformers and currently is a member of CIGRE A3.43 Working Group "Tools for lifecycle management of T&D switchgear based on data from condition monitoring systems." Since 2018 he is an innovation leader in Schneider Electric focusing on Identification and validation of innovative technologies, start-ups and partners for innovation in connected and smart medium voltage products. Prior to that, he was an R&D manager in Schneider Electric responsible for developing new products, systems and software in the field of medium voltage product automation.

Lorenzo Peretto is full professor of electrical and electronic measurements at the University of Bologna. Currently, he is Director of Electrical Energy Engineering Program at the University of Bologna.He is Senior Member of the IEEE and member of the IEEE Instrumentation and Measurement Society. He is Instrumentation and Measurement Society representative in IEEE Smart Grid steering committee. He is actively working to the new Standard Series IEC 61869 “Voltage and Current Instrument Transformers.” He is chairman of IEC TC38/WG55 for the new Standard IEC 61869-105 “Uncertainty evaluation in Calibration of Instrument Transformers.” He has been associate editor for a Special Issue of IEEE Transactions on instrumentation and Measurements. He has been invited lecturer related to measurement issues in power systems under distorted conditions to IEEE General Annual Meetings of PES. He is currently teaching courses in “Instrumentation for Electrical Engineering,” “Mechanical Measurements” and “Applied Measurements for Power Systems.” He is author and co-author of more than 270 scientific papers and co-inventor of 31 patents and co-author of three books.

Insulated Cables

Rusty Bascom, Marc Jeroense, Marco Marelli, James A. Pilgrim, and Roland D. Zhang

Abstract The history of cables started in the nineteenth century with telecommunication and low power cables, first insulated with natural rubbers and later with oil–paper insulation. Since then, the cable systems have been further developed and evolved as a reaction to societal, grid and environmental needs. The technical responses have driven the cable industry to a vivid playground for advanced technologies. Paper–oil insulated cables are now accompanied by different types of polymeric insulation. Metal–water barriers have been introduced when learning about some detrimental effects of water. These same barriers are now being challenged by environmental requirements. Putting new requirements on cable systems does not suffocate the cable industry. Rather on the contrary, the R&D community responds with inventive solutions that bring the products and solutions to a level needed to operate the grid in a safe, reliable and environmentally responsible manner. The future will force the cable industry to speed up in production capacity, power, voltage, depth and inventiveness in a pace that has not been observed in the twentieth century. No showstoppers have been identified, and therefore, we can look forward with trust and confidence that cables from LV to EHV, AC to DC will play a pivotal role in the future grid.

1 Introduction

The entire industry of insulated cables including manufacturers, academy, and users moved in large steps in the recent years in the direction of introducing new technical solutions and to identify new applications.

This evolution shows signs not just of continuation, but acceleration. The way insulated cables will play a role in the future electricity supply systems will be

---

On behalf of Study Committee B1.

R. Bascom · M. Jeroense · M. Marelli (✉) · J. A. Pilgrim · R. D. Zhang
CIGRE, Paris, France
e-mail: marco.marelli@prysmiangroup.com

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_5

largely influenced by how the power network will develop. It is generally agreed that two models are possible:

- An increasing importance of large networks for bulk transmission capable of interconnecting load regions, large centralized renewable generation resources including offshore facilities, and to provide more interconnections between the various countries and energy markets
- The emergence of clusters of small largely self-contained distribution networks, which will include distributed energy resources (DER), energy storage and demand side management (DSM) intelligently managed so that they are operated as active networks providing local active and reactive support.

These two models are not exclusive but rather they are both needed in order to reach the ambitious environmental, economic and security targets sought for.

Similarly, insulated cables would not benefit from one or the other model but rather will be triggering the possibility of their fast and effective developments.

1.1 The Role of CIGRE

To get ready for this, Study Committee B1 "Insulated Cables" is focused on high-voltage (HV) and extra high-voltage (EHV) transmission applications, but with a renewed interest in distribution, embedded generation and smart grids medium voltage (MV) cable system applications. The broad approach is also valid when considering the life cycle of cable systems, as SC B1 is engaged to cover theory, design, applications, manufacture, installation, testing, operation, maintenance, end of life and diagnostic techniques of insulated cable systems (Fig. 1).

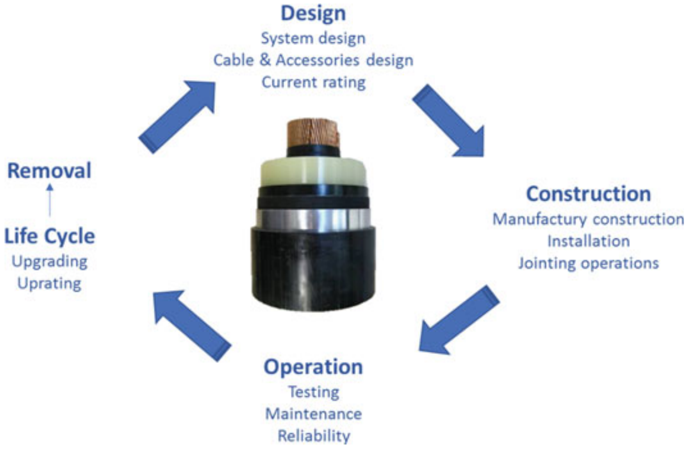


Fig. 1 Life cycle of insulated cables

Among all factors that are being considered, there are some that have a growing interest and are a clear sign of the trends that will be seen also in the near future.

The importance of public acceptance for large infrastructures, the time needed from concept developments to final execution of transmission lines, and their overall cost of investment and of operation are all connected and should be regarded as of primary importance.

Also, the attention about the environmental impact of cable lines (and more in general, of power transmission lines) and the cable life cycle (including carbon footprint for production and operation, as well as material recyclability) are constantly increasing and will be key factors for the next generations.

Growing importance is being given—and will be given—to the education of these new generations and to the increasing number of stakeholders of insulated cables and their applications.

There are other factors that are emerging in the recent years and that will certainly impact on the future developments. In particular, there will be a larger effect of digitalization across all industry fields: This will surely bring benefits in the manufacturing processes but also will create new opportunities in transmission applications and in particular in the active management of local energy communities. The digitalization and the globalization have effect also on the speed of the evolution, accelerating the learning curves about materials, processes and applications.

Other keywords for the evolution of the electricity supply systems will include resilience, sustainability and security. The solid roots of Study Committee B1, guiding the progress of Insulated Cables since more than 90 years, will help to focus on those aspects that will be of essence for the future.

2 Historical Perspective

Insulated electric cables trace their origins to the 1800s when conductors insulated with glass tubes, rubber and gutta-percha (tree sap-derived latex) were used for mining and telegraph service. A submarine telegraph cable consisting of rubber, hemp, tar and pitch was first used as a telegraph cable in 1841. In Europe, paper insulation was first used in 1890 using a paraffin wax soaking the paper insulation for a 10-kV 50-km circuit in what was called a Ferranti cable. A similar circuit was commissioned in 1891 and remained in service for 42 years, eventually leading to the construction of impregnated paper-insulated cables with a lead sheath. In the 1920s, oil-impregnated paper insulation developed by Emanueli was pivotal in suppressing insulation ionization and permitted the development of higher-voltage self-contained fluid-filled cables up to 138-kV cable. Self-contained cables were generally designed to operate at a slight overpressure. In North America, paper insulation was used in the 1880s with the development of vacuum drying and oil impregnating technologies. A 290-km DC system operating at ±120 V was used for underground circuits. AC cable systems then started to displace the DC network. Pipe-type cables became the dominant high-voltage cable system in North America in the second half of the twentieth century after some utilities compared the characteristics of pipe-type and self-contained cable types.

Evolutionary developments in paper insulation technology occurred through the twentieth century. During this time, extruded insulation technologies were developed. In the 1930s, polyethylene was developed in England, and cross-linked polyethylene extrusion technology was developed in the 1950s. The impact of moisture (water treeing) on the polymer insulation materials was becoming apparent in the 1960s and led to the introduction of metallic moisture barriers (primarily extruded lead at that time). The 1960s also showed the technological development of ethylene-propylene-rubber (EPR) insulation for commercial cable insulation applications.

As the technology for extruding high-quality cross-linked polyethylene became commercially viable for cable production in the 1970s, the use of linear low-density polyethylene insulation diminished due to the much lower maximum operating temperatures, and this use was completely displaced for new cables by the end of the twentieth century.

In the 1970s, laminated paper–polypropylene insulating tapes were commercially produced and applied to paper-insulated cables, both for self-contained fluid-filled cable systems and pipe-type cables. Pipe-type cable use was prevalent in North America with limited applications in other parts of the world through most of the twentieth century, but concerns about the volume of dielectric insulating liquids in these systems, higher maintenance requirements and limitations on current-carry capacity resulted in the reduction in utility-driven applications for new pipe-type systems and, as a result, the need for manufacturing worldwide. However, the extensive use of pipe-type cables by some utilities established this cable type with the expectation of continued use as “legacy” systems in the USA for years to come. Some pipe-type cable circuits are being evaluated to retrofit with some type of extruded cable technology to eliminate the dielectric liquids in these systems. Self-contained fluid-filled cables remain widely used throughout the world, but extruded cables are displacing these systems as well.

When some of the earliest paper-insulated transmission cables were approaching the age associated with their design life (~40 years such as the first Ferranti cables), efforts were put forth to study the ageing characteristics of these cables. The accumulated loss of life was evaluated based on historic operating temperatures. It was determined that the remaining life of the cable system due to typical insulation ageing was longer than the expected design life, thus allowing in many cases the extension of the cable’s operating life beyond 40 years.

In addition to the cable itself, the cable industry transitioned from the use of field-moulded extruded cable splices to pre-moulded designs that were less sensitive to workmanship issues and could be assembled in less time. Termination design technologies evolved from the exclusive use of ceramic bushings to polymeric bushings that were both lighter and less sensitive to mechanical damage. An additional benefit was eliminating the possibility of distributing shattered porcelain bushings during violent failures.

Low-temperature (4 K) superconducting cables were developed and proven in laboratory settings, but were only used on a limited basis in controlled commercial applications. High-temperature (70 K) superconducting cables were developed late in the twentieth century and used in limited applications for commercial projects, often with government subsidies. These systems were sometimes considered where the benefits of high current density at lower voltage was needed for short distances, such as generating stations to avoid the cost of step-up transformers. Liquid nitrogen cooling stations are required every 5–10 km for AC applications and every 20 km for DC applications. The necessary cooling technology is commercially available, and redundant systems allow maintenance to be performed without interrupting operation. However, the cryogenic cooling plants continue to be a technological challenge for longer applications.

In the late twentieth century, monitoring and diagnostic technologies for cable systems improved for cable systems. Fibre-optic-based distributed temperature sensing was first applied to power cables in the 1990s which facilitated identifying locations of high operating temperature and optimizing cable system power transfer capabilities. Other monitoring technologies permitted detection of insulation partial discharge in cable and accessories in field settings, and dissolved gas-in-oil analysis techniques were refined to assess the condition of paper-insulated power cables.

3 Power Cable State of the Art

Cable system technology has mostly evolved during the early part of the twenty-first century with manufacturers developing, qualifying and producing extruded AC cables up to 500 kV for commercial applications, with higher-voltage cables being tested. The number of extra high-voltage cable systems is increasing worldwide. As insulation quality has improved, manufacturers have produced higher electrical stress cables and accessories that provide greater opportunities to retrofit formerly paper-insulated civil infrastructure that may have previously been constrained by smaller conduits.

Conductor materials are copper or aluminium. The choice can be done on technical bases or in function of the metal price. Copper has seen wider use particularly for high-capacity transmission voltage cables. AC cables can now utilize copper conductor strands coated with oxide or enamel to reduce AC losses and make larger conductor sizes viable for high-current capacity cables. These larger conductor sizes have meant that manufacturers and installers are more closely considering the impacts of large diameter cables installed within conduits and managing the movement of the cables to avoid mechanically impacting the connected accessories (splices, terminations).

HVDC cables insulated with polymeric insulation were also developed and commercially proven in the early part of the twenty-first century, eliminating some of the components associated with paper-insulated HVDC cables (oil–paper insulation and lead radial moisture barrier). The cost of converter stations has also dropped in recent years allowing the viable application of shorter-length HVDC transmission for both land and underwater applications.

Fig. 2 A typical horizontal directional drilling rig

Installation methods for underground cables remain focused on open-cut trenching technology. Trenchless methods including pipe-jacking, micro-tunnelling and, especially, horizontal directional drilling (HDD), a technology borrowed from the petrochemical industry, have allowed cable system installations in areas that prohibit other methods. Horizontal directional drilling for transmission cables has been applied to installation lengths of up to 2.2 km (Fig. 2).

Some of the early transmission voltage extruded cable systems have already reached or are approaching an installed age of 40 years, so utilities are seeking to evaluate the remaining life of these cable systems.

The cable industry continues to evolve to improve reliability, increase manufacturing capacity, reduce the overall life cycle costs and enhance power transfer capacity.

4 New Societal Requirements

If the transmission capacity is not enhanced in an efficient way through investing into new lines, or the reinforcement of available lines, especially through cable systems, the electricity price could increase in one single country, especially considering the integration target of renewable energy, e.g. in 2040 to 75% in Europe.

According to the ENTSO-e's TYNDP 2018 (ten years network development plan) "*A lack of new investments by 2040 would hinder the development of the integrated energy market and would lead to a lack of competitiveness. In turn, this would increase prices on electricity markets leading to higher bills for consumers. By 2040, the "No Grid" extra bill (€43 billion a year in the average case) would be largely above the expected cost of the new grid (150bln€ in total in the TYNDP 2016 plus internal reinforcements, 25% discount rate). A lack of investments will affect the stability of the European grid and could, in some regions, threaten the continued access to electricity which also has a cost for society*".

Energy must be affordable. Underground cable systems are generally more expensive than the application of overhead lines. But considering the total cost of ownership (TCO), especially the permission, losses, environmental impact during the operation, etc., the decision for the application of one of the transmission methods could be different.

Due to the non-controllable and decentralized renewable energy, system operators have to ensure the frequency and voltage stability by using the new technologies/solutions, e.g. application of MVDC/LVDC cables, and need regulatory and policy coordination in a higher level as well as innovative market design to ensure the flexibility in the transmission systems. In order to ensure and enhance the security of power supply, flexibility and resilience of the transmission lines, an improved use of data analytics shall be applied, e.g. through the integrated FO elements in cable systems.

The responsibility of system operators shall be to safeguard the legal and environmental compliance and control the performance by setting the higher standards and raising the priority of environmental protection during installation and further operation/maintenance of cable systems.

Moreover, the attitudes to corporate social responsibility (CSR) and health safety environment (HSE) are the central task to obtain the rules and requirements. The learning and training in those fields are the precondition of establishing, improving and compliance with performance requirements.

5 New Grid Requirements

Grid expansion and reinforcement will be treated as crucial issues for the further grid.

In the network with a high proportion of cabling, the availability of the grid shall be newly calculated. The new maintenance strategy shall be developed in order to fulfil the requirement of the high quality of grid performance, e.g. by the application of monitoring systems such as real-time thermal rating (RTTR)/distributed temperature sensing (DTS), distributed acoustic sensing (DAS)/distributed vibration sensing (DVS), online failure monitoring, etc. One central question needs to be answered: How to repair a cable system in the shortest time, especially considering offshore networks and interconnectors?

Some issues are in further development, e.g. the (emergency) repair preparedness plan including all steps for a cable repair, contracting the service level agreement for the cable repairs, sourcing of bottleneck materials, etc.

By application of cables, especially long AC cables, the network impedance and/or network resonance frequency could be changed. This could lead to overvoltage unless adequate compensation is available through shunt reactors. Therefore, project-specific studies shall be conducted to check the feasibility and operability.

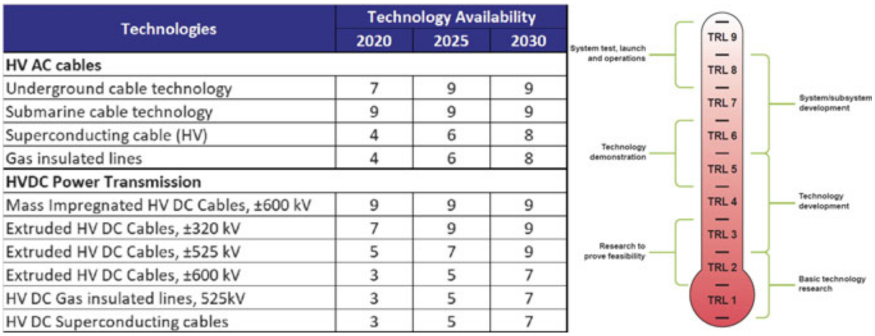
Due to the public acceptance of underground cables, more partial undergrounding projects are now in the planning and the execution phase. Some aspects shall be considered beside the technical requirements: cost, obstacles in cable routes and environmental impacts during the construction, etc.

E-Highway will be built in the year 2050 in Europe with a mixture of AC/DC overhead lines, cables (insulated with a range of different insulation materials), hybrid lines, eventually also with gas insulated lines (GIL) and superconducting cable systems, etc. The new aspects to be considered are:

- frequency
- possible displacement of the controllable generation
- impact of RES integration on the transient and voltage stability.

The system design needs to be adapted according to the new grid codes. Research and investigation will be essential to meet the challenges of TSO, manufacturer and stakeholders combined. Further operability challenges are growing.

Also, evolution of technologies and their readiness shall be constantly monitored (Fig. 3).



Technologies	Technology Availability		
	2020	2025	2030
HV AC cables			
Underground cable technology	7	9	9
Submarine cable technology	9	9	9
Superconducting cable (HV)	4	6	8
Gas insulated lines	4	6	8
HVDC Power Transmission			
Mass Impregnated HV DC Cables, ±600 kV	9	9	9
Extruded HV DC Cables, ±320 kV	7	9	9
Extruded HV DC Cables, ±525 kV	5	7	9
Extruded HV DC Cables, ±600 kV	3	5	7
HV DC Gas insulated lines, 525kV	3	5	7
HV DC Superconducting cables	3	5	7

Fig. 3 Technology readiness level for cable technologies from ENTSO-e (Source ENTSO-e TYNDP 2018, Technologies for transmission system)

6 Market Trends

New technologies can emerge as a reaction on slowly appearing market trends as well as more swiftly born requirements. On the other hand, new technologies sometimes are born out of the womb of a bright scientific mind. But even in the latter case such a new idea will often have the biggest chance of survival if there is a connection to trends and expectations.

The cable industry is part of a market in which trends are more forceful than previously and the trends in the market are answered by new technologies at a higher pace than ever. Looking into the crystal ball of the future, we might expect this process to keep the same level of intensity or even increase. Industry is already rising to the challenges presented by introducing new technologies and will most probably do so even in the near and medium and far future. So, let us have a look upon the current trends in the cable industry from a technology perspective.

6.1 Remote Generation

Electricity is increasingly generated at locations more remote to the closest connection points of the electricity networks, meaning that the distance to the centre of gravity of consumption also has increased. In order to keep the, mostly ohmic, losses to an acceptable level, high-voltage engineering has taught us for more than a century ago that one then should increase the voltage and thereby decrease the current necessary for transmitting a certain amount of power.

Another reason for the higher voltage is the fact that the assets that are being built far away from the locations of consumptions can be expensive. Upscaling the remote generation, simply more power, then results in an advantage through economies of scale. That is, it is better to invest in a huge remote generation than a small one to reduce the cost per unit of power. So, in the end we expect to transmit huge amounts of remote power rather than small amounts.

More remote locations might be accompanied with harsh environmental conditions such as large water depths, strong winds, waves and sea currents and more extreme temperatures, both high and low. One well-known example is the offshore wind parks, with locations becoming further away from the coast line to take advantage of the stronger winds and therefore larger energy density. Water depths are increasing such that the platforms and pylons must be floating. The pylons and cables are subject to recurrent movements from the wind and the waves. Yet another example is the interconnection of electricity networks that are far located from each other. In certain cases, waters with extreme depths must be crossed.

Also, environmental effects can put catastrophic stresses on the assets, like those induced by earthquakes, extreme storms, flooding and fires.

6.2 Local Generation

The transformation of the global electricity networks due to the impact of the climate changes has two distinctly different strategies: one that is characterized by centralized and large generation and another one that is characterized by local and small generation. Whereas the earlier described trend of generation becoming more remote and therefore often, but with exceptions, large, the local generation is best described by smaller powers, lower voltages and smaller distances. Individuals investing in solar panels on the roof of houses, a smaller group investing in one or very few on-land wind mills are examples of local generations that require new ways of integration, regulation and operation. Cost efficiency is a leading word in such applications. The old question whether such local micro- and mini-grids should be built with alternating current or direct current systems is now becoming a very important issue. This is because the electronics required for conversion are becoming lower in cost and there are now some very significant operational and safety advantages in the use of DC. Already there are medium voltage DC solutions, and this may extend to low-voltage DC systems.

6.3 More Interconnectivity

Integrating networks, both on a local and a more global scale, results in increased complexity. We must also realize that equipment connected to cable systems, such as converter systems, overvoltage protections, flexible AC transmission systems and the like, are also evolving. All these changes might result in dielectric stresses in terms of overvoltage, harmonics both in current and voltage that must be dealt with by the cable systems.

The grids of the future will probably have more layers than we have today. The highest level nowadays called the overlay grid that might be operated at ultra-high DC voltages, eventually going all the way down to the just mentioned MV and LV grids. We must learn more about the interactions of these systems and the possible impact on cable system designs.

Especially in densely populated areas, all these different grids and voltages levels come close together. Sometimes a huge amount of power must be fed into the centre of such densely populated areas. Technological solutions must be developed to offer a solution while respecting space constraints and environmental and safety aspects.

6.4 New Generation Types

Thermal, hydro and nuclear power generation have dominated the types of generation for many decades. The percentage of renewable energy generation types has increased the last two decades and will continue to increase in the future. Types of generation that the grid will consist of, besides the ones mentioned, are onshore and offshore wind, local small and global and large solar generation, wave power and sea current power. The traditional thermal, hydro and nuclear power generation tend to have a quite predictable and constantly high output of power. The new renewable types of power generation are characterized by much more unpredictability and fluctuations that will have impact on for instance the thermal designs of the cable systems.

6.5 Fast Introduction of New Technologies

New cable system technologies are introduced to the market and implemented in the grid in a faster pace than ever. This will have an impact on the level of acceptance of the market for these new technologies. Often these new technologies are responsible for the transmission of huge amounts of power. An outage of such a system has huge consequences. As a response, the cable industry will probably see an enhanced level and amount of testing regimes and an increased level of required quality control.

New technologies will be monitored to guard the predicted but yet unknown operational performance.

6.6 Longer Use of Existing Assets

In the last few decades, the industry has invested a lot in the grids as we know them today. The pace of investment has not decreased, but on the contrary increased significantly. From a financial point of view, it will be a challenge to replace the existing cable assets that will reach their end of life all at once. One way to deal with this fact is to measure off-line or on-line parameters that can reveal something about the status and healthiness of the cable system. The idea is that with such knowledge it then will be possible to judge whether a particular asset is still able to fulfil its function or that one possibly has to decide to de-rate or replace the asset.

6.7 Increased Environmental Awareness

Our planet is pushed hard by the activity of all humans and their industry. More and more people in poor regions deserve a better and sustainable life style. This quite often means an increased availability and consumption of electricity, at least for those that have no or little access to electricity at all. All in all, it means that our cable industry has a significant responsibility to develop, manufacture and implement cable system solutions in a sustainable manner. Raw materials, transport, manufacturing, installation, in-service utilization and recycling shall be done in a responsible and environmentally optimal manner.

These seven global trends are connected to new technologies that have lately been introduced that are being introduced and that will or might be introduced in the near or further future. We will have a closer look at some of these.

7 New Technologies Answering on Trends

7.1 Higher Voltages HVAC Submarine

Four and five hundred kV underground cable systems have been available for a long time. Due to higher financial and technical risks and challenges involved the use of these highest voltages has not gone as fast in the case of submarine solutions. HVAC submarine cable projects become in general more cost-effective when the three cores are assembled in one armouring package (Fig. 4). Such 3-core cables can then be installed in a single campaign instead of three in the case of three single-core cables. As installing submarine cables is expensive, projects based on 3-core cable in general

Fig. 4 Example of 3-core submarine cable (from TB 610)

are more cost-effective. The challenge of such 3-core cable of highest voltage and power is the sheer size that surpasses 100 kg/m and comes into the diameter range of 200–300 mm. Handling such cable systems must be engineered carefully. The circumference of such cables is covered by at least one layer of armouring. In case such cables are laid at moderate depths, there is no need for so much structural strength in the armour. New solutions with a mixture of polymeric wires and metal armour can be used to arrive at a more cost-effective solution.

In certain cases, the solution with three single-core submarine cables is still the better option. To decrease the armour loss, one can use armour made of stainless steel, copper or other materials resulting in reduced losses.

SCFF (self-contained fluid-filled) submarine cables have been used for the highest voltages already for some considerable time, whereas XLPE submarine cables for the highest voltages like 400 kV have been used only lately. In some parts of the world, the voltage level of 220 kV now becomes a more common solution for offshore solutions, whereas 275, 300 kV or higher still are the exception to the rule. These new technologies will probably be used more in the foreseeable future.

7.2 Ultra-High AC Voltages for Land Sections

In certain parts of the world like Canada, India and China, power is sometimes transmitted by ultra-high voltages like 745, 1000 and even 1200 kV AC. Overhead lines are being used as the only means of transmission, because no cable technology exists capable of withstanding such voltages. It might be necessary in future to transmit small distances by cable-like solutions as part of these very long and ultra-high-voltage transmission lines. Whereas traditional cable technologies may not be the first thought-of-solution, superconducting cables and gas insulated lines (GIL) might be a possible technical solution for such applications.

7.3 High-Voltage Direct Current

Starting in 1954, with the first large-scale commercial HVDC cable link, the mass impregnated cable technology was introduced for DC applications (Fig. 5). For several decades, this MI technology was alone and was not challenged by the polymer cousin as it existed in AC applications. But since the 1990s, extruded DC cable systems became available, firstly at moderate voltage and powers. Both voltage and power levels have increased since then, and certainly since the first decade of the twenty-first century, the number of projects, the voltage and power levels have increased in a significant and fast manner. Voltages in the range of 500 and 600 kV are projected, and in the laboratory even higher voltages have been reached. Also operating temperatures that were traditionally maximized to 50–55 °C for MI cable

Fig. 5 Examples of HVDC cables with different insulation technologies (courtesy of NKT)

systems and 70 °C for extruded cable system are gradually increasing towards 80–85 °C and 90 °C, respectively. This has been possible by optimizing the systems and opening for new technologies. MI cables, being a family member of lapped cable systems, were enriched with a cousin already known from SCFF-AC cable systems, now known as the polypropylene lapped paper tape (PPLP) cable. The extruded DC family which is still dominated by the DC cross-linked polyethylene is now accompanied by nano-filled XLPE solutions as well as cable systems based on thermoplastic insulation systems. All these technologies are characterized by having announced a higher operating temperature. As in certain parts of the world extremely huge amounts of power are transmitted by ultra-high voltages along long distances, it is not impossible to expect that some parts of these lines in future will be realized by cables at voltages higher than 500–600 kV.

Crucial to the development of these technologies is a deep understanding of the physical phenomena that take place inside the dielectric. The different disciplines like chemistry, knowledge of dielectrics, thermodynamics, mechanics, manufacturing and measurement technology all come together along the long road starting with an idea, via development to commercialization. Non-destructive measurement technologies such as the pulsed electro-acoustic (PEA) method or thermal step method (TSM) to measure space charges and advanced leakage current cells are means of taking the technologies to the next level. In general, advanced measurement and analysis methods are instrumental for the development of future cable systems.

7.4 Larger Conductor Area

Although higher voltages are the classical means of increasing transmission power with reduced losses, also higher current capabilities are still needed. Such capability can be useful in meeting fault conditions of neighbouring systems, overload capabilities for other reasons as well as changing environmental thermal conditions. The other means to meet such challenges is to be able to withstand higher temperatures. But larger currents can thus mean larger conductor areas that surpass the 2500–3000 mm^2 limit. Cables of course become heavier and larger, and the transport over land of such cables becomes more challenging. Very large aluminium cross sections reducing cable weight will certainly be seen in future cable systems.

7.5 GIL

Gas insulated lines as an extension to the well-known gas insulated systems (GIS) exist for AC and are being discussed for DC applications (Fig. 6). The advantage of such systems is that there is no practical upper limit to the size of the cross section of the current-carrying component in the middle of such tubes, at least not in the sizes of interest. Such AC and DC GIL systems could carry several (3–8) GW of power in one system. It will probably be in this region where GIL's will have an advantage over traditional cable constructions, because one GIL can meet a double- or triple-cable system. For lower powers, cables probably will remain the better solution for reasons of cost and installation swiftness. Among the disadvantages of GIL systems are currently mentioned the lack of experience with long lengths, the large size of the component and the slow installation speed. GIL as per today are only operated in a few systems at AC voltage and DC GIL is under development and will probably first meet a piloting phase before it may become more widely available.

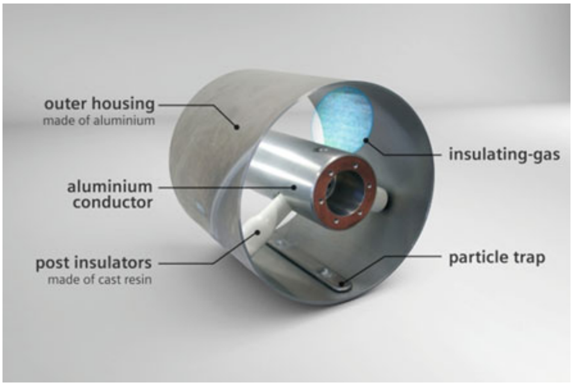


Fig. 6 Explicative construction of GIL (courtesy of Siemens)

As GIL is a very compact solution for huge powers, it can be a candidate for congested areas and city infeed. Especially with alternative insulating gas systems avoiding the use of SF6, the GIL can be of new interest for certain applications.

7.6 HTS

High-temperature superconducting (HTS) cables (Fig. 7) have been around for some time for AC voltages at the MV level. No DC solutions are in operation yet, although such full-scale systems have seen the light of day in the laboratory. The principle of HTS cable systems is that of cooling the special conductor to a very low temperature of liquid nitrogen of about −196 °C. The conductor is made of special ceramic taped materials like YBCO or BSCCO that loses their ohmic resistance at and below such temperature. HVAC HTS cables use HTS conductor tape to build a stranded conductor as well as in the screen. The opposing magnetic fields cancel totally. MVAC HTS cables often have all three phases on top of each other all inside the cryostat and thus cancel their magnetic fields too. The HVDC design is very similar to the HVAC HTS design; however, no superconducting screen is used. In cold designs, the dielectric is operated at cryogenic temperatures and is cooled down to that of the coolant. Other designs place the dielectric outside the cryostat, thus operating the dielectric at ambient temperatures. These systems are not maintenance-free.

The power that can be transmitted with HTS solutions is a multiple of the one of conventional cable systems. Current up to 5 or 6 kA in AC mode and exceeding 10 kA in DC mode can be achieved. 574 MVA at 138 kV AC has been demonstrated, but higher voltages up to 300 or 400 kV AC are anticipated. The feasibility of a 320-kV DC system has also been demonstrated.

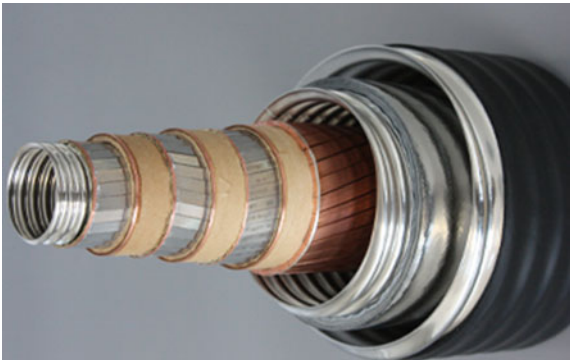


Fig. 7 Example of high-temperature superconducting cable (courtesy of Nexans)

7.7 Deep-Water Cables

Fibre-optic cables have been laid in extremely deep waters for many decades. The most well-known is probably the transatlantic telegraph cable installed in the nineteenth century. The reason that power cables have not been laid in larger depths than a few tens of metres until only lately is the weight of power cables is a factor 100 or so larger than the lightweight telegraphic cables. Tensile forces during the laying of cables from an installation vessel are directly proportional to laying depth and cables weight in water and will become for that reason quite large in the case of power cables. The deepest power cable ever laid up to today is the SAPEI cable with a maximum depth of more than 1600 m. Laying cables at such or larger depths is possible by following two principle roads. One way is that of lowering the specific weight of the cable, and the other way is of increasing its structural strength. The latter means also balancing the cable such that axial tension will not result in excessive torsional bending stresses. Repair at such depths is challenging and joints must be designed for such depths. That is, if one does not want to avoid repairing a longer section by starting and ending the repair at more moderate depths alongside the deepest section. Future cable technologies will be developed to cross larger depths.

It is essential to understand that realizing cable connections through deep waters is not only about cable design. It is just as much about the installation technology where expensive assets like installation vessels are key. Before one starts laying the cable, a thorough installation analysis for the particular cable, route and vessel must be performed.

7.8 Dynamic Cable System

When cables are connected to floating structures, such as offshore wind parks or oil and gas floating assets, the cable will be hanging in the water and experience movements induced by vessel motions and currents (Fig. 8). High-voltage cables with a metal–water barrier must be able to withstand such movements. The classical means of sealing a cable is by using a lead sheath. Lead is a very poor choice in terms of withstanding recurrent mechanical strains. Solutions that have been used so far are corrugated welded copper sheaths in oil and gas applications. Small- and full-scale laboratory tests have proven that solution to be a functional one. Designs of dynamic cables shall also consider eigen-frequencies of movement that shall match neighbouring risers and cables to avoid clashing. The horizontal movement of the floating asset shall be taken into account by designing extra length of cable that floats free in the water close to the floater. This is often accomplished by using weight, anchors and buoyancy units mounted to the cable. The connection point of the cable to the platform shall be mechanically stiffened by stiffeners or restrictors to avoid excessive bending and fatigue.

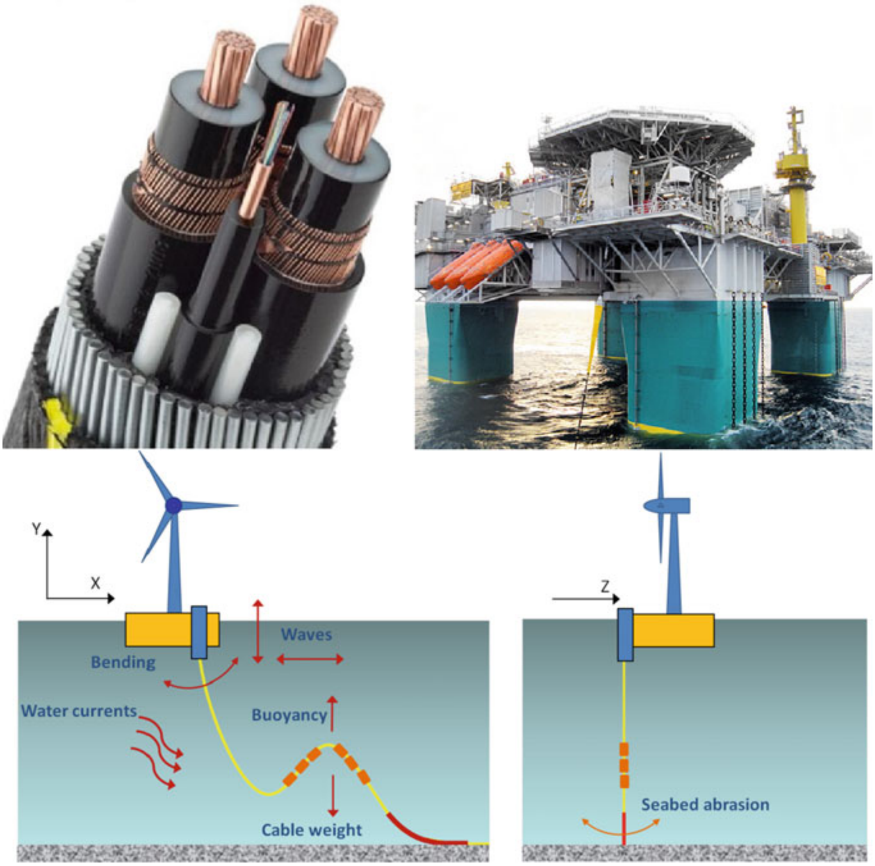


Fig. 8 Typical array cable (courtesy of Prysmian), oil platform (courtesy of NKT) and examples of dynamic cable applications when connecting to floating platforms or windmills (from TB 610)

Lower-voltage AC cables lack a metal sheath; only a metal screen is used. The screen—often of the wire type—shall be designed to withstand the mechanical stresses induced by the recurring movements. Inter-array cables are examples of such cables. The voltage above which metal sheaths are being used is becoming higher. Nowadays, 66-kV wet designs are being used. Future AC voltage using wet design cables might increase.

For all solutions, the armour shall be designed such that it keeps its functionality even when experiencing the long-term, static and dynamic stresses.

7.9 MVDC and LVDC

Focus tends to be on the high end of the technology, meaning, higher voltages, powers and currents. As a reaction to power generation becoming more local, lower voltage and lower power solutions operating at DC with either, constant DC voltage and variable current or with constant current and variable voltage may be a viable solution. Technological solutions already exist for far-higher stressed higher-voltage systems. MVDC and LVDC cable systems, however, will be characterized by cleverly developed, low-cost solutions. The harmonics and overvoltage of micro- and mini-grids might be relatively more severe than in EHV systems. From a manufacturing point of view, it might be not reasonable anymore to further optimize the insulation system and the DC operating stress will probably be low again as compared to the EHV solutions. For that reason, MVDC and LVDC systems might be developed based on the aspects of over voltages, harmonics and cost-effective manufacturability rather than on the aspects of high stress as in the EHV systems.

7.10 Multifunctional Cables

Complex 3-core submarine cables have increased power and size. With such knowledge, it should become possible to combine different cable cores into one 3-core or multi-core construction. Combining a plus and minus DC core with an AC auxiliary or control core is such a possibility.

7.11 Subsea Solutions

Cable systems are sometimes laid earlier than other components in larger projects; a platform might arrive many months or a year later than the cable. In such cases, cables must be wet stored. This means that the cable end is hermetically sealed and mechanically stiffened such that it can be lowered onto the seabed and pulled up later as well as pulled in or pulled up to the structure it shall be connected to.

As installation and vessel time is expensive, solutions that require a minimum of time to connect cables into for instance wind mills are cost advantageous. Such plug-and-play termination and joints will become available and required by projects.

Oil and Gas industry has a long-term strategy where more and more assets are placed onto the seabed and not anymore on a supporting floating structure. The advantage for that industry is reduced cost, because the, often, manned platform is expensive. A totally maintenance-free and remotely controlled template structure on the sea bed will be less costly from an operational expenditure point of view. If such a template is placed onto the sea bed first and the cable is to be connected after, then the connecting operation shall be performed in a wet environment. Such terminations are called wet-mateable connectors. They are available in the medium voltage AC range. Future technology might push that limit to higher voltages and also of the DC type.

7.12 Monitoring Cable Systems

Cable systems become more heavily monitored for reasons explained in the section "Market Trends". Fibres integrated in cables can monitor, continuously in time and space, temperature and strain in the fibre (Fig. 9). When cleverly located in the cable system the fibre can monitor the temperature and strain in the cable during installation and operation. Today's distributed sensing technologies are based on different optical scattering principles: Rayleigh scattering, Brillouin and Raman scattering. All have different pro's and con's. The main development needed for the future is the increase in length of cable systems than can be monitored. Today's maximum lengths that are reasonably possible to monitor are within the 50–100 km range.

Temperature measurements will give the possibility to monitor overloading and hot spots due to possible changes in thermal environment during the life time of the cable system. Whereas strain measurements give the possibility to monitor the strains during more complex installations, during the life time of a dynamic application and even to monitor vibrations. The latter can be an option to have an early warning of 3rd party damages.

PD measurements, off-line or on-line, are a technology that give the possibility for warning of early degradation. In on-line systems, these signals can be gathered locally and send wireless to a data-gathering unit and made available to the system operator who can take appropriate actions. The current challenge is the electrically

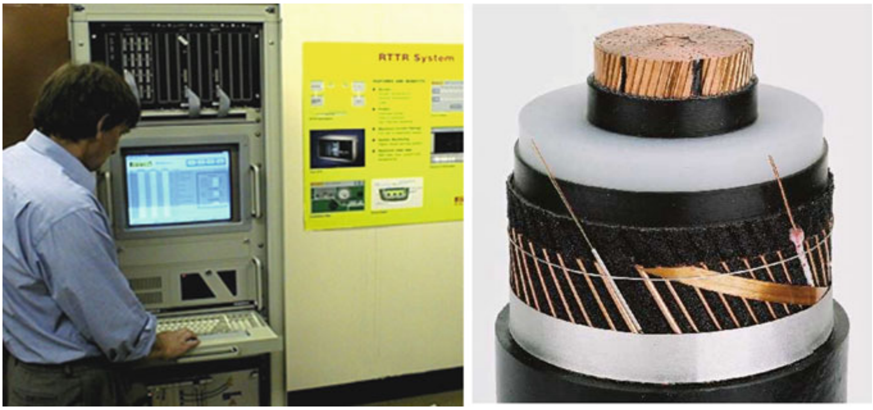


Fig. 9 Thermal monitoring system and power cable with embedded fibres (from TB 247)

noisy environment that potentially results in a low signal-to-noise ratio. Especially for higher voltages this can pose a limitation.

7.13 Fault Localization

Cable systems increase in length. Projects with several 100's of km's of route length are today not an exception. In case of a cable fault due to an external or internal damage, the asset owner wants to repair the fault as quickly as possible to keep down his loss of income and possible related liquidated damages. One of the early steps in the process of repair is that of fault location. Future fault pre-location technologies that have an accuracy of at least 1% or better will be needed. This can be accomplished in different ways. On-line fibre solutions that constantly monitor cables, are one. Another one is time-of-flight measurements at both ends of the cable. Mathematical methods can be used to increase the accuracy if one has a more detailed knowledge of the cables system response to pulses. Underground cable systems can be sectionalized, and on-line or off-line fault location techniques can be used in parallel thus increasing the total accuracy of the fault location and reducing the time to locate the fault.

7.14 Solutions Specific for Life Cycle Management

Cable systems and especially the usage thereof have a footprint on the earth. It is in all of our interest to keep that footprint to a minimum. While operating current and future technologies we must be aware of all steps in a cable systems life with respect to the effect on the environment. Ingoing materials like metals and polymers shall be chosen such that the total life cycle is optimized in terms of environmental footprint. This means that an analysis must be made from the cradle to the grave. From mining, sub-processing, via transport to manufacturing all the way down to the judgement of necessity and possibility of recyclability. Studies have shown that the largest negative impact of cable systems is due to its ohmic metal (mostly conductor) losses during the life time. The losses are generated by the current flowing from the generator to the user. In case the current and power originates from for instance coal powered plants the impact is far larger than if it was generated by renewable energy sources. At the end of the life time of a cable system it should be judged whether removing the system, separating and recycling all materials has a net positive impact or not. If so, this shall be done. Metals, thermoplastic and cross-linked polymers can be preferably recycled to the original application or if (not yet) possible: can be recycled to different degrees.

7.15 Testing Regimes and QC Strategies

New technologies must be thoroughly tested and qualified in the laboratory and proven to be capable of performing the function it was designed for on an industrial scale. Material tests, measurements for understanding, type tests and long-term test are known tools for developing and qualifying technological and technical solutions. Different routine tests and factory acceptance tests are required or recommended for existing technologies. It is important that new technologies are accompanied, if necessary, by additional measurements or tests that check the functionality of the design and the product to be supplied. Considering the increase in power and voltage and the harsher environment a future cable systems will experience, proper quality assurance shall be developed together with these new technologies. Testing regimes and quality control strategies are intimately connected to new technologies.

8 Research Needs

As identified earlier in this Chapter, insulated cables will make a significant contribution to the performance of large networks for bulk power transmission, and in connected new sources of decentralized generation to our power networks. However, sustaining the highest possible levels of reliability will require research in a number of fundamental areas. This section reviews those areas, and highlights some strategic research themes that will need to be addressed by the entire industry.

8.1 Accurate Estimation of Life Expectancy

The new requirements placed on insulated cable systems include their ability to withstand a range of new stresses. This is particularly true for cables in transmission networks, which historically have operated under small loads for the majority of the time. Grid operators continually strive to achieve the best whole life economic performance from their assets. This requires fundamental research on the following topics:

> **Service Ageing of AC XLPE**: some of the earlier XLPE cable installations are now approaching the end of their conventional design life. In the past, it was shown through service experience that paper-insulated cables could frequently operate beyond their conventional design life. Although service experience with transmission class (>220 kV) XLPE cables has typically been very good to date, there is a very limited population of cables which are sufficiently old to have reached end of life. The asset management techniques used to prioritize cable circuit replacement projects are driven by the results of asset health studies. Given the lack of service experience with genuinely aged XLPE cables, it is of paramount importance to

develop techniques which can reliably predict the end of life of such cables. This will require a holistic approach, taking account of all system components. Alongside improving our understanding of the degradation of XLPE under in-service stresses, it will also be necessary to develop models which account for the contribution of the cable sheath and jacket to the overall remaining life. This will allow the development of prognostic, rather than diagnostic, condition monitoring tools.

HVDC Systems: considerable effort has been invested in improving our understanding of the effects of space charge on the long-term ageing of XLPE HVDC cables, both paper and polymeric insulated. As our grids become more dependent on HVDC interconnections, some of which will be approaching mid-life, it will be imperative to translate laboratory scale understanding of these issues into practical assessments which can be performed on assets in service.

Wet Insulation Systems: many cable systems connecting offshore renewables to the grid comprise sections which are either a semi-wet, or fully wet design. Although accelerated testing has been conducted as part of type approval, the stresses imposed by short term tests may be very different to those seen in long-term operation.

Multifactor Fatigue in Offshore Cables: systems installed offshore are subject to different electrical, thermal and mechanical stresses to those on land. This class of cable is relatively new, particularly in industries such as offshore wind. Further research will be required to determine how these systems respond to such stresses over the course of decades, and also to determine appropriate life expectancies. This may become of great importance if wind farms are re-powered, or turbine life proves to be longer than expected.

All of these factors lead us towards the need to improve the way in which we capture in service knowledge about cable behaviour.

8.2 The Grid as a Source of Ageing Data

Testing conducted at laboratory scale has evolved to be as representative as is economically practical, however testing for periods longer than one year is rarely feasible. Developments in sensing and communications hardware mean that it is now possible to obtain a wealth of information from in-service assets. The challenge is to make use of the volume of data that could be generated at grid scale. Traditional analysis methods, as are used for laboratory scale tests, will not be appropriate in dealing with such huge data sets. Great opportunities exist through engaging with Artificial Intelligence and Data Science communities on topics such as:

- Deriving meaning from sparse data sets across multiple, geographically dispersed, assets.
- Automated analysis of high volumes of large data sets
- Identifying linkages between multiple different measurement streams which correlate to, or give warning of, potential failure scenarios.

The tools, knowledge and experience gained can in turn be used to enhance Asset Management decisions, and further develop remaining life models.

Alongside this, information can also be fed back to the design process. This will allow safety margins to be reviewed as the conditions on the network evolve.

8.3 Improved System Design

Embracing the learning available from the grid operational parameters has the potential to improve system design, but research will be required to extract the information held within it. Potential areas of work include:

Thermal Design: through monitoring the actual thermal performance of cable systems in operation, it will be possible to validate thermal design assumptions, potentially delivering cost savings. This is particularly important for cables in harsh thermal environments, for example those that are deeply buried, crossing other cables, or near to other heat sources. Changes to local climates may also lead to “extreme” events occurring more frequently, and it will be necessary to consider carefully at the design stage what conditions could be expected for the life of newly installed cables.

High-Temperature Performance Insulation: recent innovations in insulating materials technology have sought to deliver new dielectrics capable of short term operation at higher temperatures, or which can conduct heat more readily; as circuit loadings become harder to predict, and the impact of a failure more severe, this capability will prove valuable to grid operators. Further research is needed to bring these solutions to market, and to verify that their long-term performance will be sufficient.

9 Improved System Operation

A key research question for system operation is: “how can we decrease outage times in a more stressed grid?” Achieving this will require a number of fundamental innovations:

Fault Localization: the wide spread use of extra long (>100 km) cable circuits is increasing the urgency of finding new mechanisms for fault localization. The most pressing challenges to be addressed are the reduction of uncertainty in initial localization (locating a fault to within 1% of 700 km, for example, adds to the time taken to pin point the fault site and commence repair). A second objective will be to increase localization capability for high impedance faults, reducing the need to resort to "burning" down the fault, potentially removing evidence of the original cause.

Cable as a Smart Component: historically the cable system was designed such that it could not overheat under expected operational conditions. The drive to reduce costs in the offshore renewables sector means that systems must be developed which actively curtail the load on the cable in the rare occasions when extreme generation conditions occur. Achieving this through distributed temperature sensing will require new systems capable of high accuracy measurement over longer distances.

Realizing Value from Surveys: it is necessary to routinely survey subsea cable systems, for example to demonstrate an appropriate depth of burial. Enhanced monitoring using fibre-optic systems could defer more expensive marine surveys, while new techniques could be developed to deliver more information from surveys which are undertaken. For example, pre-installation survey data may contain information about the thermal environment.

Pre-emptive Defect Detection: at the present time techniques such as partial discharge measurement are not capable of locating discharge signatures of remote defects early enough to allow a planned, pre-emptive repair. Research is required to determine whether methods such as acoustic fibre sensing will have the possibility to detect this or not.

10 Conclusions

Insulated power cables play an integral part of modern electric power systems at all voltage levels. Cables are used for a variety of applications including in-station bus ties, underground connections from overhead lines entering substations and complete underground transmission and distribution cable circuits. Underwater cables also play critical connections for a multitude of applications including offshore renewable projects as well as major AC and HVDC interconnection projects.

The Electric Power Industry is continuously evolving. There are new enabling technologies to explore (Fig. 10), new needs for standardization to follow, new strategic orientations to steer, and all these will have consequences in the domain of Power Cables.

CIGRE Study Committee B1 is cooperating with many associations, institutions, interest groups and standardization bodies that have stakes in the field of Insulated Cables, with the aim to pave the way for modern power systems, capable to supply electric energy with high reliability, through economic solution, with the best environmental protection.

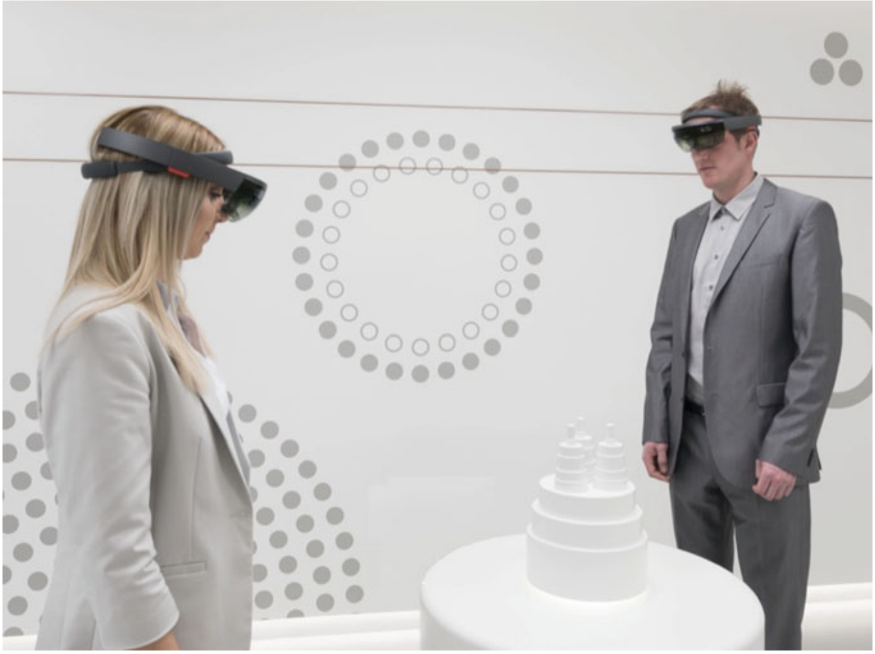


Fig. 10 Use of newer technologies for educational purpose (Courtesy of TenneT)

Acknowledgements Authors thank colleagues from Strategic Advisory Group SAG B1 for their contribution in the review of the Chapter: Pierre Argaut, Ken Barber, Wim Boone, Geir Clasen, Christian Jensen, Pierre Mirabeau, Jon Vail.

Literature

The following documents, reported in chronological order, are widely used in the preparation of the Chapter and include elements to better understand the state-of-art of Insulated Cables and to see the seeds for future developments.

- CIGRE 21.17, TB 194—Construction, laying and installation techniques, October 2001
- CIGRE D1.11, TB228, Service aged insulation—guidelines on managing the ageing process, June 2003
- CIGRE D1.11, TB292, Data Mining techniques and applications the power transmission field, April 2006
- CIGRE B1.10, TB379, Update of service experience of HV underground and submarine cables, April 2009
- CIGRE B1.27, TB 490, Recommendations for Testing of Long AC Submarine Cables with Extruded Insulation for System Voltage above 30 (36)–500 (550) kV, February 2012
- CIGRE B1.32, TB 496 Recommendations for Testing DC Extruded Cable Systems for Power Transmission at a Rated Voltage up to 500 kV, April 2012
- CIGRE B1.11, TB 606—Upgrading and Uprating of existing cable systems, January 2015
- CIGRE B1.40, TB 610—Offshore Generation Cable Connectors, February 2015
- CIGRE B1.43, TB623, Recommendations for Mechanical Testing of Submarine Cables, June 2015
- CIGRE D1.23, TB636, Diagnostics and accelerated life endurance testing of polymeric materials for HVDC application, November 2015

- CIGRE B1.34, TB 669—Mechanical forces in large cross section cables systems, December 2016
- TYNDP 2018 Scenario Report, 2018, ENTSO-E
- TYNDP 2018, Technologies for transmission system, EN TSO-e
- CIGRE B1.55, TB722 Recommendations for Additional Testing for Submarine Cables from 6kV up to 60kV, April 2018
- CIGRE B1.45, TB756 Thermal Monitoring of cable circuits and grid operators use of dynamic rating systems, February 2019.

Earle C. (Rusty) Bascom, III holds B.S. and M.E. degrees in electric power engineering from Rensselaer Polytechnic Institute and an M.B.A. from the University of New York at Albany. He began his career in 1990 working with underground cable systems at Power Technologies, Inc. and, later, Power Delivery Consultants, Inc. before founding Electrical Consulting Engineers, P.C. in 2010 where as President and Principal Engineer he continues to provide engineering services in the analysis, design, specification, installation oversight and operational characteristics of underground and submarine transmission and distribution cable systems. He is a Senior Member of the IEEE, Power & Energy Society, Chair of the Insulated Conductors Committee (2018–2019), member of the Standards Association, a member of CIGRÉ, the US alternate representative to CIGRE B1, TAG and Working Groups B1.35, B1.50, B1.56 and B1.72, and a registered professional engineer in the USA in New York, Florida, Texas, Arizona, Maryland, Delaware, and the District of Columbia. He has authored 60 technical papers and publications and is the holder of one patent. He can be contacted at r.bascom@ec-engineers.com.

Marc Jeroense was born in Middelburg, The Netherlands, on 27 August 1966. He graduated frsom the Hogere Technische School in Vlissingen and studied at Delft University of Technology, faculty of Electrotechnology. He started working for the former NKF (Nederlandse Kabel Fabriek) where he in parallel worked on his Ph.D. on the subject of HVDC cables. He moved to Sweden in 1997 and started working for ABB Corporate Research in Västerås and continued working on cable development, both AC and DC. In 2001, he moved to ABB's cable factory in Karlskrona, Sweden, and had different positions as Product Manager, HV Laboratory manager and Global Head R&D. In 2017, he started working for NKT through the acquisition of ABB's cables business by that company. In 2018, he founded the consultancy company MJ MarCable Consulting AB of which he is CEO and expert. He has been member of CIGRE since 1993 and has taken part in several working groups as specialist and convener under the umbrella of Study Committee B1. In 2018, he received the CIGRE Technical Council Award for his work in that committee and he is a Senior Member of IEEE.

Marco Marelli has a master’s degree in electrical engineering. He developed his career in Prysmian where he is currently Head of System Engineering in the Projects BU, with responsibilities on power and telecommunication cable systems. His expertise covers in particular HV/EHV and submarine cable systems, both AC and DC. He spent indeed more than 20 years doing design and engineering works for large projects worldwide including some of those recognized as milestones in the cable industry. His work within CIGRE as SC B1 Member, Convener of Working Groups and Special Reporter at the General Session has been recognized with the “TC Award” in 2010 and the “Distinguished Member Award” in 2012. He is the author of several papers and he has been part of several technical and scientific committees. Since August 2016, he is the Chairperson of CIGRE Study Committee B1 “Insulated Cables”.

James Pilgrim holds a B.E. in electrical engineering and a Ph.D. in electrical engineering, both awarded from the University of Southampton in the UK. Until 2019 he was an Associate Professor, based within the Tony Davies High Voltage Laboratory at the University of Southampton, leading a range of research projects concerning high-voltage assets. In January 2020 he joined Ørsted as Lead Cable Specialist. He has 12 years’ experience in the field of high-voltage cable systems, specializing in the assessment of current ratings and laboratory testing of cable systems. Within Cigré, he has served as UK member of working groups B1.35, B1.50, B1.56 and B1.64. He has authored in excess of 50 technical papers, is a Senior Member of the IEEE and is involved in standards development through IEC TC20 WG 19.

Roland Dongping Zhang was born in 1974 in China. He received his BA for German Philology in 1997 and the Ph.D. for cable engineering at University Duisburg-Essen in 2009. Afterwards he joined the E.ON Offshore GmbH (former company of TenneT Offshore GmbH) and was responsible for the cable connections of offshore wind farms in the German North Sea. Currently, he works for the Asset Management Germany/System Technology of TenneT TSO GmbH and leads the team that is responsible for engineering, quality assurance, testing, etc., of underground, submarine, DC and AC cables at the TenneT Germany. Since 2016, he has the chair of German National Panel of CIGRE B1 and the membership of Study Committee of CIGRE B1 insulation cables.

Overhead Lines

Herbert Lugschitz, Taku Yamakawa, and Zibby Kieloch

Abstract Existing overhead lines of the transmission grid have been designed to build up a network or to strengthen it—as it was seen at the time of their erection. Due to the liberalization of the electricity market in the last years, the demand for production and consumption of electricity has changed. Also, more and more renewable energy sources (wind, solar, water) need to be integrated into the exiting transmission grid. Overloads of the lines must be prevented. Several ways to overcome these problems exist. Among them are:

- build new lines
- change of components on existing lines (e.g. other conductors with higher current capacity)
- increase the line voltage on existing lines (e.g. from 220 to 380 kV) or change from AC to DC
- application of thermal rating and dynamic line rating on existing lines.

The chapter gives an overview which possibilities to strengthen the OHL grid exist and which approaches can be seen for the future. Other possibilities than OHL exist of course, but this is not the scope of Study Committee B2 "Overhead Lines" and will be covered by other Study Committees. For high voltage, extra high voltage and ultra-high voltage, the big majority of new lines will be overhead and will especially remain the most used technique to transport electric energy over long distances with high capacity. Long-term reliability, long service life, cost efficiency and consideration of environmental aspects are required. Modern approaches, materials, methods and design help to fulfil these requirements.

On behalf of CIGRE Study Committee B2.

H. Lugschitz (✉) · T. Yamakawa · Z. Kieloch
CIGRE, Paris, France
e-mail: Herbert.Lugschitz@cigre.org

T. Yamakawa
e-mail: taku_yamakawa@jpower.co.jp

Z. Kieloch
e-mail: zkieloch@hydro.mb.ca

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_6

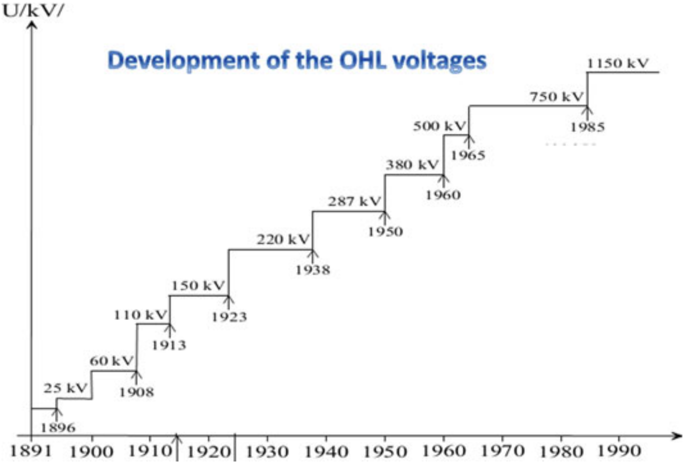
1 Introduction

Overhead lines (OHL) play an important role for the power system of the future and its challenges. They are the oldest and—till today—the most commonly used transmission method worldwide to transport bulk electrical energy over big distances on land. Extra high-voltage lines may exceed a route length of 1000 km for the transport of several 1000 MW per electric circuit in AC or DC, up to voltages of 1.150 kV. The development of OHL voltages over the years is presented in Picture 1.

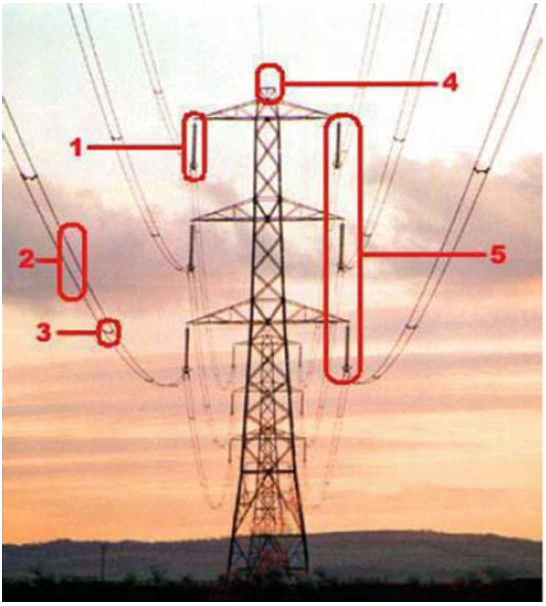
Study Committee B2 deals with overhead lines. The field of activities covers design, construction and operation of, including the mechanical and electrical design of line components (conductors, ground wires, insulators, accessories, supports and their foundations), validation tests, the study of in-service performance, the assessment of the state of line components and elements, maintenance, refurbishment and life extension as well as upgrading and uprating of overhead lines.

The basic methodology to design and build OHL has been established since decades and is improving continuously. Electrical conductors must be insulated from the earth potential and against themselves. OHL use air for insulation. The conductors are fixed by clamps and are mounted on insulators made of porcelain, glass or composite materials. Picture 2 shows a typical transmission tower with two electrical systems (three phases each) and its components.

Existing OHL of the transmission grid have been designed to build up a network or to strengthen it—as it was seen at that time. Due to the liberalization of the electricity market in the last years, the demand for production and consumption of electricity has changed. Also, more and more renewable energy sources need to be integrated into the exiting transmission grid. Overloads of the lines must be prevented. Several ways to overcome these problems exist. Among them are:



Picture 1 Development of OHL voltages, from 1891 to 1990 [1]



(1) Insulator
(2) Phase conductor low-power lines often have a single conductor; higher power lines may use multiple sub-conductors.
(3) Spacer to hold the two sub-conductors apart
(4) Earth wire at the top of the tower or pylon
(5) The three phase conductors on one side of the tower make up one electrical circuit. Most lines have two circuits, one on each side.

Picture 2 Lattice steel tower with two 400 kV electrical circuits (5), Fig. 3.1 from CIGRE publication 338 “Statistics of AC underground cables in power networks”. *Remark: typical thermal capacity with two subconductors aluminium 800 mm*^{2} *app. 2 × 1500 MVA, with 3 subconductors app 2 × 2250 MVA*

- build new lines
- change of components on existing lines (e.g. other conductors with higher current capacity)
- increase the line voltage on existing lines (e.g. from 220 to 380 kV)
- application of thermal rating and dynamic line rating on existing lines

The present chapter gives an overview about achieved methods and approaches for the solutions mentioned above. It strongly refers to publications of CIGRE.

2 State of the Art

The configuration of an OHL follows several preconditions. The principle design parameters are:

- **destination of the line**: (city) feeder, transmission grid, distribution grid, feeder from a power plant, merchant line
- **environment, topography**: urban, rural, flat/hilly/alpine, climate, wind and ice, soil conditions, possibilities for access
- **reliability, lifetime**

- **technical requirements**: ampacity, lifetime, voltage, AC/DC, number of electric circuits, route length
- **standards**: design standards, material standards, limits for EMF, radio interference and audible noise
- **structures, supports**: tower configuration, number of circuits per tower, optimized average span
- **tower material**: lattice steel, tubular steel, concrete, wood, compound
- **conductors**: cross section, number of subconductors per phase, material
- **corrosion protection**: galvanized, coating, wood protection
- **maintenance, repair**: live-line work or not, access to the line, fault finding and repair

2.1 Standardization

International and national standards for the design and operation of OHL are helping with achieving a high degree of design and quality of materials [4].

Regulations and standards prescribe minimum values, e.g. for levels of reliability. Higher levels can become necessary depending on the desired function of the line or on the environment along the route. The decision must be taken for each project separately on a case-by-case basis. Keeping in mind that OHL can live 80 to 120 years—if designed for this period—an estimation of the environmental conditions for this period shall be considered (e.g. for wind, rain, ice). Especially natural disasters in the past may give reasons for reliable line design. It is of course not easy to look into the future. Responsible design should provide margins for these uncertainties, even though cost may increase.

2.2 Environmental Changes

The environment is changing in many countries or regions. Tremendous efforts are being made to estimate the environmental conditions and to minimize negative effects from and on overhead lines. The emphasis put on use of land, visual impact of lines, pollution, energy efficiency, global warming aspects and various hazards (like noise, electromagnetic fields) is continuously increasing. Requirements on minimum environmental impact during the life of the equipment will necessitate life cycle assessment, including recycling of older equipment. Assessment of the impact on the environment has become a necessary part of the investigation done prior to obtaining permissions for new lines, which is for many projects carried out in an environmental impact assessment procedure.

In industrialized countries and in metropolitan areas of developing and developed countries, it is increasingly difficult to get new right-of-way for overhead lines. Asset owners and operators are therefore often tied to existing line routes with increasing need to operate existing facilities closer to the limits, implying use of more sophisticated control, monitoring, and data processing equipment. The pressure for going underground has increased and must be expected to increase more. Underground cables and overhead lines should be seen as complementary rather than alternative solutions to build new links. Both are technical solutions and have their advantages and disadvantages. Each project must be considered on a case-to-case basis.

Other environmental trends of importance are increased emphasis on energy efficiency and use of renewable energy sources, and an increasing intolerance in the society necessitating the use of measures to ensure adequate security of supply.

In many countries exists an increasing demand for strict rules on preserving environment and reducing negative impacts from overhead lines.

OHL can be camouflaged by appropriate coating of towers and even conductors or can be “hidden” if the landscape allows this. Picture 3 shows a “camouflage line” in the Austrian Alps with dark green coated towers and dark green coated conductors.

Picture 3 Two OHL towers with two systems 400 kV each can be seen. Left: galvanized steel tower, clearly visible: right “camouflage line” with dark green coated tower and conductors, nearly invisible [1]

2.3 Changing Social Requirements

Consumers and manufacturers are relying on guaranteed electricity supply. It is more and more difficult to de-energize OHL for maintenance, and the resilience of the electric system needs to be higher and higher. The local communities are claiming for more authority in decision-making related to energy management including development of renewable energy systems, generation–consumption balance, energy mix, considering it may be an attractive strength of their territory. All these reasons lead to asset owners and operators having to get more out of existing lines in terms of life expectancy as well as power transfer.

Many stakeholders will be expecting maximizing utilization of the existing assets to maintain electricity rates at reasonable level. Also, various requirements from not only conventional stakeholders such as inhabitants, but other parties such as system users, are increasing.

Public authorities, regulators, consumers, all these target groups ask the designers of OHL and of electric power systems

- to build OHL which design principles are focused on a very low probability of failures, damages, human accidents and economic disadvantages
- to develop an electric power system which guarantees a high level of continuity of service.

2.4 Audible Noise, Electric and Magnetic Fields, Impact on Other Services

OHL may produce audible noise under unfavourable weather conditions. Methods are available to reduce this (e.g. multiple subconductors, phase arrangement, conductor arrangement and surface treatment) [1].

OHL produce electric and magnetic fields (EMF). Their permissible values are defined in international and national regulations. Impacts on sensitive facilities may come from OHL, from EMF. This can lead to shielding measures or to greater clearances to objects.

3 New Grid Requirements

The changes in the power sector include the unbundling of the generation, transmission and distribution activities, the abolishment of institutional barriers for independent power producers, changes in the financial structure of asset owners and operators and an increased emphasis on competition. Third-party access to the transmission system and the fast installation of wind and solar power plants lead to a more intensive and unplanned use of the system and will enforce an improved power flow control increasing the demand for power transfer of the electric grid. This is happening at the European scale changing flows on EHV grid and at the regional scale changing the flows on the HV grid.

The increasing competition in the energy market is changing the traditional roles in the power industry. The access to grid gives rise to short time horizons for planners as well as situations whereby lines will be operated at the maximum thermal load.

The consequences of environmental events such as wind, floods, fire and ice storms can be more severe than ever before due to the reduced network redundancy. New technologies can help to overcome bottlenecks for a certain period of time. Due to increased opposition against new line projects in many countries, the design process and the authorization phase need more time than before. The shutdown of an OHL for maintenance is harder to achieve than before.

To summarize, the transmission line business has become more challenging; however, new techniques allow for new solutions and approaches to overcome obstacles and objections.

3.1 New Needs of Public, Authorities, Regulators, Consumers

The demands and needs lead to cost-efficient designs involving new design tools and new materials. The design of towers can help to achieve public acceptance (i.e. aesthetically pleasing). Another aspect is the effective management of the existing assets.

The following aspects are often raised from these target groups:

- Are the standards adequate as far as public safety and continuity of service are concerned?
- Are representative climatic data available and are the weather assumptions valid, how can climate change be considered?
- Assessment of the reliability of existing overhead lines. Effect of aged components on the OHL reliability.
- Develop emergency response plans with appropriate manpower, material and equipment resources to address (identified) OHL emergency situations. Improve preparedness.
- Find the optimum balance between the costs of reinforcing (upgrading) OHL to a higher reliability level and the costs of preparedness including restoration actions and revenue lost after possible OHL failure events.

3.2 New Needs of Technical and Asset

From these target groups, the main aspects raised concern maintenance, vegetation management, power transfer capability and other uses of supports

- Diagnosis methods to know precisely the reliability of the line (failure mode and probability)
- Estimation of the remaining life of insulators, supports, foundations, conductors and accessories and how to manage all technical data
- Management of line-related data in information systems (condition of components, maintenance plans, corridor management, etc.)
- Use of geographic information systems (GIS) to integrate environmental, climatic and other data related to the line situation.
- Increase the power transfer capability of existing OHL (e.g. change AC to DC, new conductor materials, high temperature conductors, thermal rating, increase voltage)
- How to manage the risks due to load flow capacity increases in existing overhead lines
- Use of OHL lines for other functions (e.g. for communication data with optical fibres in the ground wire, antennas for mobile data technologies)
- OHL with high transfer capability over very long distances (DC, extra high voltage)
- Reduced life cycle cost.

3.3 New Needs of Operators

The major concern of this target group is the technical performance of OHL in all conditions

- New methods for maintenance (robots, drones, live-line maintenance)
- Right of way management (ecologic right of way management, vegetation, access)
- Line performance under dynamic mechanical loading
- Line reliability under normal and specific climatic conditions.
- In time tracking methods (vegetation control, fire tracking, clearances).

3.4 Future Needs of Science, Education and International Organizations

SC B2 defined the main subjects of concern and research that science and universities can work on. They are:

- information for the update of standards (IEC, CENELEC, national standards, etc.)
- Support the involvement of students and young engineers in work of CIGRE Working Groups
- Get information about new developments in the field of materials and equipment
- Basic research to better understand mechanical and electrical phenomenon affecting OHL.

3.5 Lifetime, Life Cycle

OHL have a lifetime of 80–120 years, if designed for this and if well maintained, though some components may need to be replaced (e.g. conductors and fittings after 40–60 years, corrosion protection 25–45 years). With modern methods, the condition of components and the remaining lifetime can be estimated.

- Lattice steel structures: Maintenance coatings for corrosion protection can be extended if e.g. the "In factory Duplex-system" is applied during the production of the tower. It has been experienced in many countries in the world, that the quality of air has improved (less pollution), which can lead to intervals for maintenance coatings of up to 45 years.
- Transmission tubular metallic poles: Thick layers of coating material can prevent maintenance coatings during the lifetime of the structure. Recently, a promising new method has been presented in Japan for protecting tubular bracings of towers [3].
- Small-size metallic poles can be galvanized and coated which allows in general a lifetime without additional coatings
- Concrete tubular poles live for decades without greater maintenance efforts.
- Composite towers are a new development for transmission lines. Experiences from lower voltage lines lead to expect long-lasting structures
- Wooden poles are used for voltages up to 110 kV. The protection of the wood material is a remarkable effort for maintenance.

Various survey techniques and sensors help with improving life cycle management of assets. A need for better, more accurate methods for managing life cycle of the existing assets is seen. A better knowledge of the condition of existing assets helps to assess their end of life.

4 New Technologies and Materials

System expansion planners and OHL planners are confronted with uncertainties in modern power systems, coming from changed power production, renewable generation, energy storage, shifting political goals, and the continuing difficulty in building new overhead lines, demand, economic preconditions and in addition with uncertainties from future climatic conditions. This unpredictability of power flow and environment means that predictions of normal load and losses over the life of a new line (up to 80 or 120 years if designed, built and maintained for such a lifetime) need to be taken seriously when choosing the main design parameters, e.g. conductor size and number and many others.

Recent advances in new materials and technologies have provided transmission utilities and operators with multiple options for better designs, more efficient operation and maintenance of assets.

Overhead lines offer the possibility of flexible design in a certain range. The motivation for flexible design is that, due to such unpredictable shifts, overhead lines can be adapted to the new situation to gain maximum opportunities. The simplest examples for such flexibility involve, e.g. the use of high temperature conductors, which give the possibility to increase the power flow of existing lines with no or small changes on towers. Conductor phase spacing and bundle designs that allow future increases in AC current. The flexible design of OHL is an important advantage, e.g. to support renewables.

Further improvements of the line utilization may also result from real-time monitoring of the conductor temperature considering the weather conditions prevailing at the time (thermal rating). Another way is to change AC circuits to DC circuits on existing lines, with no or minor changes on the towers. Lines can also be uprated by increasing the voltage.

All such considerations must be made case by case, as not each line can be uprated and measures to increase the ampacity may need no, little, much efforts, or can even be impossible

A large number of topics of concern and/or interest for the future grid can be grouped as follows:

Operation and Maintenance

- Condition assessment and estimating remaining asset life
- Online monitoring
- Maximizing use of existing ROWs while minimizing outages of existing lines
- Methods and tools for diagnostic and maintenance
- Extending transmission line life
- Risk management of OHLs

Design

- Increase capacity and reliability of existing lines
- New materials for use with OHL
- DC line design
- Capacity increase and reduction of active and reactive losses

- Risk assessment of structures and foundations
- Design criteria for ice conditions
- Finding qualified and experienced design staff.

Construction

- Improved assembly and erection of structures
- Work safety, linesmen training
- Live work
- New construction techniques

Weather and Environment

- Weather impacts
- Climate change and atmospheric hazards
- Public acceptance
- Access and environmental constraints
- Environmental impacts
- Overhead lines and underground cables.

OHL can be uprated, uprated and refurbished and their asset can be extended. These expressions are often misunderstood or unclear. CIGRE publication 353 "Guidelines for increased Utilization of existing Overhead Transmission Lines" gives clear definitions [11]:

- **Uprating** is defined as increasing the electrical characteristics of a line due to, for example, a requirement for: higher electrical capacity or larger electrical clearances.
- **Upgrading** is defined as increasing the original mechanical strength and or electrical for increased applied loads such as wind, ice and any load case combination or increasing electrical performance such as pollution or lightning performance.
- **Refurbishment** is defined as being the extensive renovation or repair of an item to restore the intended design working life. Life extension is an option of refurbishment which does not result in the complete restoration of the original design working life.
- **Asset Expansion** is defined as increasing the functionality of transmission lines.

In the following, examples for new materials and new methods are given. The above-mentioned aspects are covered.

4.1 Uprating of Existing Overhead Lines

4.1.1 High Temperature Low-Sag Conductors

CIGRE Technical Brochure TB 763 “Conductors for the Uprating of Existing Overhead Lines” [10] explains the main methods for OHL uprating, among them for: ***Reconductoring with High-Temperature, Low-Sag (HTLS) conductors****—Replacement of the original line conductor with an HTLS conductor, allows a substantial increase in the line rating by going to a higher maximum thermal capacity without changing the structure loads or requiring physical structure modifications to increase clearances.*

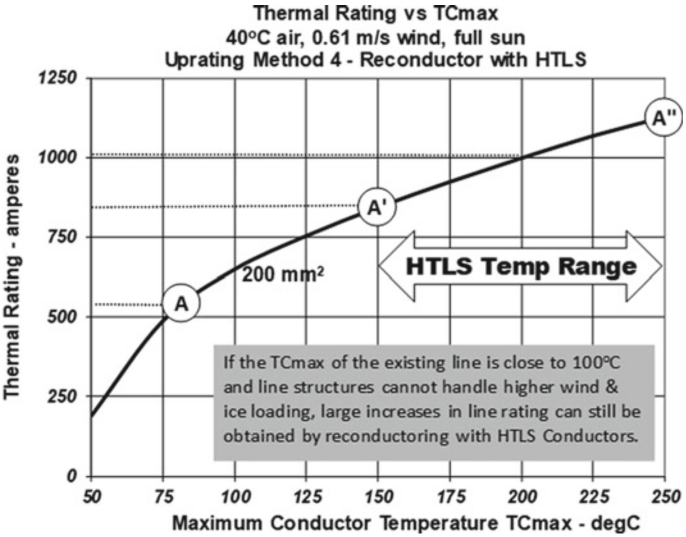
High temperature low-sag conductors (HTLS) are made of special alloys and can be used at temperatures of up to 210 °C. Such conductors can carry more electric current than standard conductors with an allowable temperature of 80–90 °C. The new materials limit the sag and conductor pull to prevent respective minimize adaptions of towers including preventing replacements by higher towers. HTLS conductors are used for reconductoring for the uprating of existing lines as well as for new lines. Different conductor designs are shown in Picture 4.

The new conductors brought a wide range of new types and abbreviations. A not complete overview on conductor types is:

- AAAC All aluminium alloy conductor
- ACSR Aluminium conductor steel reinforced
- TACSR Thermal-resistant aluminium conductor steel reinforced
- G(Z)TACSR Gap-type (Super) thermal-resistant aluminium alloy conductor steel reinforced
- (Z)TACIR (Super) Thermal-resistant aluminium alloy conductor invar reinforced
- ACAR Aluminium conductor alloy reinforced
- ACSS Aluminium conductor steel supported
- ACCC Aluminium conductor composite core
- ACCR Aluminium conductor composite reinforced.

Such conductors can increase the thermal capacity of an OHL remarkably. Depending on the permissible conductor temperature, the increase can be up to

Picture 4 Different types of high temperature low-sag conductors (from left: 3 M, CTC, Lumpi-Berndorf) [1]



Picture 5 Increase of capacity (amperes) depending on the conductor temperature for a certain project [10]

200%. This needs of course the investigation of clearances to ground and obstacles prior to the installation of such conductors. Also, the mechanical loads from the new conductors on the existing towers need to be evaluated. Picture 5 shows an example of the increase of capacity depending on the conductor temperature for a certain project.

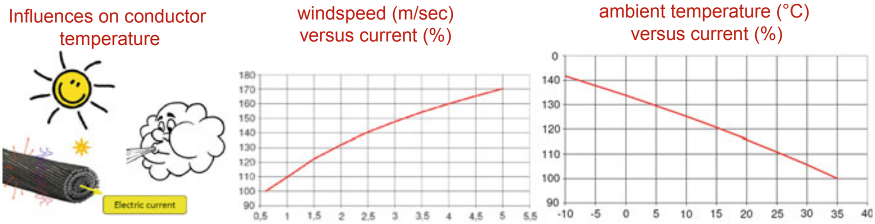
Each project must be investigated on a case-to-case basis. HTS are often "tailor made" for a project. The higher the load, the higher the current, the higher the losses. This must also be considered.

4.1.2 Thermal Rating and Dynamic Line Rating

CIGRE Technical Brochure TB 763 "Conductors for the Uprating of Existing Overhead Lines" [10] explains the main methods for OHL uprating, among them for: ***Dynamic Line Rating****—Line monitors and weather measurement devices can be used to determine the rating of the line in real-time. Such ratings are typically higher than static line ratings but are more complex to implement in system operations.*

Dynamic line rating uses the actual temperature of the conductor and the actual environmental parameters to determine the permissible electric load in order not to violate clearances or other restrictions. The ampacity of an overhead line depends on several factors which need to be considered:

- clearances to ground, buildings, obstacles
- maximum allowable conductor temperature (mechanical aspect)



Picture 6 Principles of thermal rating, high wind and low temperature allow higher permissible current in the conductors

Table 1 Correlation between ambient temperature, wind speed and current capacity

Ambient temperature (°C)	Wind speed (rectangular) (m/s)	Current capacity (%)
30	0.6	100
20	0.6	115
20	2	150

- substations must be prepared for higher current
- load flow considerations of the grid
- legal situation (permission) to run the line with the desired current.

Picture 6 shows the principle: the higher the ambient temperature—the lower the permissible electric load; the higher the windspeed—the higher the permissible electric load. The optimum for a high current capacity of an OHL are cold winter nights (no solar radiation) and wind at high speed perpendicular to the line direction.

Wind blowing on the conductors has a very high influence on the current capacity. Table 1 shows the correlation. The values are examples under optimized conditions, not a general statement.

Several systems for DLR exist, using thermal sensors directly on the conductor, sensors for the conductor pull, or calculating methods from the environmental data and many others.

A recent comparison shows that methods using sensors on the conductors and methods using weather data and historical data correspond very well. One method can confirm the other and eases the decision for the most appropriate approach for a certain application. Paper [2] explains the deviation is approximately 1% only when comparing the two ways of DLR.

Thermal rating and dynamic line rating have become common practice for many TSOs worldwide. The gained additional capacity depends on the actual climatic conditions and cannot be seen as a general approach. Each project must be considered on a case-by-case basis.

4.1.3 Voltage Uprating

Voltage uprating means to increase the operating voltage of an existing OHL to increase its capacity. Necessary measures on structures, insulators and conductors must all be checked for the envisaged purpose and mostly need to be modified more extensively than would be required for thermal uprating. This must be counterbalanced with the costs and the gained additional capacity. The increase of capacity for voltage uprating with unchanged conductors is in the range of 70% when changing from 220 to 380 kV.

The basic voltage design technical considerations are [11]:

- Clearances to ground, to support structures, to over crossings of other power lines, roads and railway lines and clearances to adjacent structures and vegetation;
- Conductor motion and electrical phase-to-phase clearance between conductors
- Clearance between earth wires and conductors
- Insulation requirements for power frequency, switching and lightning surges;
- Clearance for live-line maintenance
- Conductor surface voltage gradient, corona onset voltage and radio interference voltages which are influenced by conductor diameter and conductor bundle diameter
- Audible noise.

With higher voltages, the electric field increases and probability of audible noise will increase, if a certain limit is exceeded. This may lead to the increase of internal phase-to-phase clearances and the installation of additional subconductors or conductors with larger diameters. Additional mechanical loads form wind and ice due to bigger or more conductors must be considered. This all needs to be investigated; see Table 2. In addition, the legal possibilities shall be checked.

4.1.4 Conversion AC to DC

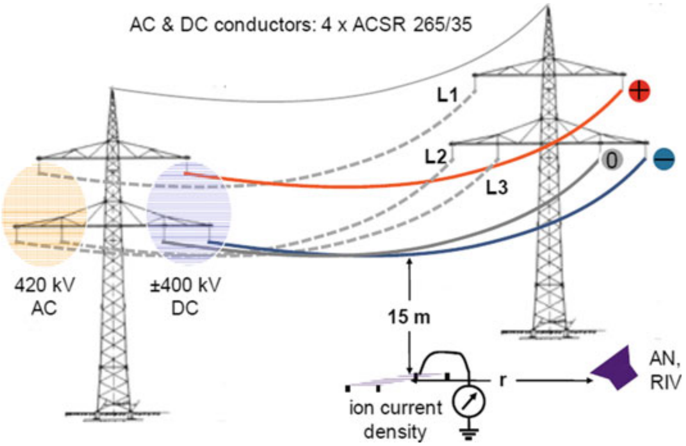
The conversion of an existing AC overhead line to DC can increase its ampacity. The big advantage in general is the better control of the grid with a DC line. The efforts for adaptions on the line, the new built AC/DC- and DC/AC-converter stations at the ends of the line must be counterbalanced with the gained advantages. In general, DC lines are used to transport large quantities of energy over long distances (typically exceeding 600 km) as point-to-point connections. For shorter lengths AC lines are usually more economic.

A pilot project with the so-called hybrid line (one circuit at an existing OHL shall be changed to DC, the other one remains AC) is being constructed in Germany to check technical possibilities and electrical influences. Picture 7 shows the principles of such a line.

Table 2 Influence of parameters for voltage uprating [11]

Parameter		Electric fields	Magnetic fields	Radio interference	Audible noise
Phase to phase distance	↑	↑	↑	↘	↓
Conductor height above ground	↑	↓	↓	↘	↘
Number of sub-conductors (for a given total cross-section)	↑	↑	=	↓	↓
Sub-conductor spacing	↑	↗	=	↗	↗
Total conductor cross-section	↑	↗	=	↘	↘

↑ Strong increase
↗ Slight increase
↓ Strong decrease
↘ Slight decrease
= No significant effect



Picture 7 Line configuration for AC–DC conversion, one system AC, the other one DC (*Source* B2 Session 2013 Auckland, Symposium papers 141, 142) [1]

4.2 New Tower Design

Over the decades of OHL business typical standard tower configurations have been developed and are in use, which are optimized in terms of material, transportation, erection, maintenance, costs and lifetime. Many utilities started considerations for a new tower design to get—or to increase—the acceptance for new OHL. Several towers in alternative design are known from countries all over the world. Most of them are single solutions; some even have the function as eye-catchers. CIGRE publication 416 shows examples. Five of them are in Picture 8 [5].

Only few new designs are suitable as new standard configurations. One of them is being built in The Netherlands where this “wintrack tower” will be erected in hundreds in future. These towers are built as steel poles; two poles are one tower. Other materials, as concrete, were under consideration. Apart from the different visual appearance, the right of way is smaller than with standard towers. Maintenance work needs special tools and facilities. Picture 9 shows a suspension and a tension tower. In the right picture, the transition from a standard lattice steel tension tower to a wintrack tension tower can be seen.

Other examples for new tower design have been installed in Denmark and the UK. Picture 10 presents examples for such double-circuit 400 kV OHL.

The **left** design “eagle” has been built over many kilometres with more than 500 pieces. They consist of tubular steel poles and two crossarms, building the form of

Picture 8 New tower design; from left: Finland, France, USA, Finland, Spain (*Source* CIGRE publication 416)

Picture 9 Wintrack towers in the Netherlands, here as a double-circuit 400 kV line with one system on each pole; left: suspension tower, right: tension tower (*Source* Austrian Power Grid)

Picture 10 New 400kV tower design in Denmark (left) and in UK (right) (*Source* Bystrup architects)

an eagle. An adapted design has lattice steel tower bodies and crossarms, but uses tubes for the bracings.

The **right** design "T-pylon" is based on tubular steel poles and tubular crossarms. The conductors are mounted in the form of a diamond. The towers' height is 35 m above normal ground; this is smaller than standard lattice structures with two or three crossarms. If maintenance work is necessary, it can be done using cranes. The structures are galvanized and coated; it is expected that maintenance coating will become necessary not before 80 years.

It shall be mentioned that the compaction of OHL is a good way to reduce the visibility of the line in the environment. But it is not the solution for every project. Compaction must be considered carefully, as the gained visual advantages may create disadvantages for other aspects. Especially audible noise, electric and magnetic fields must be calculated and calibrated when thinking about compaction.

4.3 New Materials for Structures

New fibre reinforced polymer (FRP) materials show benefits for the electrical utility industry in terms of durability, lightweight, high strength-to-weight ratio, environmentally inert nature, and their electrical non-conductive properties. In the last years, FRP has become more and more common in various industrial applications in aerospace, military, shipping, car, civil engineering and sports gear industries. Such composites can also be used as construction material for OHL structures. First lines in the lower HV range have already been built with such materials [7, 8]. Picture 11 shows examples for such towers.

One of the advantages of FRP is that unlike steel, FRP does not rust or corrode which would be especially beneficial in coastal or industrial areas. There are various resin systems available to the fabricator, which provide long-term resistance to almost every chemical and temperature environment. Properly designed FRP composites

Picture 11 110 kV towers made of composite material. Left: tower in lattice design, right: tower made of tubular poles (*Source* Cigre Working Group B2.61 “Transmission Line Structures with Fibre Reinforced Polymer (FRP) Composites”

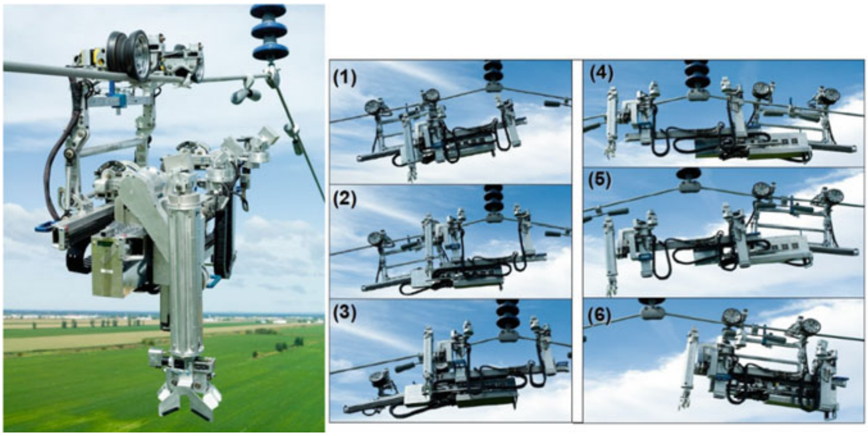
parts have long service life and minimum maintenance as compared to most typical materials used for utility structures.

For LV and MV lines, it is of interest that in comparison with wood poles which can absorb considerable amounts of moisture which affect its electrical conductivity; FRP absorbs less than 1%, so its electrical properties stay relatively consistent. FRP products are resistant to boring by insects and/or woodpeckers. Compared wood treated with preservatives, which cannot be recycled and introduced toxins into the soil, FRP materials exhibit no leaching of chemicals into the environment. The weight of an FRP composite pole is typically 50–70% lesser compared to a wood pole. The low weight reduces transportation costs and enables the use of smaller and lighter vehicles for transportation and installation. At the end of their usable service life, FRP poles can be recycled and used in applications where the initial shape can be used, like fence posts and culverts.

The use of FRP as a material for the manufacture of utility structures is relatively recent. While thoroughly tested, the lack of a long-term use history may be of concern to some prospective users.

4.4 Maintenance with Robots

Robotic in assessment and maintenance of OHL are becoming more and more common at many utilities. Such machines can check conductors and insulators and can climb walls and structures. They assist asset managers in evaluating damages and end of life and are a valuable tool to evaluate damages [6].



Picture 12 LineScout Robot from Hydro-Québec; the robot is designed for live-line work up to 765 kV and can manage obstacles as suspension clamps (left: picture courtesy of Hydro-Québec; right: Pouliot et al. (2009), © 2009 IEEE) [6]

Four robot classifications can principally be identified:

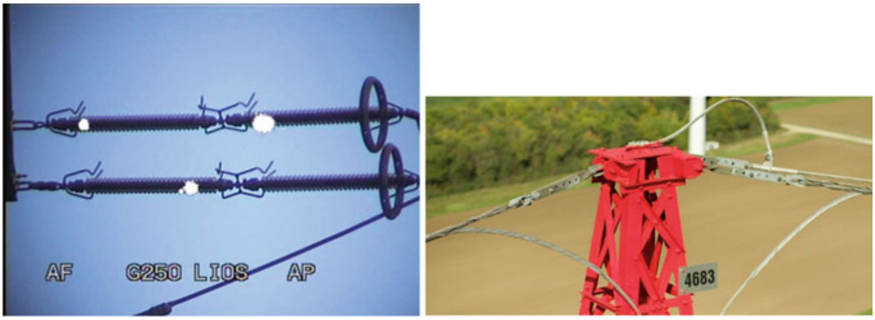
4.4.1 Line-Suspended Robots

They are designed to serve as the extended eyes and arms of the transmission lineman. Their basic design function is to perform visual inspection of transmission lines that cross difficult areas, such as large rivers or mountainous areas. Also, they may detect and locate corrosion pits and locate broken steel core wires of conductors, measure the remaining cross section of such steel wires as well as temporary repair of components.

Such robots are able to travel over the live or ground conductor of OHL, and many of them are able to pass through or cross over different obstacles (clamps, spacers, etc.); see Picture 12. Line-suspended robots are also used to remove ice from conductors in order to release mechanical stress from OHL under severe winter conditions.

4.4.2 Unmanned Aerial Vehicles (UAV)

These are helicopters with trained personnel to capture information for an intended purpose. They give clear images and unique inspection view when they fly close to the transmission lines. In addition to normal images, pictures in the infrared (IR) and ultraviolet (UV) spectrum can be taken. IR images are taken from insulators and conductors. Hot spots due to pollution on the insulator surface or weak connectors on the conductors can be detected (see Picture 13). UV images will reveal corona



Picture 13 Left: corona discharges due to heavy pollution on insulators, detected from an UAV (overlaid UV and visible recording) [6], right: check of earth wire connections

discharges which can originate from damaged conductor strands or from mechanical damage to the insulators.

The technical development for this application is fast and very promising for the future. Such robots have achieved autonomous operation and can wirelessly transmit images and other information to ground. In some countries, before using a UAV, a flight plan approval is required by the authorities. Unmanned aerial vehicles (UAV, multicopter, drones) assist with inspections of OHL also with emergency inspection. Battery life and how to translate images into useful reports need special attention. UAV can be classified as fixed-wing aircraft, helicopter, multicopter (Picture 14). The operating range of these systems varies much in the range of some hundred meters (multicopter) up to autonomous operating time between 1 and 2 h (helicopters). The load they can carry is between some kilos for multicopters and fixed wing aircrafts, and up to 100 kg for helicopters.

Laser scanning of overhead lines is another typical field of application for UAVs. Mostly LIDAR technology is used, for the actualization of existing line documentation, vegetation control in the right-of-way, line routing for new OHL projects, and many others.

Picture 14 Unmanned aerial vehicles for inspection of OHL. Left: Fixed-wing aircraft, middle: multicopter, right: ground system vehicle for helicopter [6]

Picture 15 138 kV double dead-end structure replacement utilizing the LineMaster™—Chicago, IL. © Quanta Services [6]

4.4.3 Ground-Based Robots

Such robots are designed to remotely capture and control energized conductors and execute tasks that are far beyond human capability from a mechanical and electrical stress perspective. This technology has been used for more than 15 years and can be used for line structure repair and replacement, insulator replacement, etc. A big advantage is the reduction of time needed and live-line work; see Picture 15.

4.4.4 Other Types of Robots

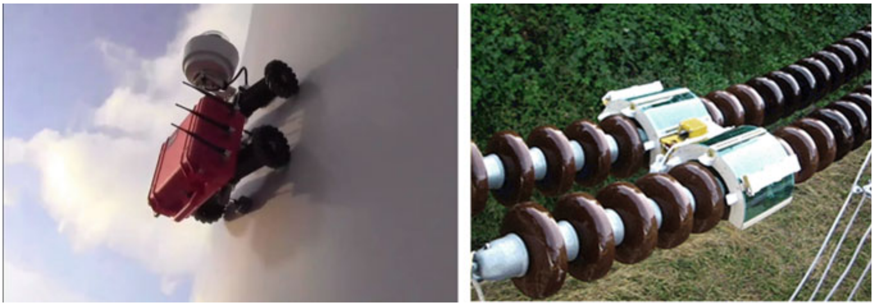
For inspection and maintenance of OHLs, there are still some components that remain mostly off-limits to robots. Towers, insulators, and jumpers may require the use of specialized robots for inspection and maintenance. Therefore, other types of robots have been developed for less-conventional works, such as tower/pole climbing, insulator inspection, and insulator cleaning (Picture 16).

Robots can install and remove aircraft warning spheres mounted on ground wires, provided they are designed for being mounted respective being replaced by robots. The presence of aircraft warning devices is also a problem when conductors or earth wires shall be replaced, as the conductors cannot be pulled out due to the spheres.

4.4.5 Future Vision for the Use of Robots

It is expected that the use of robots will increase. From today's point of view, the following drivers provide the motivation to meet this future vision:

- Safety of both workers and the public

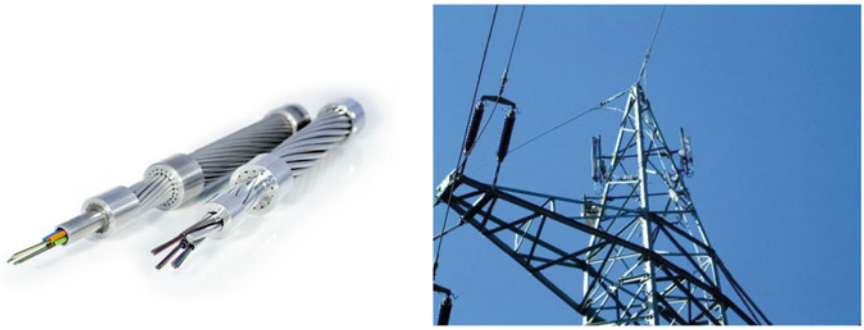


Picture 16 Left: Metallic surface climbing robot from helical robotics; right: live-line insulator cleaning robot (Korea Electric Power Research Institute) [6]

- Effective use of capital and maintenance budgets
- High level of reliability for the transmission system
- Environmental and societal responsibility
- Resilience.

4.5 Asset Expansion of OHL

A typical asset expansion is the use OHLs for telecommunication purposes. Many OHL carry earth wires with integrated optical fibres "Optical Ground Wires—OPGW", and even conductors with fibres have been installed (Picture 17). Such lines can take hundreds of fibres and help to strengthen public and private information grids, together with land cables and radio links. For the same purposes, many OHL towers are equipped with antennas, receivers and amplifiers for telecommunication (Picture 17). With new Internet systems, e.g. 5G, the number of installations of



Picture 17 Left: ground wires of different types with integrated optical fibres (source Lumpi-Berndorf), right: telecommunication antennas mounted on an OHL tower (Austrian Power Grid)

such facilities will increase. Telecom providers in general appreciate the possibilities to use OHL towers for their antennas, and in many countries regulations exist that grid owners have to allow such installations on their structures.

4.6 New Overhead Lines

To build new lines is one of the possibilities to overcome the needs to strengthen the grid. For high voltage, extra-high voltage and ultra-high voltage, the big majority of new lines will be overhead and will especially remain the most used technique to transport electric energy over long distances with high capacity.

The design of new OHL considers all of the relevant aspects which have been explained in the chapters above and combinations of these if appropriate. Good experience exists with this approach. Which method or decision is the optimum for a project must be investigated on a case-by-case basis. General statements cannot be given and make no sense.

5 Conclusions

There is an increasing demand of new lines in many countries. This concerns the replacement of existing lines, the erection of new lines and the increase of the capacity of existing lines. The big majority of those lines will be overhead lines (HV, EHV and UHV).

It is increasing difficult to build and maintain highly reliable overhead lines while keeping cost for the lines low. It is also difficult to provide highly reliable supply of power while optimizing available resources (financial and manpower).

The development of new, advanced technologies and materials in designing and maintaining overhead lines can help to keep the chosen risk level in design and maintenance while keeping reliability level high.

Long-term reliability, long service life, cost efficiency and consideration of environmental aspects are required. Modern approaches, materials, methods and design help to fulfil these requirements.

References

1. Green Book: Overhead Lines, CIGRE (2016)
2. Nementh, B., Göcsei, G., Szabo, D., Racz, L.: Comparison of physical and analytical methods for DLR calculations. In: Paper 023 (7-1) CIGRE-IEC Conference, Hakodate, Japan (2019)
3. Tsujinaka R.: Tower coating method with zinc plating and epoxy resin powder painting in Japan. CIGRE Session Paris, SC C3, Proceedings PS3 Q3.5 (2018)

4. European Standard EN 50341: Overhead electrical lines exceeding AC 1 kV—Part 1: General requirements—Common specifications“ and National Normative Annexes NNA, CENELEC (2012)
5. CIGRE publication 416: Innovative solutions for overhead line support (2010)
6. CIGRE publication 731: The use of robotic in assessment and maintenance of OHL (2018)
7. CIGRE colloquium: Seoul, South Korea, September 2017
8. WG B2.61: Transmission Line Structures with Fibre Reinforced Polymer (FRP) Composites
9. CIGRE publication 498: Guide for Application of Direct Real-Time Monitoring Systems (2012)
10. CIGRE publication 763: Conductors for the Uprating of Existing Overhead Lines (2019)
11. CIGRE publication 353: Guidelines for increased Utilization of existing Overhead Transmission Lines (2008)

Other Relevant Publications by CIGRE

12. CIGRE publication 141: Refurbishment and upgrading of foundations (1999)
13. CIGRE publication 147: High voltage overhead lines. Environmental concerns, procedures, impacts and mitigations (1999)
14. CIGRE publication 179: Guidelines for field measurement of ice loadings on overhead power line conductors (2001)
15. CIGRE publication 216: Joints on transmission line conductors: field testing and replacement criteria (2002)
16. CIGRE publication 244: Conductors for the uprating of overhead lines (2004)
17. CIGRE publication 256: Current Practices regarding frequencies and magnitude of high intensity winds (2004)
18. CIGRE publication 274: Consultation models for overhead line projects (2005)
19. CIGRE publication 278: The influence of line configuration on environment impacts of electrical origin (2005)
20. CIGRE publication 291: Guidelines for Meteorological Icing Models, Statistical Methods and Topographical Effects (2006)
21. CIGRE publication 299: Guide for the selection of weather parameters for bare overhead conductor ratings (2006)
22. CIGRE publication 294: How overhead lines are redesigned for uprating/upgrading - Analysis of the replies to the questionnaire (2006)
23. CIGRE publication 306: Guide for the Assessment of old Cap and Pin and Long-Rod Transmission Line Insulators Made of Porcelain or Glass: What to and When to Replace (2006)
24. CIGRE publication 331: Considerations Relating to the Use of High Temperature Conductors (2007)
25. CIGRE publication 332: Fatigue Endurance Capability of Conductor/Clamp Systems—Update of Present Knowledge (2007)
26. CIGRE publication 344: Big Storm Events—What We Have Learned (2008)
27. CIGRE publication 350: How Overhead Lines (OHL) Respond to Localized High Intensity Winds—Basic Understanding (2008)
28. CIGRE publication 385: Management of Risks due to Load-Flow Increases in Transmission OHL (2009)
29. CIGRE publication 388 B2/B4/C1: Impacts of HVDC Lines on the Economics of HVDC Projects (2009)
30. CIGRE publication 410: Local Wind Speed-Up on Overhead Lines for Specific Terrain Features (2010)
31. CIGRE publication 425: Increasing Capacity of Overhead Transmission Lines (2010)

32. CIGRE publication 426: Guide for Qualifying High Temperature Conductors for Use on Overhead Transmission Lines (2010)
33. CIGRE publication 429: Engineering Guidelines Relating to Fatigue Endurance Capability of Conductor/Clamp Systems (2010)
34. CIGRE publication 438: Systems for Prediction and Monitoring of Ice Shedding, Anti-icing and De-icing for Power Line Conductors and Ground Wires (2010)
35. CIGRE publication 471: Working Safely While Supported on Aged Overhead Conductors (2011)
36. CIGRE publication 477: Evaluation of Aged Fittings (2011)
37. CIGRE publication 485: Overhead Line Design Guidelines for Mitigation of Severe Wind Storm Damage (2012)
38. CIGRE publication 561: Live Work—Management Perspective (2013)
39. CIGRE publication 545: Assessment of In-Service Composite Insulators by Using Diagnostic Tools (2013)
40. CIGRE publication 583: Guide to the Conversion of Existing AC Lines to DC Operation (2014)
41. CIGRE publication 598: Guidelines for the Management of Risk Associated with Severe Climatic Events and Climate Change on OHL (2014)
42. CIGRE publication 601: Guide for Thermal Rating Calculations of Overhead Lines (2014)
43. CIGRE publication 631: Coatings for Protecting Overhead Power Network Equipment in Winter Conditions (2015)
44. CIGRE publication 643: Guide to the Operation of Conventional Conductor Systems Above 100 °C (2015)
45. CIGRE publication 645: Meteorological Data for Assessing Climatic Loads on Overhead Lines (2015)
46. CIGRE publication 695: Experience with the Mechanical Performance of Non-conventional Conductors (2017)
47. CIGRE publication 708: Guide on Repair of Conductors and Conductor-Fitting Systems (2017)
48. CIGRE publication 744: Management Guidelines for Balancing In-house and Outsourced Overhead Transmission Line Technical Expertise (2018)
49. CIGRE publication 746: Design, Deployment and Maintenance of Optical Cables Associated to Overhead HV Transmission Lines, JWG D2-B2.39 (2018)
50. CIGRE publication 748: Environmental Issues of High Voltage Transmission Lines for Rural and Urban Areas, JWG C3-B1-B2 (2018)
51. CIGRE publication 767: Vegetation fire Characteristics and Potential Impacts on Overhead Line Performance (2019)
52. GB CIGRE Green Book Nr 4: Technical Brochure, The Modelling of Conductor Vibrations (2018)

Relevant active Working Groups of SC B2

53. WG B2.60: Affordable Overhead Transmission Lines for Sub-Saharan Countries”
54. WG B2.64: Inspection and Testing of Equipment and Training for Live-Line Work on Overhead Lines
55. WG: B2.69: Coatings for Power Network Equipment
56. WG B2.74: Use of Unmanned Aerial Vehicles (UAVs) for Assistance with Inspection of Overhead Power Lines
57. WG B2.59: Forecasting Dynamic Line Ratings
58. WG B2.62: Compact HVDC Overhead Lines.”
59. WG B2.63: Compact AC Overhead Lines
60. WG B2.61: Transmission Line Structures with Fibre Reinforced Polymer (FRP) Composites

61. WG B2.65: Detection, Prevention and Repair of Sub surface Corrosion in Overhead Line Supports, Anchors and Foundations
62. WG B2.67: Assessment and Testing of Wood and Alternative Material Type Poles
63. WG B2.66: Safe Handling and Installation Guide for High Temperature Low-sag (HTLS) Conductors
64. WG B2.68: Sustainability of OHL Conductors and Fittings—Conductor Condition Assessment and Life Extension

Lugschitz born 1954 in Vienna, has been working in the field of overhead lines (OHL) for more than 40 years. This covers the complete overhead line business, including technical planning, tower design, calculation and erection of OHL, authorization procedures (Environmental Impact Assessments), alternative tower design and public relations activities. He has been employed as Senior Officer in Asset Management at Austrian Power Grid (APG). In this period, he also participated as technical expert for OHL projects in Africa and Asia for the African Development Bank, European Development Bank, Gesellschaft für Technische Zusammenarbeit GTZ, and UNIDO. He was member in several CIGRE Working Groups of Study Committee SC B2 "Overhead Lines" since the 1980s and was Austrian delegate in B2 from 2004 till 2014 (observer and member). He is chairman of B2 from 2016, and will continue in this function till 2022. He has several functions in standardization bodies. Among them he is Austrian delegate at CENELEC for the establishment of the European Standard EN 50341 "Overhead electrical lines exceeding 1 kV AC" and is chairman of the Technical Committee "Overhead Lines and Embedding of Power Cables" of Austrian Electrotechnical Association—OVE. He was chairman of Association of Austrian Electricity Companies "Österreichs Energie"—section "Grid Matters" for many years.

Yamakawa born in 1963 in Osaka, has been working on design, construction, maintenance of EHV overhead and underground transmission lines since 1985. He has been engaged in maintenance of AC 500 kV overhead and underground transmission lines as the Chief Electrical Engineer. And he has also been engaged in construction of AC 500 kV overhead line as the director of the construction office and as the Chief Electrical Engineer. He is employed as Department Director in Transmission System & Telecommunications Dept at Electric Power Development Co., Ltd.—J-POWER. He was the member of Japanese Domestic Committee of CIGRE Study Committee B2 "Overhead Lines" from 2005 till 2008, and he is the acting chairman since 2015. And he is Japanese delegate in SC B2 since 2016, and he is the member in Customer Advisory Group (CAG) and Strategic Advisory Group (SAG) of SC B2. He has actively participated in the national technical research committees of IEEJ (The Institute of Electrical Engineers of Japan) regarding overhead transmission line. He was the chairman of the technical committee “Recent technology trend of overhead transmission line conductors and fittings” on IEEJ. And he has several functions in standardization bodies in Japan.

Zibby Kieloch has M.Sc., in civil engineering from Warsaw University of Technology. He has been designing overhead transmission lines at voltages up to 500 kV at Manitoba Hydro, Canada for over 25 years. Most recently, he is responsible for one of the largest HVDC projects in North America—Bipole III Transmission Line Project. He has been a CIGRE member and the Canadian Representative on the Study Committee B2 since 2005, making contributions to a number of Working Groups. Since 2012, he has been the Convenor of the SC B2 Customer Advisory Group. He is also an active member of the Canadian Standards Association technical committees responsible for overhead line design and conductor design standards.

Substations and Electrical Installations

Mark Osborne and Koji Kawakita

1 Introduction

1.1 Objectives

This chapter will focus on how changes in the energy landscape will challenge the design and asset management strategy of future substations and electrical installations. Whilst there seems to be a strong future role for electricity, it is important to understand the effect that some of these issues will have now, since substations are enduring facilities that must be resilient to the interim changes from political and economic short-term decisions.

The scope of the chapter includes the substation, collective infrastructure and auxiliary systems which serve to provide a resilient electricity network and the means to safely and securely access a sustainable power system.

The active technology employed within the substation boundary (e.g. transmission and distribution equipment (SCA3), power transformers and reactors (SCA2), DC systems and power electronics (SCB4), protection and automation (SCB5) and information systems and telecommunication (SC D2) will be covered in the relevant Study Committee chapters.

The text will focus on how the following external drivers and the development of the network of the future will impact substations:

- Societal interactions and expectations.
- Environmental and sustainability pressures.
- External technical challenges from the technology connecting to the grid.
- Emerging technologies and applications.

On behalf of CIGRE Study Committee B3.

M. Osborne · K. Kawakita (✉)
CIGRE, Paris, France
e-mail: koji.kawakita@cigre.org

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_7

- Asset and risk Management.

The substation can be defined as critical infrastructure, central to delivering secure essential energy services to the nation. This chapter will consider some of the new functions the substation may need to accommodate in its role as a hub for energy e.g. distributed SmartGrid services, such as control functions, secure communication, data coordination and synchronised timing.

1.2 Background

Substations and similar electrical installations are essentially a portal to the electricity network. This access point enables both generation and demand to connect and utilise the benefits of being connected to a wider more resilient network. This is also the point where the system operator can observe and control the system, whilst the utility can intervene with assets to maintain reliability and availability of the network.

During the 1960s and 1970s the electricity transmission grids rapidly expanded, based on a clear design intent. They were conceived for bulk power transmission, which took power from a relatively few large generating sites and delivered it through decreasing transmission and distribution voltages to distant load centres. Prior to this, power systems were local to thier need, typically with local generation to meet this demand as it grew.

Most countries had state-owned companies with responsibility for the overall architecture of the design, operation and management of the whole power system. Over the subsequent decades, very significant changes have occurred which have altered the structure of utilities, but also affected the regulatory regimes and operating conditions, which can impose differing stresses upon the increasingly ageing assets.

The first major change to occur involved separating generation and transmission components, and then (in some countries) converting the companies to privatised and regulated entities. Changes such as these were intended to produce open generation markets with international power grids facilitating cross-border competition. The intention was to yield cost efficiencies. It involved converting some utilities from service providers into businesses focused on yielding stakeholder value. These moves led to major changes in substation management practice and have provided the framework for dealing with the more recent change.

The second and much more radical change followed a greater political focus on reducing environmental impacts and their consequences. Just like the climate, substations will experience more volatility as the networks become less predictable and will need to become more responsive to change. As a consequence of these upheavals, those original assets now have to operate in changed and evolving networks. This clearly has an impact on the management of lifetime care given to these assets. Optimal performance will continue to be wanted from the delivery of electrical power. It will require the correct and adequate infrastructure in place to deliver these changes.

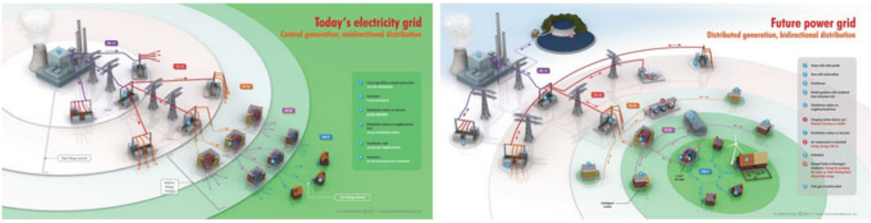


Fig. 1 View of the electricity grid and substations as used today and in the future

A major risk will be the disruption to society caused by loss of load events following an in-service failure of major assets.

This is covered much more extensively in Technical brochure 764 [1] ‘The expected impact on substation management from Future Grids’ produced by Working Group B3.34 which reviews the impact, particularly on existing substations with ageing assets and their traditional ways of working. The Technical Brochure describes how these changes may impact upon the management of assets, intervention strategies and resource challenges. An important facilitator has been the growth of data collection, transmittal and use in the last decades (Fig. 1).

The changing needs of society have been one of the key factors in determining the ongoing need for substations; however, it is not the only driver and some of the relevant issues will be discussed here. Most of the change and innovation in substations is a consequence of developments in other industries, which have been adopted slowly from their relevant sectors, e.g. power inverters, robotics, digitalisation, etc.

There will always be a mix of old and new technologies at any one time in a network [2]. It is not unreasonable to expect existing infrastructure to be utilised and operated well beyond its original design life if no major problems or risk present themselves.

Whilst it is difficult to see a future where the substation is not central to the delivery of power;

- At the primary equipment level, the changes will be slower, plant will always need to be either installed or replaced. It will need to be monitored and if necessary maintained and then subsequently recommissioned back into service. This is difficult without a substation or similar electrical installation of some sort to safely deliver this function, without having to switch out major parts of the power system.
- On the secondary system level, data and change management is going to be an increasing factor in the control of network security, especially from the cyber perspective. Invariably where software and firmware are installed on devices, a secure and robust process is necessary for version control and any legitimate updates or patches, where controls are needed to ensure both external and internal threats such as malware are repelled.

New technology is normally held back by the need to ‘interface or integrate’ it into the legacy systems. This requires significant engineering resource and usually limits the capability of both the old and new technologies. One option, may be to work out how to ‘overlay’ different vintage technologies, and this would also help to reduce the introduction of single-mode failure risks.

The role of the substation is likely to expand in the coming decades to adapt to more sustainable and renewable energy sources in addition to the growing move towards electrification of heat and transportation. The substation sits at the heart of the sustainability agenda, enabling electrification for all, in particular developing regions of the world, currently with limited access to reliable energy supplies. It will also be central to the successful delivery of concepts like electric vehicles and energy storage which will change the way we think about and use power systems.

1.3 Evolution of Substations to Date

In the 1996 CIGRE Paris session, a paper was published [3] entitled ‘The Future Substation: A Reflective Approach’ (23–207) on behalf of the Substation Study Committee. The position paper provided an assessment of the substation community’s thinking at the time on issues which would challenge substation design and operation in the future. It refined the decision-making criteria down to four elements;

- Functionality—what is necessary?
- Technology—what is feasible?
- Economics—what is affordable?
- Environment—what is acceptable?

The role of the substation is an enduring one, but it will need to adapt in response to many changes. These include the external impact of new generation patterns coming about from renewables and demand-side management making the network more complex, this subject was tackled in [4] the Technical Brochure 380 ‘Impact of new functionalities on Substation design’. Changing aspects of society and stakeholder expectations will also be influential in the need case for new substations. The economics associated with new build especially where space is limited will influence the choice of technology. The uptake of optimised configurations is anticipated based on improved availability and faster replacement rather than duplication.

The capability and performance of modern equipment will influence the configuration and operational philosophy employed in new substations. Better reliability and increasing automation along with new methods of monitoring and asset management may prioritise design away from routine maintainability to risk and reliability focused intervention.

1.4 Looking Ahead

The issues back in 1996 are still very relevant, however, there have been some additional changes since then which may reprioritise the thinking. As we look towards 2050 from a substation design and operation perspective, utilities need to adopt philosophies which consider the following scenarios:

- Climate change—rising temperatures, rising sea level and increasing occurrence of extreme weather conditions will affect the substation physical environment.
- The impact of substation and energy infrastructure on the environment—the road to Net Zero by 2050.
- Increasing role of external ‘stakeholders’ in decision-making that will affect the substation lifetime.
- Existing substation assets will be driven harder and under different network conditions from those perceived decades ago when they were specified, manufactured and tested.
- Accommodating the role of energy storage in the balancing of society’s energy needs.
- Extreme operating environments offshore, possibly submarine and in time outer space.

2 Changing Societal Requirements

The substation is the key interface between the power system, customers and consumers. There is a growing community of stakeholders who have some element of interest with the substation, whether as a user of the service it provides, or a provider of a service to the substation, the system operator, local communities adjacent to the facility or the manufacturers who supply equipment.

The United Nations proclaimed in 2012 the ‘International Year of Sustainable Energy for All’ and set 2030 as the target for universal access to modern energy services [5]. In addition, electrification has been voted by the US National Academy of Engineering survey as one of the’ Greatest Engineering Achievements of the twentieth Century’ [5] There are several obstacles to electrification including low demand, low load density, unaffordability by customers, poor infrastructure, high cost to develop infrastructure, political instability and economic risks such as assuring an adequate rate of return.

There are several likely solutions to the obstacles which include the design of low-cost substations as well as making the processes for the supply and installation of these adaptable to specific local circumstances. Furthermore, infrastructure development through private investment participation, technical support by professional organisations and delivery of scalable national development initiatives are required to meet ambitious targets to electrify all people by 2030. In response to this, CIGRE

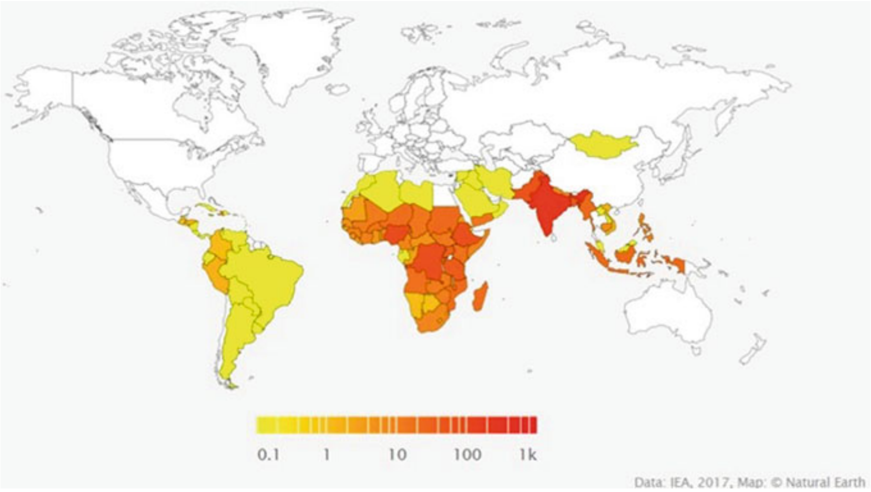


Fig. 2 Population without access to electricity, 2016 (millions)

Study Committee B3 published a [5] Technical Brochure 740 '*Contemporary solutions for low-cost substations*' to document guidance for the design of cost-effective and fit-for-purpose substations to provide electricity to those needing that basic service in developing countries, as well as remote locations in these countries. Specific focus upon sub-Saharan Africa was identified due to the significantly higher gap in electrification in this community (Fig. 2).

Addressing world energy poverty in coordination with the shift towards more renewable sources of generation such as hydro, solar and wind may coincide with common substation infrastructure development, and reducing energy poverty in Africa would be a good example.

The following list highlights some of the key issues which affect the longer-term stakeholder relationship with substations:

- Globalisation—the sourcing of plant, equipment and services.
- Increasing reliance on electricity—this indicates a growing demand on existing substations and need for many more facilities to support the myriad of new services and customers needing to connect to the grid.
- Distributed services—the decentralisation of services, this will apply to control and network access, but fundamentally will necessitate that the substation in some guise will be central to achieving a safe and secure system
- Digitalisation—the move away from human intervention and the ability to be plug and play such that devices are self-configuring.
- Autonomy—the increasing role for self-supervisory systems and self-configuring networks, this will necessitate secure links to the control functions.

Globalisation across the manufacturing sector; these bodies develop the technology and determine the direction of new ideas, especially where new networks are evolving. The development of standard or modular solutions will make the ability to roll out a cost effective project more feasible, however the following issues need to be considered. These suppliers are also developing a 'service provider' function to provide end-to-end solution management. Communication and coordination skills between the different projects are vital to the successful delivery of a substation and the adjacent infrastructure. Fundamentally, high quality engineering skills are becoming a relatively rare commodity, so the development of robust flexible solutions is necessary. Another key area to consider and get right is the procurement strategy which delivers a fit-for-purpose solution and contracts and warranty to support the substation both during construction and during service with regard to product support for issues like cyber resilience, equipment interfacing and compatibility, particularly for substation extensions.

The design and operation of the substation will increasingly need to cater for the change in the expectations of new engineers and dedicated expertise and career lifetimes. The challenge will be to balance between commercial and technical skills—the quality and detail in a specification will help to make this more achievable.

Provision of a service—other sectors, such as telecoms, have separated the link between assets and the output. The challenge for substations is the capital cost required to construct/replace when the income is based on capacity and security of a large entity such as a network, rather than return-on-equity for the asset capital value.

Understanding the total cost of ownership and timing of new concepts in a heavily regulated market. Security—Managing cybersecurity across the power grid. The substation is the key access point, so much effort and investment required to secure these sites from external as well as internal threats.

There is a question around, whether the energy industry is no longer the trusted development partner but is often seen by society as resistant to change and holding back on development.

2.1 Regulation

Regulation and Competitive Markets will require utilities to optimise their delivery costs to provide reliable infrastructure and the ongoing support services to maintain and operate the assets. This may work for a predictable environment, where many of the decisions are based on long financial lives rather than the useful asset life. It will be necessary to consider how existing assets feature in delivering the future requirements and how this can be incentivised through regulation.

The traditional concept of utility regulation is very likely to change in the coming decades. There is a move from the concept of regulating the assets based on their worth to one of identifying what services the customer and consumer want from the energy system.

This will require utilities to review how they run their business and be able to demonstrate they are meeting their customers' needs, as well as ensuring assets are safe and reliable and that either shareholders or governments can justify their investments.

3 Sustainability Challenges

There are two aspects to consider, firstly the impact of external environmental changes on the substation and secondly what does the decarbonisation agenda mean for the substation technology, infrastructure and operation.

Ultimately, these changes will need to consider the resultant impact on personnel health and safety whilst operating in or near an HV facility.

3.1 Environmental

As the role and location of substation and electrical facilities grow at an unprecedented scale, the impact of the climate is likely to experience more extremes more frequently. This will become even more of an issue as new territories are explored and facilities developed in deserts, offshore, underwater and ultimately outer space. The challenge with offshore substation is addressed in [6] technical Brochure 483 'Guidlines for the Design & Construction of AC Offshore Substations for wind power plants'. In many respects, this is likely to drive the development of smaller, more compact and robust modular substations, which can be quickly installed, remotely monitored, self-supervising and essentially replace on fail. A dilemma that will increasingly face utilities, will be how to justify the additional costs and resources necessary to ensure their facilities can withstand these increasingly more frequent extreme events. Adopting quick response approaches using more mobile and modular deployment capabilities may help to address these challenges.

3.2 F-Gas Regulations

The matter of substation insulation selection is a key factor in determining the type of technology employed. The possible evolution paths for gas-insulated switchgear (GIS) substation technology will be addressed.

Driven by environmental targets to reduce carbon footprint related with SF6 gas emissions, the industry is developing new SF_6-free equipment. In the EU, the evaluation of the availability of SF_6 alternatives by 2020 according to Art. 23 of Regulation (EU) No. 517/2014 is an important driver behind recent developments. There are two issues to address, one is the use of SF6 for arc quenching purposes in switching devices and the second is the more passive application as an insulator to achieve much smaller electrical clearances typical of gas insulated switchgear (GIS).

With regard to the first challenge, some manufacturers are focusing on replacing SF_6 with new gases. Others are focusing their research on expanding the well-proven vacuum technology which has been already in use for several decades in applications.

The retrofitting of existing equipment with alternative or new gases appears very challenging due to different aspects between manufacturers design. Alternative gases have a lower arc quenching and cooling capability, and interaction with other materials (grease, gaskets…) and cold climate operation is not always guaranteed. The proprietary nature of alternatives is also a limiting factor along with costs and other potential future ‘unknowns’.

In the meantime, there is focus around applications where SF_6 is used as an insulation gas (not an interrupting medium), e.g. back parts, measuring transformers, GIB. Further work is required around the health and safety aspects for the new gasses during gas handling for maintenance and after incident.

Irrespective of whether SF6 is banned or not, it will need to be efficiently managed in electricity substations for a long time. Consider how PCBs in oil are still safely managed in small populations of oil insulated equipment over the past few decades, following the ban on use many years ago.

3.3 Environmental Management

Sustainability is key stand asset management, in particular whole life consideration around the design and equipment used to construct and operate a substation. Substations have been in service for many decades, ever since electricity was generated and required distributing. Over time, issues are discovered with materials and the operating environment which is not safely managed can present a risk to the utility and the public. Firstly, electricity fundamentally requires electromagnetic fields to propagate and at all time it is important to consider the impact of these both in terms of exposure levels to personnel and the public, but also their impact on the equipment installed and operated within the substation facility. As more cyber-related applications appear within the substation, its electromagnetic compatibility (EMC) and sensitivity to adjacent equipment and external generated impulses such as lightning and solar flares should be understood. The hardening of the ‘smartgrid’ requires some consideration especially the aspects around communication systems which are now intrinsic to the success of these systems. The Earth’s resources are a limited commodity and just like every other industry, ours need to be considerate and effectively recycled where possible. This can range from recovering metals, repurposing ceramics or recovering obsolete but still working protection relays to help replenish spares and keep older systems working where possible. There are a few materials still in substations which must be carefully managed, especially if there is a fault and the risk of uncontrolled dispersion occurs. Prime examples are building materials like asbestos in older facilities, PCB oil in older switchgear.

The other factor to consider is social amenity management. Two of the key ostensible risks are substation fires and acoustic noise which can have a significant impact

Fig. 3 Ordinary outdoor versus modern indoor substation

on third-party properties and the public. These can be managed via fundamental choices at the design and specification stage, such as the selection of technology, insulation fluid, civil design or the use of active suppression systems. These factors must be understood at the planning stage where they can be effectively managed, not an afterthought once many of the cost-effective options are no longer available.

Furthermore, as the role for the electricity substation expands, there is a need to make substation infrastructure more acceptable from a visual and social perspective is a driver for future development. We can no longer expect to build the cheap and easy options of AIS in large fields as we once did, albeit this was the state-of-the-art technology at the time. The need to consider the integration of substations into the community and suburbs leads to smaller sizes and architectural additions (Fig. 3). Time is an increasingly scarce and expensive commodity. A proportion of utility cost and risk is due to network constraints in particular securing outages. Therefore, technology, solutions and practices that can reduce the time to complete an activity offer a number of benefits. From the environmental perspective, this manifests itself as quickly deployable solutions or modular designs, which maximise off-site assembly minimising the disruption to the public during construction or network interventions.

3.4 Safety

Incidents and faults will happen, no matter how much care and attention is paid to the design and testing of equipment. The art is to minimise any impact on personnel and the grid overall. Traditionally, resilience has been achieved through equipment redundancy and protection systems to cater for these faults and the associated outages necessary to repair the equipment and return it to service. Better observability and diagnosis, plus the prediction of equipment ‘end of life’ can assist a move towards grids that can sense and heal where it is less resilient or constrained and contingencies can be supplied. The substation will be at the heart of healing the grid, hosting the sensors, switching and intelligence to provide adequate autonomy to operate reliably during adverse weather or force majeure.

It is important to remember that at any one time, a utility will have a broad range of different technologies, so one strategy cannot be applied to everything. A tailored approach to asset intervention will be required.

New substations are generally going to be smaller, more compact and less obtrusive. The concept of ‘fit and forget’ is not unrealistic as the primary and secondary systems are being developed with more self-supervision, remote inspection and autonomy requiring less need for human intervention. This, in turn, reduces the need for staff to be present and therefore the risk of injury to personnel. A key consideration which is not always evident when building a new facility or replacing an old one is the possible need to change or extend the substation in the future. More often than not, financial and regulatory limitations will restrict the ability to build this in where the need is not certain at the time of investment. Furthermore, the configuration, technology choice and operating practices can profoundly affect the ability to achieve this in the future if required. This is important to consider from a safety perspective, in particular considering what basic facilities would be required if the need came about and it needed to be constructed and operated?

Legacy and existing substations will always need to have relevant intervention policies for different genres of technology. However, the use of non-intrusive inspections and monitoring will help to reduce the need for permanent staffing. This is particularly relevant where there is risk from stressed or ageing assets which could be prone to destructive failure and cannot be replaced immediately.

It is always important to consider the application and operating environment any equipment is going to be expected to serve;

- How can this be assembled, installed and commissioned?
- How will ongoing monitoring and maintenance be addressed over the asset lifetime?
- What interventions will be necessary and how can this be achieved?

It is increasingly likely that applications like remote monitoring and robotics will be used to replace the routine inspection activities. These provide a more consistent measure, but will only do what they are programmed to do. (they also need maintaining themselves!). It may be possible to consider safety clearances differently if humans are never going to be expected to enter these spaces.

The Technical Brochure [7] TB 734 Management of Risk in Substations provides more detailed explanations behind many more issues highlighted here.

4 New Grid Requirements Impacting on Substations

This section considers the influence that the change in technologies connecting to the grid and evolving changes system operation behaviour will impose on the functionality of the substation and the equipment there-in.

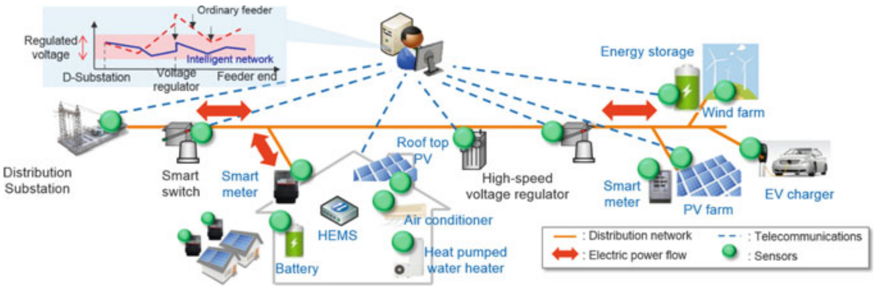


Fig. 4 Evolving challenges in the distribution network

- Expect lots of new smaller Distributed Energy Resources (DER) requiring access to substation facilities.
- Mature grids will need to tend to repurpose and upgrade existing facilities. Lots of new inverter-based technology will be connecting in and near substations.
- Outage management will need to be more flexible as more parties connect to the grid.

A great opportunity for the substation community, as a whole, is the changing role of the distribution sector from a passive demand-based network controlled by the interface to the transmission network. As more dispersed and renewable generation connects into the distribution network, the broader the role becomes for the substation whether Transmission or Distribution, to actively control power flow, regulate voltage and connect new customers like that of the transmission network. Essentially, distribution needs to increasingly adopt transmission philosophies, but on a smaller scale and this begins in the substation (Fig. 4).

4.1 New Functionality

The substation is a concentration of network functionality, and as the power system becomes more complex and integrated, the need for substations grows as they become more important than ever before.

Historically, the role of the substation varies significantly depending on where it is located in the network, however with the changing nature of the grid and more dispersed generation resources, active control will be required at all voltage levels through the network not just at transmission. It is unlikely that only one voltage level will ever become prevalent; therefore, a network hub or substation will continue to be required to;

- Transform from one voltage level to another to minimise energy losses.
- Access the network—for new customers and asset interventions.
- Manage network resilience—provision of redundancy and enhance capacity.

- Manage safety—intelligent reconfiguration to locate and to isolate faults.
- Communication hub for network asset control and monitoring.

The substation will need to adapt to different types of technology, functionality or new services such as;

- Low short-circuit level operation, possibly requiring new type of protection.
- Need for more ancillary network services such as Synchronous compensators (provision of inertia).
- More DC (MV or HV) in the longer term.
- Bi-directional power flows due to Energy storage.

These may have a few small configuration issues for the substation, but these will not significantly affect the substation operation and management, other than that specifically for the new technology. [2] TB 380 'The impact of new functionality on substation design' expands on some of these issues [2].

The key point to address here will be how the change in network parameters affects the response of existing assets, specifically the protection and its sensitivity to lower fault currents and low system inertia contribution. As the electrical characteristics of the network change, short circuit level (SCL), inertia and power quality, the substation will become more instrumental in understanding and reacting to what is happening in the network rather than relying on modelling and predetermined actions. This should also consider how the testing and performance of protection and control can be automated to cope with adapting to large changes in SCL and inertia.

The evolution of the SmartgGid, in particular, the greater utilisation of power electronics is bringing the primary and secondary sectors closer together, fundamentally creating an integrated substation, possibly even the solid-state substation.

Improving system awareness, this will be necessary to make the substation adaptable to changes and utilise the substation as a centre for autonomy. Installation of network balancing solutions energy storage, synchronous compensation. The substations can be used to improve the local observability of local DER. Furthermore, there is a role for the substation as a virtual machine coordinating the response of active controllers in the vicinity. Finally, it will still be the key interface between remote generation via the transmission system and the increasingly more active distribution system.

4.2 SmartGrid Support

Concepts like dynamic ratings, regional autonomy and risk-based asset management will require a better understanding of the substation performance and reliance on information systems to provide real-time network status in order to provide theenhanced services described above and other sections of this chapter.

The system operators will increasingly be facing a more volatile future grid, experiencing extreme conditions more frequently. The asset managers will need to provide more information about the loading and overload capability from busbar to busbar of the circuits.

The substation has a key role in gathering the data necessary to understand what impact increasing loadings and nature of these changes have on the reliability and the asset life. Secure data collection and online monitoring augmented with weather forecasts and load prediction will help to support this transition from deterministic to adaptive or dynamic ratings-based network conditions.

This is a role for expert systems and artificial intelligence (AI) to establish overload capability of all the assets in a circuit, and provide network operators more flexibility to respond to abnormal network congestions. The applications must consider the capability of all assets (including protection, connectors, bus runs and cables) in the circuit and not just the largest element, such as line or transformer. Depending on the stability, resilience or data security factors the applications to calculate these ratings may need to be calculated at the substation and not always centrally. In the longer term, it is also likely that substations will need to communicate with each other for not only asset data, but also for control commands as part of the regional or network resilience schemes should communication with the control centre be lost. This would see substations central to the self-healing grid concept.

4.3 Network Resilience

The network will be exposed to a variety of disturbances whether natural (hurricanes, flooding, etc.) or man-made (terrorism, malicious damage, cyber threats, etc.), the scale and coordination of which may result in major network blackouts or disruption to power supplies. The design and integrity of the substation and particularly its ability to recover or endure these disturbances will have a significant impact on the ability to ride through and support restoration of the surrounding networks and eventually the power system.

The big economic question that resilience raises is justification of the capital and operating costs required to provide the level of service reliability necessary to support the recovery. These events are low frequency but high impact and potentially a national emergency. Whilst the substation is not alone in restoring power, it will be central to any network restoration scheme. As the networks become more distributed, utilities and the system operator will need to understand the role each of its substations play in these schemes and what is necessary to support the restoration process. This will typically focus around the dilemma of redundancy versus duplication and prioritisation for substation intervention.

It will be increasingly important for utilities to understand which elements of the substation are most susceptible and key to providing a resilience network, specifically;

- Auxiliary supply provision—providing diversity and secure supplies. Backup generation reliability, testing and fuel stocks.

- Intrusion detection both physical and cyber. How to ensure the integrity of the substations light current systems—limit vulnerability to latent risks embedded in the myriad of firmware and software systems to be found in the substation.
- Communication services to support any of the modern IED technology used for protection and control.
- Resilience of critical systems, in particular, electronics to the effects of electromagnetic pulses (EMP).

One further issue that needs to be considered in this respect is the testing and ability to demonstrate that these enhanced services will work when required and are being suitably serviced and maintained to ensure this capability is required when everything else is on its knees. Quite often these functions can be cut back during economic efficiency drives and cost reviews. It is important to ensure critical sites such as blackstart or control hubs are prioritised during such activities.

4.4 Substation Security

This is addressed at a number of levels, physical, ancillary and cyber. Whilst the substation is at the heart of the network resilience, this can only be maintained through ensuring the auxiliary supplies necessary to support the primary and secondary systems are robust to faults and external impacts. Often an afterthought, these include site supplies to transformer and power electronic cooling, fire management, the DC battery supply and chargers to all the protection, control, automation and communication systems.

Substations are the means by which networks manage security of supply, through large bussing complexes with highly resilient infrastructure. This is likely to orient towards larger volumes of smaller dispersed sites coordinated by wide-area control to provide self-healing networks. This will be a slow evolution, driven by the nature and location of generation and load demands. This widening of the meshed grid may improve overall network resilience whilst the large magnitude of substations means the loss of a facility is less significant than the current view in transmission. Does this mean we move from N-2 towards N, as the number of substations increases? In turn, the lower voltage sites may be more concerned with local control issues like voltage regulation or power quality.

Change management and role-based access control strategies become critical as digital substations become commonplace. Utilities need to facilitate the opportunity for auditability where we combine physical and cybersecurity functionality. e.g. Bluetooth locking to know who is going into the site or cubicle.

5 New Technologies and Genres

The technology employed in substations is extensive, ranging from the primary equipment which has changed little over the last five decades to substation automation and intelligence which employs the latest microprocessor and cloud-based technology.

Asset Life—there is a view that most primary assets have a 40–50 year lifetime and decisions are made on this concept. The changing nature of the networks will need this to be reconsidered, possibly in respect of capacity or the service provided.

There are a number of likely trends, however, the cross-cutting influence is that functionality is generally becoming more concentrated and adaptability is increasing.

New technologies, such as transducers, robotics, drones, superconductors and new materials may solve some of the current challenges in the substation and grid performance but, on the other hand, will require a new set of skills and management approaches to handle them.

New types of substation assets and systems are emerging, such as offshore installations, the wider use of power electronics (particularly voltage source converters) and energy storage. These must be managed as complex systems often exceeding the substation fence and forming bigger and more intelligent systems to control network flow boundaries.

Use of robotics, automation and AI for inspection and surveillance purposes, making condition assessment more systematic and consistent. The trick is to automate the data collection and processing to quickly input into the asset management system so decisions can be quickly flagged, outages reviewed, risk assessments carried out with resource planned and allocated to determine the best intervention for the asset and utility alike.

Existing HV component technical specifications may need to be reviewed for suitability to be future grid compliant. The equipment for the future is being purchased today. If not managed properly and in time, there is a risk that these assets will not be able to perform in the future grid leading to stranded assets and costs.

The asset manager must intensify the use of dynamic and overload rating management in order to maximise the inherent loading capability at the circuit level. Furthermore, the impact on the longer term asset performance needs to be understood and managed.

The differentiation between control and protection is changing or at least blurring, making it more difficult to exclusively separate the two. New devices and protocols are being introduced at the substation level. The existing boundaries between primary and secondary systems as well as between secondary and telecommunication systems will continue to disappear (Fig. 5). A final point to make here is that utilities will need to manage the interfacing between the legacy equipment already in service and these new concepts, and this will require the development and sharing of good engineering practice and collaboration between the manufacturers and utilities. This is exactly what CIGRE aims to promote.

Fig. 5 Emerging technologies in substations

5.1 Digitalisation

The role of the Internet of things (IoT) and SmartGrids will be a big factor in how the substation and networks will have to evolve, much as the IT industry has adapted to wireless communications and Ethernet cloud hosting.

The substation is becoming the hub of asset data gathering. Historically, the secure nature of substation communications has established a robust communication network between sites. This can be further utilised and augmented to transport more network and asset data, facilitating asset condition, system monitoring and physical surveillance.

These functions will require substations to be much more remotely operable and configurable. This has a major cybersecurity impact, which is already a hot topic for transmission, where strict access rules are implemented significantly restricting the roll-out of cloud and SmartGrid solutions. To fully enable the distribution grid, these issues need to be addressed without introducing draconian processes which will stifle the evolution required in the industry.

A potential future role for substations is a viable alternative to GPS as a source of time synchronisation, e.g. the wide area provision of a secure network timing protocol (NTP).

The Substation digital twin is a concept which can include not only the Building Information Management (BIM) aspects in regard to design construction and then the subsequent asset management and operation, but also evolve the data-driven environment for asset knowledge and operation.

This evolving concept is essentially about having a soft model of the physical functions and will feature significantly in substation management. Initially, amongst the suite of design tools being developed is the visualisation of the substation whether adapted from laser surveys (LIDAR) or translated from 3D CAD packages, enabling the utility and designers to walk-through. This way, the engineers can fly through or look below the ground level for risk and optimised accessibility. This can help the operations personnel to assess access and safety when working near assets.

The role for Global Information systems (GIS) is rapidly growing in the visualisation and asset management world to develop macrodata attribution for the purposes of asset health and intervention purposes accessing maintenance history and other data sources to provide a more holistic picure of the substation.

These tools can be further evolved with asset data and condition information to establish the digital twin for any plant item and the substation itself, allowing the asset manager to fully run through scenarios prior to setting a foot on site.

Possibly one of the best developments will be how this can then be further interfaced with the substation control and automation systems to establish functions like software interlocking and risk managed hazard zones (RMHZ) around plant with the potential to fail in a destructive state.

Enhanced safety features can be developed, by augmenting personnel protective equipment with features such as head up displays, smart glasses and sensors to inform staff of the asset condition in their immediate vicinity. This can also be used to establish the location and exposure of personnel in the substation at any time.

5.2 *Power Electronics*

Power electronic applications, in particular inverters, are entering or connecting to substations, especially at lower voltages on a large scale. Most new generation sits behind a converter of some design (solar, battery storage and wind, plus HVDC).

It is reasonable to expect that in the future, substations around 30 kV could become entirely solid state and digital. This also introduces the potential for the next stage in power system development ‘plug and play’ with self-configuring and self-supervising substations. This will gradually migrate up to higher voltages, but more slowly depending on the volume and technical innovation in the coming decades.

Another case in point is the possibility of direct current (DC) networks. These are starting to emerge in the MV domain. There is definitely a the role for the substation as a facility that will accommodate the equipment and secondly the auxiliary infrastructure (cooling and valve hall HVAC) to support the inverters and protection and control systems necessary to support these networks.

5.3 Autonomy

The role of substation autonomy is a key point to consider. Substation automation is on the increase, particularly as the complexity and number of variables that can influence any one event grow. Whilst this has been extensively employed in transmission, it is typically only at the substation level and based on deterministic states. It is not common across substations at a regional level, although there are examples of operational tripping schemes and system integrity protection schemes (SIPS) around the world. The ability to operate autonomously based on local system conditions is a realistic possibility and likely to proliferate both in transmission and distribution. This is particularly pertinent as more decision-making is based on prediction or artificial intelligence becomes viable and more commonplace on both the home and transport. The key will be how these coordinating functions currently located in the control centres will migrate into the substation control systems. The big challenge at the substation level is how to install, commission and more importantly upgrade or extend, these as more connections are made. The need for ‘plug and play’ architecture which can automatically configure itself and be aware of the environment it is connecting into becomes ever-more important.

The gradual migration from hybrid IEC 61850 application to the full implementation of IEC61850 Ed2, is ongoing, built on lessons learned around testing and commissioning. The nature of the solutions enable the testing elements of protection and control functionality without necessarily physically isolating the equipment from the system. This flexibility, however, runs a higher risk if not properly implemented and needs to carefully consider cyber resilience.

The availability of remote testing and validation tools for protection and control functions, can significantly the need for circuit outages. However, Utilities need to take more of a lead in the development of their processes around the implementation of these new standards so everyone moves in the same direction rather than being tied into a proprietary solution.

5.4 Materials and Technologies

The use of new and alternative technologies is mentioned in numerous parts of this chapter, and however, there tends to be a common thread that runs through their successful introduction into the substation environment. The following points outline these key factors to consider;

- Alternative insulating materials, particularly to SF6 and derivatives need to be established and demonstrated to be economically viable. In the short-term better ways to reduce SF6 emissions on ageing equipment need to be evaluated. It is important to consider what will be the longer-term asset management issues. Is one problem being exchanged for another? What is the compatibility factor between the new and legacy materials.

- Non-intrusive techniques to identify equipment condition and in particular predict end of life and intervention timescales.
- Communication media, secure wireless control and automation—how to make ‘plug and play’ more achievable, without putting the security of the substation at risk.
- Energy harvesting particularly for sensors and automation, these need to be suitable and de-sensitised to the harsh EMC environment of the substations.

6 Asset Management and Regulation

Substation asset management seeks to find the balance and rigour in the trilemma between customers who value reliability and lower costs, stakeholder expectations, and the shareholders and suppliers who seek a reasonable return-on-investment. It is imperative that the utilities consider the total cost of ownership or whole-life value. One key point to review is the significance of the lifetime of a substation.

The changes occurring over the last 30 or so years have encouraged many utilities to shift their focus towards ‘performance driven decision making’. Society is now less tolerant of loss of service outages and regulators monitor such events as well as ensuring costs and prices are controlled. Where they are privately owned, utility shareholders want an acceptable ‘Return-On-Investment’ in recompense for funding the building of new and renewal of infrastructure assets. The utility directors need to manage these expectations. This means achieving the required performance whilst reducing costs to achieve this goal. The regulators also value these goals but need to ensure all risks are identified and controlled in an affordable way.

Risk management is a fundamental role within this context and for some utilities a legal requirement of their operating license. Where there is no government to underwrite the company, a private utility needs to insure and this insurer will also want to see risks managed. Open market and international trading mean competition which is driven by choice and costs.

In this environment, lifetime management of assets is the key to achieving a sustainable business. This applies to all service provider industries like telecommunications, rail, electricity, gas, water, etc. They each have assets that exist to be operated and provide both a service to the consumer and value to the stakeholders. Not all this change has occurred by simply good management evolving from within companies. In the UK, the regulators of many of the service utilities drove significant strategic changes within these companies. It included the development of a BSI specification PAS 55, issued firstly in 2004. This, in turn, was reissued with a wider and international collaborator base in 2008 and it further evolved into ISO 55000 in 2014 [8].

Within this context, a ‘line of sight’ is set by the executive board who have set performance targets and acceptable risk levels to be achieved at all levels within the company, from the executive to work teams on site. It is for the management teams in the company to create and deliver the tactical targets for the assets and workforce to achieve.

The development of ISO 55000 has impacted decision-making for substations but it is still early days. This ISO will continue to further impact on the operational life cycle, particularly from an investor or regulator perspective, much in the same way that quality and environmental standards have become de facto in business.

Power systems will become more transactional based on service provision, and this will require reliable and robust data to support the economic cost recovery mechanisms; it is reasonable to expect the substation will be a key source of providing this information.

Efficiency will drive new methods in asset management to reduce operational costs, including consideration of losses. This may result in more attention being paid to whole-life or life-cycle losses becoming a more key part of the procurement process.

The trend is likely to change in the actual approach to the traditional concept of 'maintenance' of assets. This will increasingly look at how to minimise the network intervention.

- New inspection methodologies will be established using non-intrusive measures, and however, problems may arise where these activities are outsourced to external service providers who have work programmes linked to a contract, which leads to problems when flexibility and cancellation of outages occur. Redirecting a team to other work can be an issue both contractually and where the skill or competence in the team is not matched to the alternate work.
- Due to the increasing grid availability requirements, obtaining outages will become even more difficult and will require higher flexibility. Initially, the planning of maintenance activities is carried out from the ideal viewpoint of the maximum transmission capability of the network and does not assume any change in the technical condition of the assets. This needs to change to acknowledge the reliability of assets as they age or are utilised differently.
- The uncertainty of renewable production and the power flow in the network outage planning for maintenance activities will need to be more flexible including maintenance work outside normal working hours. This could have an important social impact on a maintenance organisation. For offshore wind park substations-related maintenance works, the weather conditions at sea will add another limiting dimension to the planning process (Fig. 6).

One of the big factors to the whole substation data capture and processing challenge will be the role that standardisation plays in the protocols and structure for the many thousands of different data sources possible within the substation environment. Over the last decade, IEC 61850 substation protocol has evolved but is still considered a new concept in many circles. It is very incumbent on the utility to define its own dialect of the standard that suits its operations, asset management systems and suppliers. This is primarily for use within the substation boundary. On the condition monitoring front, the common information model (CIM) is also a developing concept. One of the challenges is for the utility to determine how it wants to source the

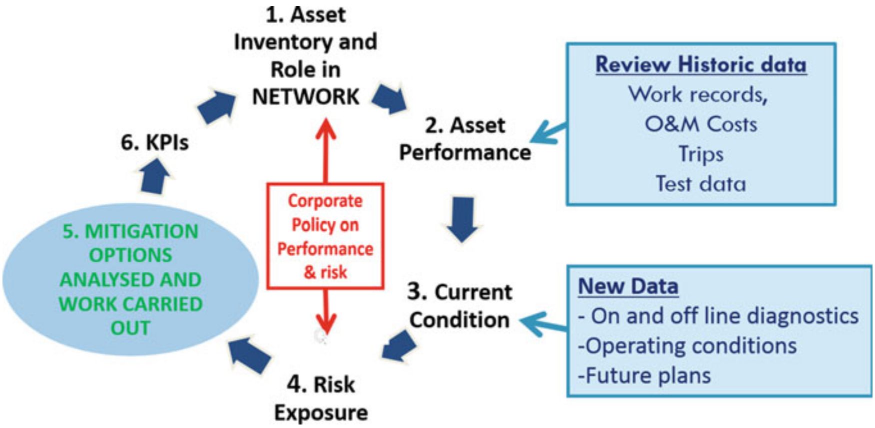


Fig. 6 Substation management strategies

data and at what stage the data is converted into information and then the subsequent decisions.

On top of what is happening inside the substation, the substation will become a hub where there will be the data coming in from the wider network which will need to be marshalled, secured and then stored remotely for processing and analytics (Fig. 7).

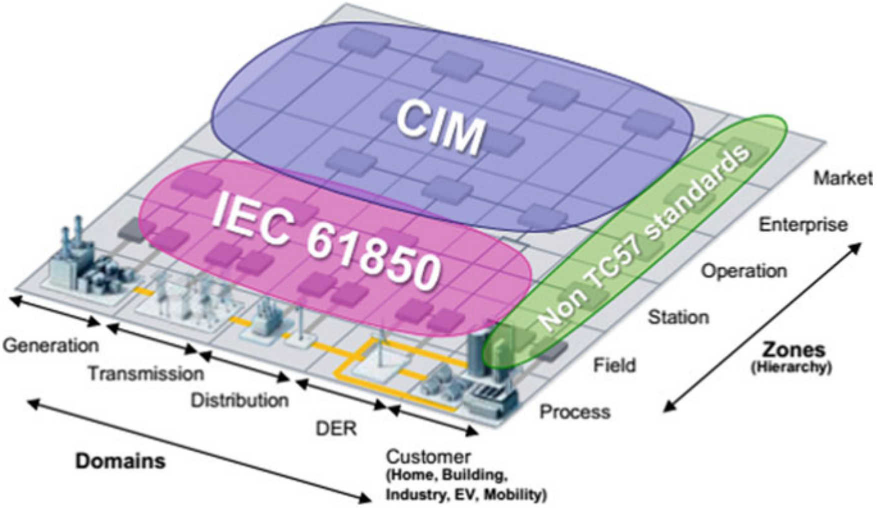


Fig. 7 Semantic domain in SmartGrid architecture model

6.1 The Rise of Information Technology

With the increase in digital systems, information technology (IT), communications and other disciplines, the power industry is a more attractive career option for young people. In the traditional business, it is not uncommon for engineers to stay with a particular company for a long time (over 40 years), though job stability does not seem to be a desire of the younger generation. Organisations will have to think carefully about how to manage knowledge and skills, whether that is to retain staff members, something which was not a big concern in the past, or focus on effective knowledge management so that knowledge does not disappear as people leave the organisation. Knowledge management practices and tools are covered in more detail later in the section.

The role of data has changed significantly in recent years, as service providers are placing more value on it. It is critical to risk evaluation, decision support systems and asset management. Controls, governance and change management are key to ensuring the voracity and effectiveness of the data quality. As new tools are evolving or migrating from other sectors such as geo-spatial information systems (GIS), building information management (BIM), IoT etc., the energy sector is becoming a hotbed for new applications. The prime applications for substations will be in the combination of these tools to visualise the performance of assets and spot emerging trends which will inform the priority for intervention and help to diagnose possible causation, ahead of asset failure. Historically, a lot of data has been captured at the asset level, but the backhaul of this data to a central archive has not been carried out. Now that the technology and data transfer is possible, it can be centrally archived and augmented with other information systems, such as artificial intelligence to provide better visibility of trends and granularity to the asset managers, who can use this to determine the best intervention for an asset and minimise unnecessary outages. To a degree, modern digital protection and control systems already have self-supervision on an individual device level, and being able to observe device family performance and fault trends across many different systems will become essential as more reliance is placed on dispersed SmartGrid functions.

One of the areas discussed in many forums is cybersecurity. Electric power networks are part of a country's critical infrastructure. If physically attacked or remotely broken into a critical operational system, such as SCADA, a country could come to a standstill. The effect will be such as we have seen by wide-scale blackouts. With an upwards trend in terrorist attacks and an increase penetration of remotely controlled field devices, it is a threat that must be understood throughout by utility and staff members need to be educated accordingly. Passwords simply cannot be written down on the asset itself for easy access. This clearly demonstrates a need for education on the importance of keeping passwords secret but also the importance of changing passwords as required. For example, during the commissioning of a substation, the passwords are also known by the vendor and the contractors. It is important that passwords are changed post-commissioning. The management of passwords for operational devices/systems is another organisational area which is absolutely critical for the business. Vendors are developing tools that will automatically manage the password changing requirements as well as role-based access control of devices.

In the last decade, education and awareness on IT aspects were quite dominant. This seems to have changes in recent years to a focus on educating managers in IT Governance, which is far broader and includes aspects like security, configuration management, etc.

The introduction of more complex technologies results in a shift of how people get trained and how knowledge is transferred within a company and also between it and service providers. In the traditional environment, it was common, and appropriate, to train people on the job. A senior person would demonstrate how the job is done, supervise, coach and guide until the work is done correctly and safely. The common methods to transfer knowledge related to someone's job would be on-the-job training combined with internal documents (procedures, work instructions) on how the job is performed.

Technologies are increasing in complexity and reach the point where a few weeks of on-the-job training won't be possible. Such an approach would simply take far too long and isn't feasible. Often the technology is fundamentally different and requires significantly different skills. Also, the rate at which technology changes is increasing, which means more formal knowledge management methods and tools are needed. This need is further increased by knowing that young people change jobs more often and knowledge, unless captured effectively, will talk out of the door.

The substation can no longer be developed in isolation, especially as the role of the Internet of things, SmartGrid and distributed generation become more established. It will be necessary for the utility to look wider, identify and incorporate stakeholders in the substation evolution:

- Academics and industry will help to establish the new ideas.
- Entrepreneurs—to take the ideas across from industry and others and realise these into pragmatic solutions.
- Multi-functional engineers who can combine the power system and technology understanding with asset management and business disciplines to aid with substation design management and operation.

6.2 Standardisation

The role of international standards and best practice guides will become more relevant as globalisation increases. The challenge will be to ensure a suitable equilibrium and representation on these bodies, especially the standards groups IEC/IEEE to ensure a balance is maintained between the user's needs and the suppliers. This would achieve a pragmatic and reasonable expectation for manufacturing and testing requirements to optimise product cost.

Standardisation has been shown in many industries (there are many examples) to produce significant changes in the way infrastructure is developed. For example, containerisation had a lasting and significant impact on the management of world trade. The power industry has been slow to adopt but there are signs of increased awareness of the benefits of standardisation in some regions, driven by costs and time pressures.

'Standardisation' is not just the development of agreed international or national standards as is suggested here but it is the broader aspect of standardising designs and the use of repeatable elements in design. This has become a necessary aspect of substation development. Rather than design from scratch, standardisation allows designers to consider broader needs, encompass future development, etc. This will develop and grow further as the need for world electrification continues. Standardisation is used to assist rapid development. It was used primarily in distribution, where the volume of facilities is much higher but now is also applicable to transmission, especially during periods of rapid network expansion or change. Standardisation will assist in the rapid development of regions and countries that do not have full electrification: sub-Saharan Africa, India, etc. This is covered in much more detail in the [4] Technical Brochure TB 389 'Combining Innovation & Standardisation'.

6.3 Resources and Skills

Collectively, utilities and the manufacturing sector are increasingly being driven through competition and regulation to operate more efficiently and to shorter timescales. This is generally resulting in a faster turnover of staff and greater reliance on process and guidelines to establish best practice, rather than corporate expertise. The time required for an engineer to become 'experienced' is significant and it is difficult to remain in one position sufficiently long enough to develop the knowledge.

There appears to be a general move in academia away from 'hard sciences'. This may be driven by a society with people unwilling to commit to long-term careers. Demographic analysis shows a significant change in attitude of society in the last 20–30 years and this trend is expected to continue impacting also educational outcomes.

In some countries, there have been significant efforts to assist in the development and maintenance of high standards of education in engineering skills. The industry is recognising that the continuation of the current trends will lead to loss of skills and base engineering skills.

CIGRE in Australia has established the Australian Power Institute for the specific purpose of encouraging the development of HV engineering curriculum in universities. This material is provided free to universities and includes lectures, tutorials, etc. This seems to be very successful. This is also being practised in other countries, the UK, for example, however, the role and image of the engineer must compete with other professions in the skills market place in terms of remuneration and reputation.

New technology is also driving the need for new attitudes and skills:

- Wind power offshore substations are relatively new and this is a technology which has become popular in areas like Northern Europe. The construction and operation of an offshore substation require new skills and knowledge, which is currently not available inside companies. Some knowledge and skills may be recruited to form part of the new organisation. However, external expertise and building new business alliances are inevitable. A specific example is related to staff working on offshore platforms. These staff members need to undergo extensive safety training and other certification related to working on an offshore platform. The management of these training requirements, certificates (to validate and renew training/certificates) and specific knowledge transfer is a new area which requires processes and systems that were previously not needed. It is one example only of a new way of doing work, which, if not appropriately managed, can add significant corporate exposure to a company.
- Similarly, HVDC multi-terminal systems are a totally new development for converter substation configurations. We need new protection, DC circuit breaker on the DC side, communication systems, etc. Work practices are fundamentally different from what a TSO is used to and often companies have only a very low number of these substations. It is often simply not economical to establish the required capabilities internally, given also the long lead-time required to establish the skills and knowledge internally. Companies often choose to outsource the end-to-end management to specialist providers. It is now common to see tenders that seek an external party to manage the procurement, construction/installation and also the maintenance for a number of years what far exceed the warranty period, and with an option to extend for additional years. Obviously, the solution must integrate into the company's power network, which is ultimately responsible for the overall performance. Service-level agreements with external suppliers are likely to increase.

External service providers who offer services for smart devices are becoming more abundant with the increased penetration of smart field devices. This may include services such as monitoring, statistics and analysis services which, in the new business model, the utility decides to outsource. It is simply becoming a new discipline that requires expertise (data analytics) or the utility looks are alternative models for labour-intensive work. Data from the utility's smart devices may be stored on the cloud with staff members given access to their data. External service providers can offer online, cloud-based tools. However, cloud-based services create new challenges in cybersecurity, privacy and reliability that did not previously exist.

All of the above changes are not small minor changes. These changes require the overall rethinking of end-to-end processes, systems and people resources and includes the rethinking of which capabilities should be established internally and what expert teams need to be hired on contract.

There is an increased focus on driving efficiencies and an increased focus on prudent and sound investments. Furthermore, many of the SmartGrid technologies and its infrastructure requirement (e.g. private communications network) cannot be justified at the device level. A long-term vision of the future network is essential.

This demands that a technical person and/or engineer has wider technical (ICT and EPE) and broader skills set and knowledge and also have capabilities in non-technical areas such as finance, risk management, business planning and forecasting.

The average life expectancy of traditional power system assets deployed has been 30–40 years. Electronic devices and software packages have a far shorter life cycle which means that processes, work instructions and procedures will change more frequently and so will the skills and experience requirements and also the training requirements change.

7 Summary and Conclusions

Energy is a core commodity necessary for society to flourish. It is now perceived much more important now than for previous generations, possibly because of the added drive to decarbonise society. This will be achieved through many more parties contributing by either adding to the energy mix or actively managing their energy demands.

In this context, it looks like the purpose and scope of the substation will possibly become more important as a place for customers to access the network and for utilities to control and maintain the reliability and security of the network and assets.

An interesting point to note is that, given the current lifetime of substation assets, utilities and suppliers should be focusing on the viability and functionality necessary to meet the Net Zero challenge by 2050 on their current projects, as any newly commissioned equipment is likely to be still operating in this period.

The substation is the key point of access into the electricity system, and there is an emerging role as a SmartGrid hub. This will become more key as more SmartGrid applications take off, with respect to collecting and gathering secure and reliable data, which in time will facilitate greater automation and autonomy blurring the lines between transmission and distribution.

There is a focus around eco-design and the sustainability factor of substation applications. Possibly the main challenge over the coming years will be about reducing the SF6 utilisation. This, however, will be compromised by the need to facilitate smaller footprint substations.

The adoption of new technology into the substation is a balance of risk and economics. The pace of change is growing and the substation community needs to become faster at successfully implementing change and being responsive to external factors. Whilst the industry needs to be aware of and consider the implementation challenges, it should avoid unnecessarily impeding the introduction of viable new technologies through lack of awareness or fear. The move towards modularity and plug and play interfaces will lead to faster installation, shorter lead times, reduced outages, especially for replacement and extension work inside existing facilities.

The pace at which pilots and field trials are implemented is an obstacle to embedding timely change and innovation. Whilst these are an effective method to advance the equipment, the challenge is to share the learning, so equipment is not unnecessarily impeded through perceived negative experience. In this regard, the active involvement of utility staff with innovation is absolutely essential and this is an area where the industry has been particularly weak in the past.

Standardisation can play an important role around configurations and modular design, and this will help to speed up the delivery and address constraint and outage restrictions. It reduces the need for conformance testing and makes commissioning easier. It is more suited to a wider scale roll-out of new and major offline replacement activities. This does become more challenging for partial interventions, where there are always likely to be mixed vintage technologies. It is difficult to apply a common set of policies.

As more parties connect to the network, the ability to get access and the necessary outages for site work will become less available and more insecure. This is already leading to the need for more non-invasive assessment being undertaken with equipment still energised.

The substation is becoming a more data-driven environment through digitisation and then subsequent digitalisation of substation functionality. There will be short-term challenges around interfacing with the legacy of systems and confidence needs to be established with plug and play. In time, this data coupled with full CIM models for all assets and functions will help to establish the substation digital twin, potentially.

The whole sector needs to establish a wider skills base, particularly substation staff to have more IT skills compared to the earlier generations. Handling site data needs to be properly managed, particularly with respect to change management and cybersecurity.

Utilities will need to ensure that the policies procedures and methods of working are reviewed in a timely manner to enable the benefit of new technology and risk-based decisions to enable the effectiveness and functionality to be realised. Training and staff development needs to be a priority, but this needs to be hand in hand with new ways to capture knowledge and also reverse mentoring so old and new engineers develop. The development of resources should be the priority, not an option.

This is a role that CIGRE will actively play by encouraging utilities and engineers to share and develop best practice with the wider community to enhance the performance of substations.

References

1. Technical Brochure 764.: Expected Impact on Substation Management from Future Grids (2019)
2. Technical Brochure 380.: The impact of new technology on substation functionality (2009)
3. The Future substation: a reflective approach (23–207), Cigre session 1996
4. Technical Brochure 389.: Combining Innovation & Standardization (2009)
5. Technical Brochure 740.: Contemporary design of low cost substations in developing countries (2018)
6. Technical Brochure 483.: Guidelines for the design and construction of AC offshore substations for wind power plants (2011)

7. Technical Brochure 734.: Management of Risk in Substations
8. ISO 55000 – Asset Manaagement Principles

Mark Osborne is a Chartered Engineer and joined National Grid in 1997. He has a Ph.D in Custom Power technology, from Sunderland University and works in the Engineering & Asset Management Group, part of National Grid Electricity Transmission. Key activities include substation life-cycle management focusing on the incorporation of new technology concepts to meet the challenges facing the electricity supply industry. He is an active member of the CIGRE B3 Substations Study Committee as Strategic Advisory Group member, Special Reporter and UK Regular Member.

Koji Kawakita was born in Mie prefecture, Japan. He obtained a Bachelor of Engineering degree from Mie University. He joined Chubu Electric Power Co., Inc. in 1986. Since then, he has engaged in research & development, design, construction, substation asset management and international consultancy services. Currently, he is a Fellow of Chubu Electric Power Grid Co., Inc. since April 2020. In CIGRE, he has been participating in Study Committee B3 since 2000. He contributed to a lot of activities such as Poster Session chair of Paris Session, Convener, Secretary and member of Working Groups. He was a regular member of Study Committee B3 from 2012 to 2018. He has been appointed the Chairman of Study Committee B3 since 2018 to present.

DC Systems and Power Electronics

Carl Barker, Les Brand, Olivier Despouys, Robin Gupta, Neil Kirby, Kees Koreman, Abhay Kumar Jain, Carmen Longás Viejo, Larsson Mats, and James Yu

1 Introduction

The worldwide electrical power system is undergoing major changes. Many parts of the world are moving away from conventional, thermal-based, synchronous generation, towards power electronic converter-connected forms of generation such as wind and solar. The utilisation of renewable energy sources, often located in remote areas, forces transmission companies and developers to move electrical power over long distance to reach the end users.

On Behalf of CIGRE Study Committee B4.

C. Barker (✉)
GE Grid Solutions, Stafford, UK
e-mail: Carl.Barker@ge.com

L. Brand
Amplitude Consultants, Brisbane, Australia
e-mail: Les.Brand@amplitudepower.com

O. Despouys
Réseau de Transport d'Electricité (RTE), Paris, France

R. Gupta
National Grid Electricity Transmission (NGET), London, UK

N. Kirby
GE Grid Solutions, Philadelphia, USA

K. Koreman
TenneT, Arnhem, The Netherlands

A. Kumar Jain
Senior Principle Project Lead Engineer, ABB Power Grids Sweden AB, Ludvika, Sweden
e-mail: abhay@jain.se

C. Longás Viejo
Red Eléctrica de España (REE), Madrid, Spain

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_8

A common approach to improving the power transmission distance or power throughput of an AC system is to add one or more devices collectively referred to as flexible AC transmission system (FACTS) devices. These devices can be connected either in shunt or in series dependent on the particular type of FACTS device but fundamentally are acting upon the reactive elements of the AC transmission system to either improve the AC voltage profile or reduce the AC system impedance.

Bulk power transmission over long distance has often been achieved with the use of high-voltage direct current (HVDC). The advantages of HVDC over AC transmission are typically summarised as:

- Lower transmission cost per km
- Lower losses per km
- Narrower right of way
- Longer distance for economic transmission via underground or subsea cable
- Greater controllability.

HVDC has also been used to interconnect AC systems that are either unsynchronised or operating at different frequencies (e.g. 50 and 60 Hz).

The majority of HVDC installations to date are of a connection arrangement referred to as 'point-to-point' transmission; that is, the power is moved from a source of generation to a load centre or, alternatively, between load centres to share load and generation and hence reduce the peak generation capacity in each AC system.

2 Introduction to Power Electronics

In HVDC, power electronics (PE) replaced the earlier mercury-arc technology in the early 1970s. However, the legacy of this earlier technology is retained in the terminology 'valve' that is used to describe a set of power electronic devices working together to control the impedance between their terminals. With the development of power electronics, FACTS applications were developed. Early applications of power electronics focused on the use of the thyristor as the main controlled switching device. In recent years, power transistor ratings and reliability have improved to the point where they can also economically be applied to both HVDC and FACTS devices.

In the following section, the types of semiconductors commonly used in HVDC and FACTS are introduced along with an indication of possible future developments [1, 2].

L. Mats
ABB Power Grids Switzerland, Baden, Switzerland
e-mail: mats.larsson@ch.abb.com

J. Yu
SPEN, London, UK

2.1 Thyristors

Today's thyristors have a blocking capability of 8.5–9.5 kV per device and a current rating of upto 6250 A DC [2, 3]. The silicon diameter has reached 150 mm; while large, this silicon wafer contains only a single thyristor. In order to build the high-voltage power electronic switches required in HVDC or FACTS applications from these devices, many thyristors are connected in series and controlled as a single switching element. However, because of the high current-carrying capability of these modern devices paralleling of devices is not required. Besides the electrical triggered thyristors (ETTs; see Fig. 1), there are also direct light-triggered thyristors (LTTs; see Fig. 2) used in modern HVDC systems.

Clearly visible in Fig. 1 is the gate etchings on the silicon wafer as implemented by two different manufacturers. These gate configurations are intended to improve the speed at which the complete silicon area goes into conduction following an initial gate pulse applied at the centre of the silicon slice, hence reducing turn-on losses and minimising the need to reduce the rate of rise of current through the device.

Fig. 1 ETT 9.5 kV 150 mm silicon Phase Controlled Thyristor

Fig. 2 LTT 9.5 kV 150 mm silicon

As shown in Figs. 1 and 2, modern thyristors used in HVDC and FACTS are ‘press-pack’ devices; that is, they are designed to fail short circuit in the event of a device failure.

2.2 Power Transistors

There have been several types of power transistor brought to the market in the last 30 years. However, due to their multiple industry applications and hence the quantity manufactured and demonstrated reliability, the insulated gate bipolar transistor (IGBT) has, to date, become the preferred technology adopted for both HVDC and FACTS applications.

The main topology used for these VSC applications in HVDC and FACTS is the submodule. There are two main types of submodule: the half-bridge and the full-bridge modules. In Fig. 3, a submodule using a single phase leg is shown, whereas Fig. 4 depicts a full-bridge submodule with two phase legs. In both cases, the phase

Fig. 3 Half-bridge submodule

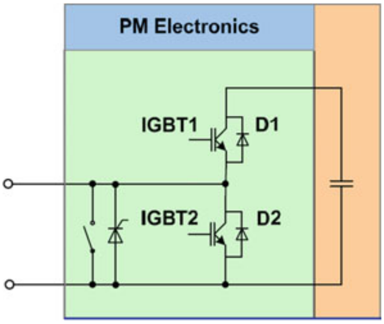
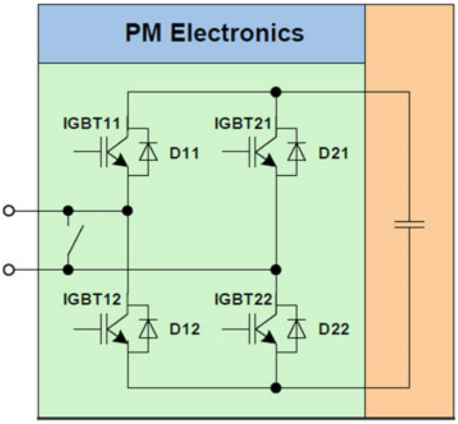


Fig. 4 Full-bridge submodule



legs consist of two IGBTs with antiparallel diodes. On the DC side of the phase leg(s), a large DC capacitor is connected which has no other external connections.

Two main considerations are important for choosing a device for multi-modular converter (MMC)-based HVDC applications which use IGBTs:

- MMC-based HVDC systems operate with very low switching frequency compared to other applications. Usually, the switching frequency is only three times the line frequency or even lower. Therefore, for an identical voltage class and technology generation, a device with a trade-off favouring the reduction of forward voltage drop will outperform devices optimised for low switching losses.
- The conduction loss, per device, always increases with blocking voltage, but generally less than proportionally, so that, in general, the conduction loss per kV of rated voltage decreases as the blocking voltage increases [4].

For today's module packages, two different types are in use by different manufacturers. The established package in the power ranges appropriate to HVDC and utility scale FACTS applications is the IHV package (IGBT high-voltage package) which was introduced as IGBT technology emerged beyond the range of industrial general-purpose drives and other low and medium power applications and into metro and mainline traction applications. This became feasible in 1995 with the introduction of 3.3 kV IGBTs [5]. 6.5 kV IGBTs were introduced in 1999 [6], the isolation capability was improved while keeping the footprint and main the terminal locations unchanged. The outline is shown in Fig. 5, and Table 1 provides an overview of currently available voltage and current ratings for the largest footprint module.

However, unlike the thyristor, previously discussed, a single IGBT package contains multiple parallel connected transistors and reverse parallel diode chips. The

Fig. 5 IHV module 190 mm × 140 mm in cutaway view

Table 1 Current ratings in 190 × 140 mm2 IHV package

	Voltage class		
	3300 V	4500 V	6500 V
Max. current rating	1800 A	1500 A	1000 A

failure mode of these devices is more complex. An initial fault on one chip can lead to a short circuit through that chip. However, the energy that then flows can result in damage to the surrounding chips and their connections leading to the device becoming an open circuit. For this reason, where series redundancy is required in order to maintain operation, even with the loss of some elements, a bypass switch is included in each module to remove the power electronics from the circuit in the event of a failure.

To overcome the need for a bypassing mechanism, some manufacturers have developed press-pack IGBT devices, Fig. 6.

As these devices have been purposely designed for the application, it has been possible to add additional diodes within the package, thereby avoiding the need for the thyristor in parallel with D2. The module provides enough surge current and explosion resistance capability to avoid the use of any supplementary bypass and explosion protection arrangement for easy stack design.

Fig. 6 Press-pack IGBTs. **a** 2.5 kV modules used in early generation of VSC-type HVDC/SVC systems up to 500 MW, **b** 4.5 kV StakPak modules

3 Established Power Electronic Applications in Today's AC Power Grids

3.1 FACTS Applications

Depending on its nature, if it is a shunt or series FACTS device, a mechanical switched device, a thyristor commutated device, or a current source converter- or voltage source converter-based device, its features are different. All the available spectra of FACTS devices have a large range of applications in today's power system:

3.1.1 Variable geographical generation pattern

Helping the power system performance when the geographical generation pattern is very variable, for example, because of intermittent energy source integration. In these situations, many different load flows may arise, as well as undesired overloads. FACTS devices can redistribute the active power flows through the AC power grid lines, so that overloading can be avoided or minimised thanks to mainly series FACTS that are able to change the line impedance or voltage angle magnitude.

3.1.2 Voltage support in steady state

Mainly thanks to the shunt devices, the reactive power exchanged with the grid can be modified and therefore the voltage profile of the AC power grid can be controlled. This feature is of special interest when there are abrupt voltages due to generation changes, or exchange programme abrupt change, or lack of voltage sources in case of displacement of synchronous generation.

3.1.3 Voltage support in transient state

Some FACTS devices such as thyristor-controlled shunt or VSC-based FACTS devices can contribute to the voltage support in the transient state, i.e. during a fault, as they can provide fast fault reactive current to support voltage and achieve a faster voltage recovery.

3.1.4 Transient stability enhancement

As FACTS devices can make the AC grid's voltages healthier, or increase active power transmission, transient stability margin can be increased. Also, some FACTS devices, such as the thyristor-controlled braking resistor, can minimise the power acceleration of a synchronous generating unit during a disturbance, which may help transient stability.

3.1.5 Wave quality improvement

Some FACTS devices can modify active and/or reactive response to improve power quality and mitigation measures against unbalanced, voltage dips, harmonics, flicker, etc.

3.1.6 Power Oscillation Damping (POD) provision

Power oscillation damping (POD) provision. Some FACTS can have implemented a POD control function, which can contribute to damp frequency oscillation by managing the reactive power and, thus, the voltage in the point where they are connected.

3.1.7 LCC HVDC operation improvement

LCC HVDC has a limited capability of controlling reactive power as its consumption depends on the transferred active power, and this fact could even lead to limitations in its transmission capability. In these cases, some parallel FACTS devices may take on the role steady-state voltage control, dynamic support to short circuit, overvoltage limitation, and in general contributing to have a stronger network and thus minimising the LCC HVDC possible operational limitations.

3.1.8 Short-circuit current limitation

3.2 HVDC Applications

3.2.1 Asynchronous Grid Interconnection

HVDC can be used as a decoupled interconnection, which allows the exchange of power, while still allowing the AC networks to operate within their operation regimes, such as control of frequency or voltage. This is in two basic forms, and there are numerous examples of each around the world:

- Same Nominal Frequency: Adjacent AC networks which operate at nominally the same frequency, but are not capable of direct AC connection for a number of reasons, such as stability, short-circuit level, etc.
- Different Nominal Frequency: Adjacent AC networks with significantly different frequencies, such as 50 and 60 Hz.

In HVDC links such as this, an HVDC link in the form of a back-to-back link is the most common, with AC lines being brought from each AC system to one converter station location.

3.2.2 Remote Generation Interconnection

Traditional large-scale generation in the form of run-off river or storage is normally located hundreds or even thousands of miles from the major load centres. In situations such as this, with a need to transmit the bulk power over a long distance, the line and station costs associated with AC solution and the DC solution favour the use of HVDC above approximately 500–700 km.

3.2.3 Water Crossing

Significant water crossings may dictate the use of DC. This occurs in traversing wide rivers or lakes, which make overhead lines impractical, forcing the use of submarine cable. The charging current associated with the cable capacitance introduces constraints on the amount of AC power that can be transmitted, forcing the use of an HVDC link for higher power and/or longer distance applications.

3.2.4 Urban Infeed

There are several drivers which may make HVDC the preferred solution to bring power into inner city areas:

- Short-Circuit Level: Many cities have evolved with a specified short-circuit current rating on the transmission and distribution equipment and switchgear. When there is a need to add generation into this network, the addition of this generation may exceed the switchgear fault current rating. HVDC can inject power into this network without significantly increasing the short-circuit current.
- Land Constraints: The availability of land in many cities is limited, and an HVDC converter station may have a smaller footprint, a lower profile and improved aesthetics and have less environmental impact in comparison with a new-generation plant with similar rating.

3.2.5 Connecting Renewables

The increasing use of large-scale renewable generation, most notably in wind, has introduced challenges to network planners and operators in how to handle the variability of this power, and the most effective means of either passively or proactively controlling the consequent power flows in the overall network. Large wind farms, whether onshore or offshore, can benefit from the controllable power flow which HVDC introduces, through control of power and frequency in the wind farm.

3.2.6 Offshore Wind

Offshore wind farms are increasingly used in conjunction with HVDC transmission, driven by both the distance from shore and the power rating, which make an AC cable connection less viable. In particular, voltage source converter HVDC technology and its flexibility to independently and simultaneously control both the real and reactive power flows, together with its more compact footprint, make it a more cost-effective solution to bring offshore wind energy to the onshore networks from several hundred miles from shore.

3.2.7 Increasing AC Transmission Line Capacity through Conversion to DC

AC line characteristics include a stability limit and a higher-level thermal limit, and the power flow through these AC lines is managed to remain at a level below the stability limit. This ensures the network stays within its normal operational steady-state operating range, such that occasional excursions close to the stability limit might be allowed, but operation beyond that and up to the thermal limit is not allowed. This applied safety margin effectively removes access to some of the transmission capacity of the AC line. Use of HVDC removes the stability limit constraint, allowing power transfer up to the thermal limit of the conductor, which allows significantly more power to be transmitted through the line.

3.2.8 Multi-terminal DC Grid

There are a few examples of multi-terminal HVDC with three or more terminals on the same DC circuit, and beyond this, the concept of a DC grid is becoming a viable alternative to the traditional AC network which is the backbone of almost all power transmission and distribution networks worldwide. The three-terminal Quebec–New England link is a long-distance HVDC link which brings hydro-energy from northern Quebec to two locations in southern Quebec and in New England, which has been in operation for over 25 years. Another older example is the three-terminal cable interconnection between the islands of Corsica and Sardinia with the Italian mainland in the Mediterranean Sea, where the main purpose is to use energy from the mainland to stabilise the two island AC systems. These are multi-terminal links with a radial connection, and the next logical development is in the creation of DC grids.

DC grids may be used in several applications, including:

- The potential for more cost-effective and efficient connection of multiple and dispersed offshore wind farms to a number of onshore AC network locations
- interconnection of multiple two-terminal DC links to allow the broader transmission and exchange of power between AC networks
- DC transmission network overlay above an existing AC network to allow efficient long-distance transmission of energy between strategic AC network locations.

3.2.9 Remote Community Supply

The ability of HVDC to transmit power more efficiently over long distances also applies at low power, to feed remote-located communities who presently have to depend on generators based on diesel or other fuel which must be transported over road or rail and which may have seasonal access restrictions. Feeding these remote loads through an HVDC link, potentially feeding multiple small local loads along this line, from one common generation source, or from the main AC network at the rectifier end, may offer a more reliable and low-cost supply to such communities over the longer term.

4 Future Medium-Voltage Distribution Applications of Power Electronics

4.1 The Evolving Distribution Networks

Many governments have committed to a low-carbon economy. A low-carbon electricity network is critical to enable and to realise such a commitment. Unlike a conventional network where centralised generation supplies all the electricity demands, more and more distribution-connected resources (most of them are in the form of renewables) are playing an increasingly active role in electricity supply security and reliability. From an engineering perspective, the phenomenon can be reflected as the controllable and bidirectional power flow between transmission networks and distribution networks; from the customer perspective, the customer can also take on multiple roles simultaneously being both a generator and an active demand response.

Distribution network operator (DNO) serves as the direct interface and takes on active coordinating role between all market participants, facilitating the markets and services in a neutral and non-discriminatory manner. This can be achieved by extending the current role of DNOs to that of distribution system operators (DSOs). An effective DSO model will reduce system balancing costs, while enabling the flexible networks necessary to facilitate customer's use of low-carbon technologies.

In summary, the distribution network is evolved to have more visibility and more controllability than ever before. Decentralisation, decarbonisation and digitalisation are today the main themes of the distribution network development. Commercial innovations and the engineering advancement alike are required to enable a smarter distribution network to meet the future requirements of our customers. The technology advancement of power electronics and its commercial availability are the catalyst of this transformation.

4.2 The Enabling Function of Power Electronics

Power electronics will play a key role in power systems of the future with multiple functionalities. An important area of application is identified in the distribution networks for larger uptake of low-carbon technologies. Moreover, with the uncertain nature associated with renewable resources (such as solar and wind) and the distributed renewable resources, enhanced coordination and management are required. The engineering challenges associated with integrating the unprecedented level of distributed renewable generations can include but is not limited to:

- The unpredictable power flow from the embedded generation
- Imbalance of energy demand between the three phases of AC supply
- Wide voltage angle can prevent the connection between key circuits
- Voltage control at distribution level
- Power quality

Power electronic device has been conventionally deployed at the renewable sector to fulfil the requirements set out in the local grid code or connection codes, such as fault ride through and reactive power control (and the voltage control) on the connected busbar. With the help of power electronics solutions, power flow can be controlled in a wide range of conditions.

The requirement to maintain a secure, reliable and economical distribution network has seen the increasing activities in the engineering developments, such as:

- The power electronic material (advancement in silicon-based power semiconductors, exploring and commercialisation of new semiconductor material such as silicon carbide)
- Hardware design (e.g. new topology of converter; solid-state transformer)

and the commercial innovation, such as:

- The planning and ownership of STATCOM at grid side
- Integrated function of synchronous condenser and STATCOM to provide frequency support.

4.3 Challenges of Power Electronic Devices

In addition to the ongoing engineering and commercial innovation in the power electronic sectors, there are still challenges over their widespread application in the power system domain. The challenges associated with proliferation of power electronic devices in the distribution grids can include but are not limited to:

- Converter topology suitable for different voltage levels in the distribution grids
- The selection of passive (inductors, capacitors and resistors) and power electronic components, with respect to size and power density
- Selection of suitable power electronic materials based on application and voltage level (silicon, silicon carbide, gallium nitride, etc.)
- Reliability of the power electronic and its associated components
- Cost of power electronic devices and associated control systems
- Efficiency and power losses related to power electronic devices.

4.4 Existing Project

A power electronic-based network upgrade can solve the issues associated with the traditional MV systems such as active control of the active and reactive power, independent reactive power compensation, harmonics and unbalanced on the AC grids. To this end, a few existing examples are presented here.

4.4.1 Example 1: ANGLE-DC Project

Angle-DC is a smart and flexible method for reinforcing MV distribution networks, operated by Scottish Power Energy Networks. Angle-DC provides controllable power electronic-based flexible connection that facilitates enhanced bidirectional power flow between two sections of the network; Isle of Anglesey and North Wales. The project aims to convert the existing 33 kV alternating current (AC) assets to DC operation and will trial the first flexible MVDC link in the GB distribution system. Moreover, the project will provide learning to bridge the gap between transmission network and low-voltage distribution DC technologies. It is expected that Angle-DC will bring a total saving of £69.2 m by 2030 and £396.0 m by 2050 [7] (Fig. 7).

4.4.2 Example 2: LV Engine

LV Engine will trial the application of power electronic-based smart transformers (STs) to facilitate the connection of low-carbon technologies (LCTs). A ST is a power

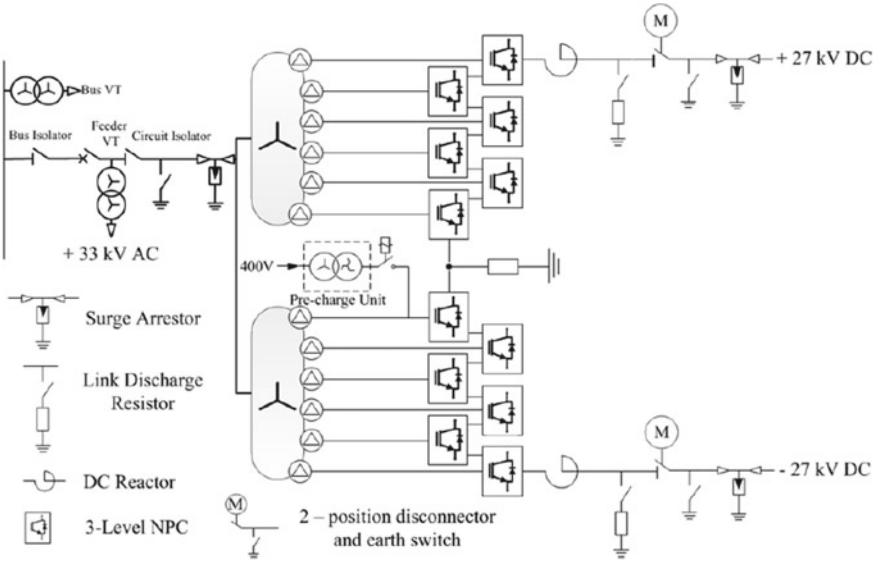


Fig. 7 Single-line circuit of the angle-DC link with MVDC topology

electronic device that provides multiple functionalities over and above standard voltage conversion of conventional transformers. SP Energy Networks run the project and aim to demonstrate a low-voltage direct current (DC) connection for LCTs. It is expected that LV Engine will bring a potential saving of £62 m by 2030 and £528 m by 2050 [8] (Fig. 8).

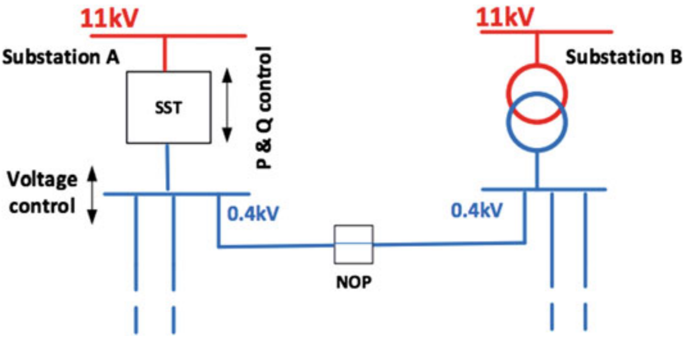


Fig. 8 Connection scheme of SST to LV network

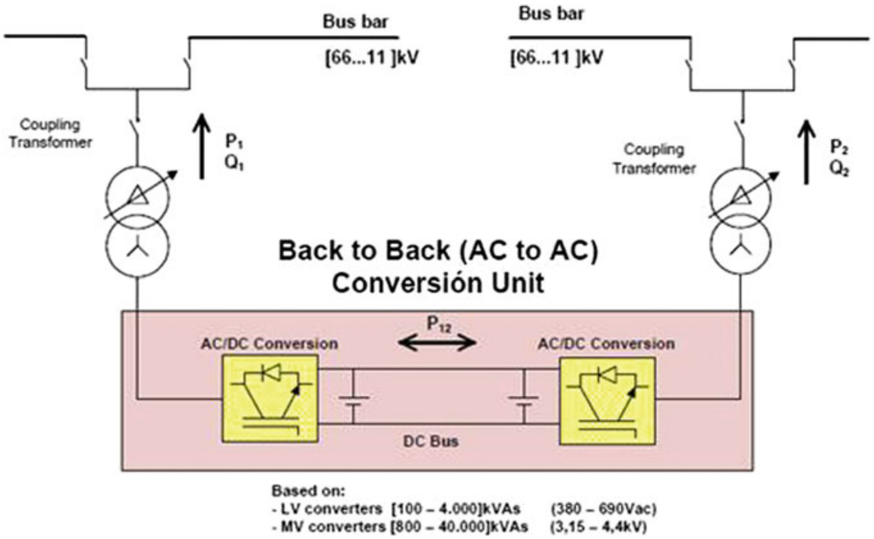


Fig. 9 Back-to-back flexible power link connection between two grids

4.4.3 Example 3: UK Network Equilibrium project

The project contains a back-to-back power electronic converter (AC–DC–AC) which allows power transfers across two different 33 kV networks, called flexible power link (FPL). The FPL will allow controlled transfers of both real and reactive power flows between the two networks. Western Power Distribution (WPD) as part of their 'Network Equilibrium' project runs this activity. It is estimated that deploying such flexible power links across the UK could release 1.5 GW of capacity by 2050 [9] (Fig. 9).

4.4.4 Example 4: Indonesia

Coupling of an industrial grid including own generation, highly unbalanced and distorted load (arc furnace) with a public grid. There is a surplus of generated energy in the industrial grid, but both grids cannot directly be interconnected. A back-to-back converter with sufficient rating towards the industrial grid to compensate the unbalanced and lower-order harmonics interconnects both grids. It reduces the unbalanced load on the industrial grid power generators, reduces the harmonics in the industrial grid and enables four-quadrant power transfer between both grids [10] (Fig. 10).

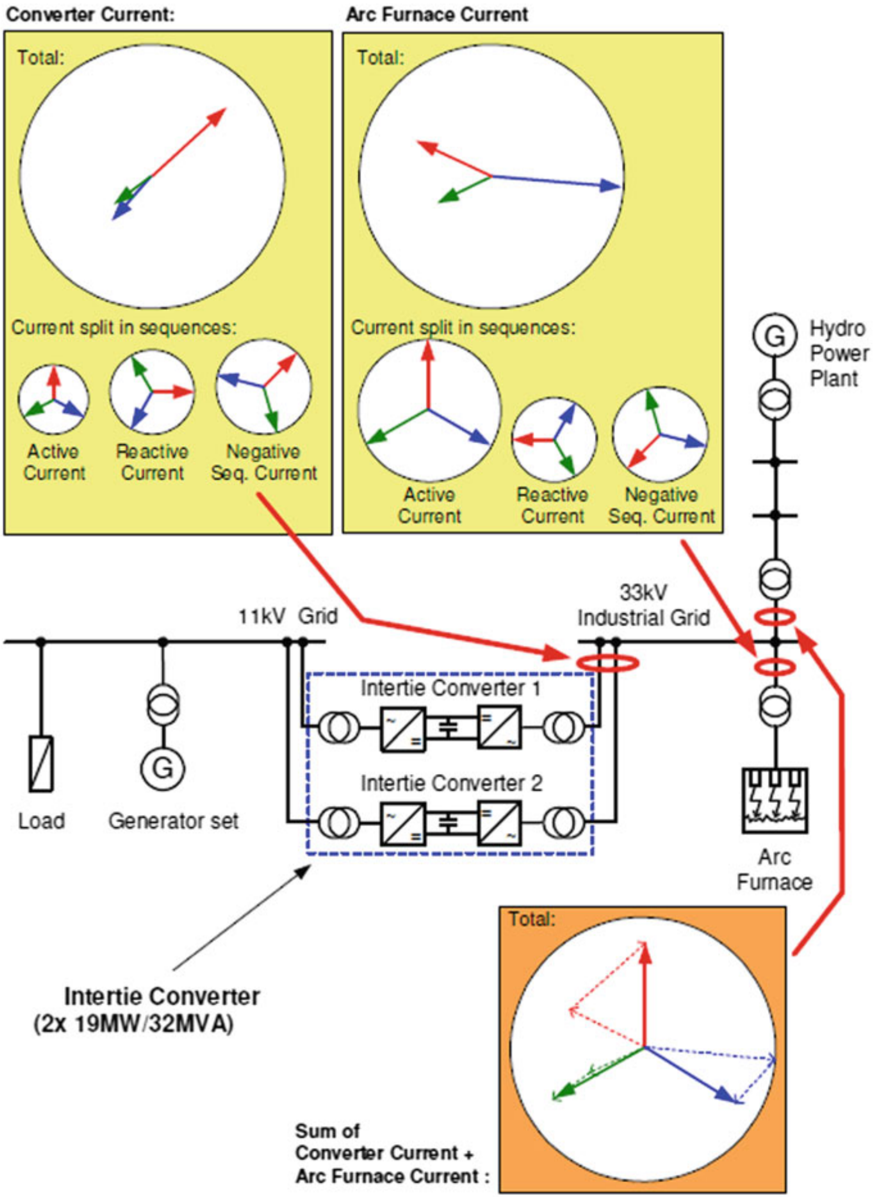


Fig. 10 Back-to-back intertie connection between an industrial grid and a public grid

4.4.5 Example 5: China—Wenchang Project

The Wenchang platform submarine cable repair project was started in 2010 to help address the urgent loss of supply security problem. The MVDC was configured as a symmetrical bipole with a rating of 8 MVA/±15 kV, such that the positive and negative poles are identical, and each pole can work independently of the other to provide security of supply to the remote platforms. The project's aim is to convert a faulted 35 kV AC line to 3 MW DC line with voltage source converter (VSC) topology as discussed in [11, 12] (Fig. 11).

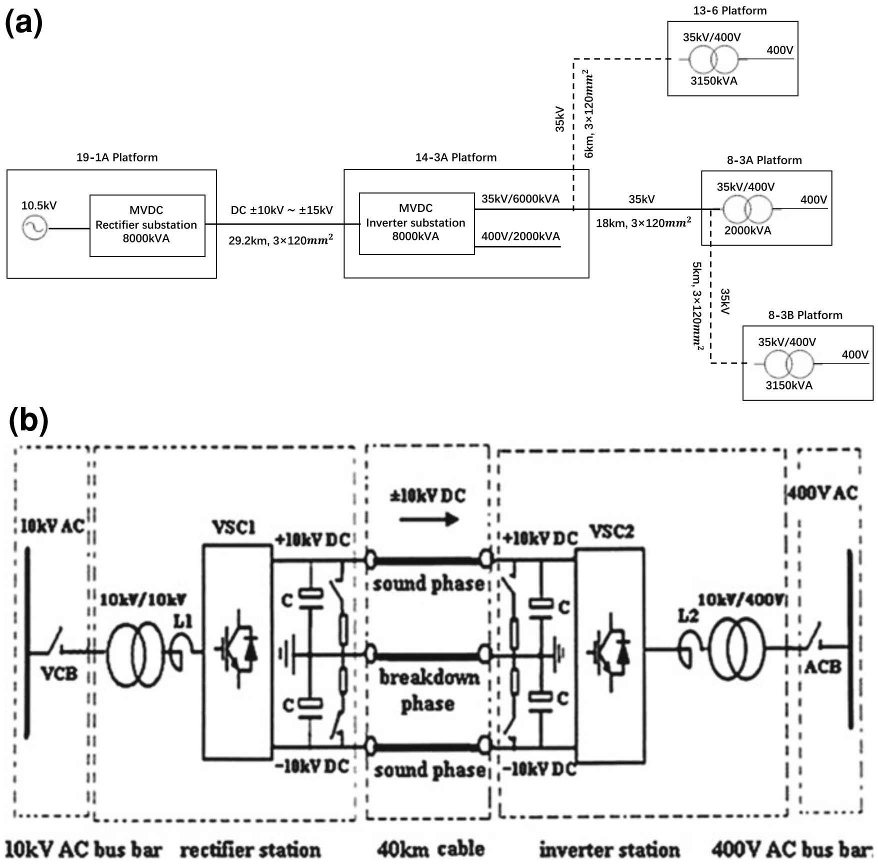


Fig. 11 8 MVA/±15 kV Wenchang MVDC project. **a** Schematic diagram; **b** AC to DC operation schematic

5 The Development of Multi-terminal DC Grids

The justification for interconnection of the power grid continues to grow to facilitate the sharing of intermittent renewable sources and to bring bulk, renewable, generation from remote sources to load centres. This requires transmission system reinforcements in the alternating current (AC) systems, and often the traditional approach might be to build ultra-high-voltage alternating current (UHVAC) lines on top of the existing transmission systems. However, the experience of the last decades indicates that the permitting process for such a solution, particularly in some areas of the world, could be very time consuming. In some cases, it may even be impossible to get permission to build any new overhead lines [13].

Until now, DC transmission has been used primarily for point-to-point transmission with two terminals, though there are a few three-terminal systems in operation. Multi-terminal HVDC transmission systems can be realised today for both line commutated converter (LCC) HVDC transmission and voltage source converter (VSC) HVDC transmission.

VSC HVDC transmission is well suited to HVDC grids (DC network with a plurality of converters, partly meshed and partly radial) as a change of power direction does not require a change of voltage polarity, as is required when using only line commutated converter (LCC) technology. However, under certain applications, it may be practical to mix both LCC and VSC technologies to build the most practical and cost-effective system [14].

5.1 Development of Multi-terminal DC Networks

The drive to build multi-terminal DC transmission systems is to, as far as practically possible, maintain the advantages of point-to-point DC transmission but to make better utilisation of both the asset investment and the environmental impact of the power system infrastructure. An example of how such a scheme could be developed can be seen by considering today's large remote offshore wind farms that are connected through a point-to-point connection, Fig. 12a. If there is also an economic opportunity to connect two AC networks together and the offshore wind farm is, geographically, on-route, then it may be deemed advantageous to add a third terminal to this network such that the wind energy can be supplied to either AC network or, during times of lower wind generation, the capability of the DC transmission equipment can be utilised to exchange power between the two AC networks, Fig. 12b. This scenario can be further expanded if one, or both, of the onshore AC systems has constraints within the onshore transmission corridor capacity. The DC transmission can be used to provide a bypass for the onshore AC grid, possibly utilising an offshore corridor, Fig. 12c. This is, of course, just one example for the utilisation of a multi-terminal DC system, and there are many other scenarios that could justify the consideration of such a DC network.

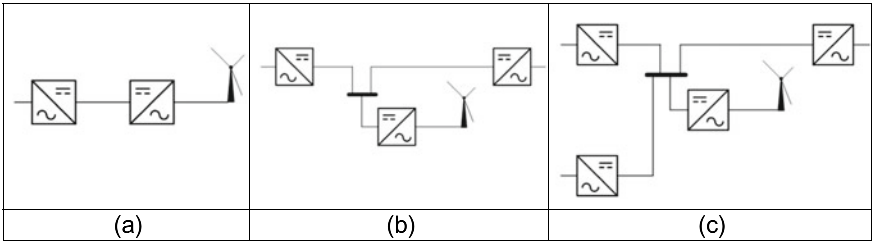

(a) (b) (c)

Fig. 12 Examples of multi-terminal HVDC connections. **a** Point-to-point, **b** three-terminal, **c** multi-terminal

5.2 *DC Grids*

Expanding the multi-terminal scenario discussed in Sect. 5.1 a 'DC Grid' can be envisaged. In the context used here, a DC grid is considered to contain some element of meshing and hence provides more redundant pathways for power transmission. The schematic pictures (Fig. 13a, b) show two possible situations where the increasing need for transmission of power has been solved by building only end-to-end transmission HVDC or in the other case an HVDC grid. In these pictures, only the

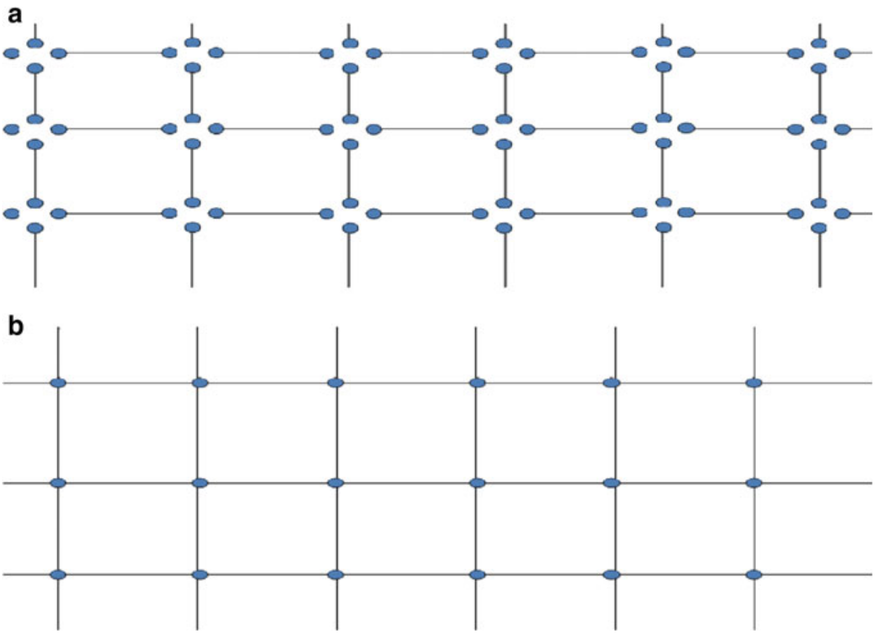


Fig. 13 **a** Overlay HVDC consisting or multiple point-to-point transmissions. Schematic picture. Circles: A DC node connected to one single converter [13]. **b** Overlay HVDC grid. Schematic picture. Circles: A DC node connected to one single converter [13]

DC lines and DC nodes are shown, where the DC nodes are drawn as dots. It is assumed that a single converter is connected at each DC node. It can be seen from Fig. 13b that the total infrastructure investment of the DC grid solution is much lower that only utilising a series of point-to-point connections. Also, the coupling between converters at the nodes is not dependent on the underlying AC network as is the case in Fig. 13a.

5.3 Equipment Development Associated with DC Networks

The development of a DC network, beyond a certain size, will necessitate the use of new equipment, not in common usage today.

5.3.1 HVDC Circuit Breakers

With an increased number of DC converters and transmission connections on a common DC circuit, it is advantageous to be able to isolate part of the circuit when that part is subjected to a fault but to leave the remaining network in operation. This is the normal way that an AC system operates but possesses some challenges in a DC system because of the low inertia of the DC network and the lack of zero crossings to facilitate current interruption. To meet these challenges, HVDC circuit breakers are needed that can both interrupt a DC current and operate rapidly, thereby mitigating the rate of increase of DC fault current.

Today, the solution developed by several suppliers and implemented on several multi-terminal projects is based on the so-called hybrid solution. In this solution, as shown in Fig. 14, the normal current path is through a mechanical switch and hence the operating losses are low; however, in the event of a breaker trip command the small power electronic switch in series with the mechanical breaker is opened. This small switch can create enough back EMF to commutate the current into a larger power

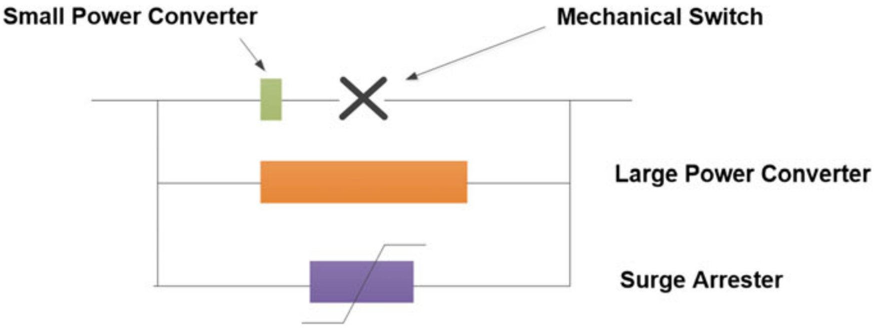


Fig. 14 A schematic of a typical HVDC circuit breaker

electronic switch. When all the current has commutated, the mechanical switch can be opened, and once this has opened the large power electronic switch can commutate the current into a surge arrester which both creates a back EMF to drive the fault current to zero and absorbs the energy associated with the fault current.

5.3.2 Current/Power Flow Controllers

In a meshed DC grid, there are multiple paths for the DC current to flow and unlike in a radial connection the power flow through a conductor cannot be directly controlled through control of the associated node voltage as this node voltage will impact on multiple current paths. This could, under some circumstances, lead to constraints in the power flow through the DC grid due to a need to limit the current in one part of the grid. A solution to this is to introduce additional, small, converters that can exchange current/power between parallel paths within the DC grid, thereby providing an additional degree of freedom to control the DC current flow. Such devices can be considered as being the equivalent of FACTS devices but for a DC grid.

5.3.3 DC/DC Converters

Future HVDC grids will most certainly face the problem of connecting existing HVDC links at voltages that are not the same as the grid, and there might also be need to make connections between grids of different voltages. This different voltage could be caused by lack of standardisation. One grid could, for example, connect offshore wind farms, and another grid could be transcontinental. In this case, it is most probable that the grid connecting offshore wind will operate at a lower voltage than a transcontinental grid. In all cases where there is a need to connect HVDC of different voltages, some kind of DC/DC converter is needed.

5.3.4 DC Grid Automation

With an increase in the complexity of the DC network, it becomes necessary to have an additional layer of control that can provide both the desired DC grid power flow, or as close as is achievable, and can also look at the operating conditions at each node and in each transmission corridor and calculate the necessary operating condition at each node to comply with any constraints that are applied to the DC grid. For example, in its simplest form the DC grid automation system should be aiming to achieve both the ordered power flow and minimise the transmission losses within the total grid. Additional features may, for example, require the operation of the DC grid to consider contingency cases, allowing for possible network disturbances.

6 New AC Grid Challenges

The energy sector is going through a major transformation. The three macro-themes of decarbonisation, decentralisation and digitalisation have created both the opportunities and challenges for power electronics applications in power systems.

6.1 Maintaining the Stability of the Power System with a High Degree of Power Electronics

The integration of asynchronous generation using power electronics converters has resulted in the reduction of short-circuit strength and system inertia. This has created operability challenges for the networks. The reduction in the short-circuit strength not only poses challenging technical requirements for new connections but may also create stability issues for the existing power electronics converters. However, the conventional assumptions and approximations relating to the strength of the AC system to support stable operation of power electronic interfaces should be reviewed and may be revised. There is a requirement of a more fundamental research to understand the stability issues of power electronic converters associated with the short-circuit strength at the point of common coupling.

6.1.1 Converter Interactions

PE-interfaced devices are controllable equipment, with very short response time. Up to now, the operation of, e.g., some far disseminated point-to-point HVDC links could be handled independently from one from another, as their action had an impact in their own area only. But the multiplication of such devices requires coordinated action from them and/or control and setpoint adjustment depending on external circumstances (short-term wind power forecast, AC network loading, etc.). This is being considered for some current projects (Power Management System in Johan Sverdrup project [15] and Master Controller for Interconnector Operation (MIO) in Kriegers Flak project [16]). In a more distant perspective, HVDC grids, strict coordination of a variety of converters connected to the same DC circuit will be even more critical due to the fast dynamics of phenomena (e.g. DC voltage variations) and the lack of margin offered by converters (no current overload capability). This was anticipated by CENELEC TC8X [17], and a practical implementation of a master control was successfully experimented with three HVDC manufacturers using offline simulation to operate various multi-terminal HVDC systems [18]. This perspective will result in new requirements, mainly the compliance of HVDC converters to a standard common interface (still to be defined) for their operation at a high level (setpoints, ramps, delays, communication protocol).

6.1.2 Protection

Challenges related to protection appear with high penetration levels of generators based on full-converter technology and HVDC converters. These devices do not provide overcurrent during a fault, so overcurrent protection schemes of transformers may not detect faults, with a risk of voltage dip in distribution networks and loads. In addition, the replacement of synchronous generators by PE-interfaced generation decreases the short-circuit power, which leads to broader voltage dip propagation, which in turn requires even more demanding fault-ride-through requirements. Furthermore, PE-based devices do not provide negative-sequence current either as standard so ground protections or distance protections may also have problems to detect faults. Up to now, grid code requirements for PE-interfaced devices (HVDC, wind turbines, etc.) mainly address power system stability issues with requirements related to low-voltage ride-through capability for instance; however, new requirements will certainly be needed to ensure smooth operation of existing AC protection under a large penetration of PE devices (negative-sequence current injection, etc.).

6.1.3 Grid-Forming Versus Grid-Following

System inertia is constantly decreasing as the result of the replacement of synchronous generator with PE-interfaced generation. Under some circumstances (e.g. isolated network due to a severe fault, very windy or sunny conditions), the share of renewable energy can be prominent with respect to synchronous generation. Various consequences result from this degradation, such as excessive rate of change of frequency (RoCoF), lower frequency nadir, reduced ramping margins, which in turn may trigger frequency-based protection (such as RoCoF relays), finally tripping generation units. Additionally, the increasing share of PE-interfaced devices tends to reduce the overall short-circuit level as renewable energy sources are substituted to synchronous generation; this results in other types of issues such as a higher risk of commutation failures for thyristor-based converters.

In order to overcome those issues, some new requirements are progressively proposed for converters to implement a ‘grid-forming’ behaviour (thus enabling the converter to maintain stiffer AC voltage and frequency from the very first instants following a disturbance, and to synchronise to an AC system frequency, similar to an AC synchronous generator), instead of currently used grid-feeding controls (based on a PLL and a current control loop). The definition of a standard understanding of that need and the underlying requirements are investigated in various working groups, for instance [19, 20].

6.1.4 Validation

The validation of any interaction issues requires the detailed network models. The first step for this is to develop a dynamic equivalent model of the network in EMT simulation environment. With a high degree of power electronics converters, the dynamic network reduction process requires further research. The model data sharing across various participants has been a big challenge. Research is required to find out how to best represent these devices in EMT simulation domain and what kind of sensitivity analysis would be required to gain more confidence about the simulation results.

There is also an increasing trend for owners to purchase replicas of the converter controllers that can, primarily, be used in a real-time simulation environment, to check the performance of a new power electronic device against other existing devices for which control replicas exist. These replicas can also be used to familiarise maintenance staff with the equipment away from the commercially operating plant. However, this approach requires a significant investment on the part of the transmission system owner, not only in the replica but in the real-time simulator along with the laboratory and operating staff associated with this.

6.1.5 Inter-operability

A need towards inter-operability between equipment from different vendors has been identified in earlier R&D projects which insisted on the definition of standard requirements on the DC side point of common coupling for converters. Some early proposals were provided in [21] where VSC converters are considered.

6.2 Unlocking Transmission Network Capacity Using FACTS Devices and Storage

There is a high degree of uncertainty around how the future of energy industry is going to look like. Future energy systems could use infrastructure very differently to how they are employed today. Several individual energy vectors—electricity, gas and hydrogen—can deliver multiple services, and there are other services that can be met or delivered by more than one vector or network. Governments may pull both together to safeguard consumer interest by adopting the whole energy system view. The decarbonisation trends in transport and heat sectors will have a significant influence on the investment requirements in the electricity transmission sector.

This uncertainty makes any big investment decision in electricity transmission sector to undergo a greater level of scrutiny, e.g. building new transmission lines. However, it creates the opportunity for the power electronics industry. The FACTS devices have the potential to unlock the additional transmission capacity without incurring a large investment. They can defer the investment for the future years, when there will be more certainty about the need case.

Research should also be extended towards maximising the use of power electronics converters. The converters can provide several ancillary services such as frequency support, reactive power support, inertia calculation, harmonic filtering and improving power quality.

6.3 Harmonic Stability

Harmonic stability is an emerging form of power system stability that can be seen as an extension of the classical small-signal stability as defined, for example, by [22]. Classical small-signal stability typically relates to electromechanical dynamics of synchronous machines and their control system and interaction through the grid and considers a frequency range up to a few Hz.

On the other hand, harmonic stability relates to electromagnetic dynamics of the grid and their interaction with power electronic converter systems (PECS) and their associated control systems. Since PECS are typically driven by open-loop power electronic switching in a frequency range of several kHz, high-bandwidth control can be associated with their grid-side converters, and harmonic stability analysis therefore requires extension of the small-disturbance stability concept to a much wider frequency range [23].

In short, harmonic instability relates to the destabilisation of grid resonances through their interaction with converter control or a harmful interaction between different converter systems through their grid connection. In both cases, harmonic instability leads to extreme inter-harmonic distortions that can usually not be predicted by classical harmonic power flow studies. Such instabilities can cause failure of cables and filter capacitors if allowed to persist, as the resulting harmonic distortions often are far beyond the design requirements for the filter components.

The observation of unstable interactions between converter and grid systems is not new. Early observations and some early analysis results were presented in [24]; however, the topic has recently gained significant importance due to the proliferation of power electronics in the grids. Some examples where issues have been reported are railway power systems following the introduction of variable speed drives in trains [25] as well as offshore wind farms and large solar PV installations [26]. Rigorous analytical studies are available for other applications such as aircraft [27], marine power systems [28] and microgrids [29].

6.3.1 Non-passive Behaviour of Converter Systems

In open-loop operation, any PECS will introduce a small positive resistance due to parasitic effects of resistance in the filter circuit and switching losses that will contribute to damping of grid resonances. PECS are typically driven by power electronic switching in a frequency range of several kHz meaning that high-bandwidth control can be associated with their grid connection. Most PECS employ cascaded feedback control loops for control of the primary energy source or load management, DC link voltage control, grid synchronisation and current control that will introduce non-passive behaviour of the PECS that can potentially destabilise grid resonances.

Non-passivity due to the control loops can be seen as a direct consequence of design. For example, the converter must meet certain requirements in terms of response to grid faults or provision of voltage or frequency support, which inherently implies non-passive behaviour. These effects typically introduce non-passivity in a low frequency range up to a maximum of a few hundred hertz and generally at least one decade below the switching frequency of the converter system. The degree of non-passivity in this band and the breadth of the band itself are strongly influenced by the tuning of the control system which in turn depends on the dynamic performance requirements for the converter system.

Another source of non-passivity is the time delay due to sampling, filtering and modulation delay in the PECS. This can be seen as an undesired effect that is hard to improve upon except by introducing faster sampling and higher switching frequencies in the converter. In a current-controlled converter system, these effects generally introduce non-passive behaviour in frequency range lower than but in the same order of magnitude as the switching frequency. The degree of non-passivity in this high-frequency, non-passive region is highly dependent on the sampling and computational delay in the control system, the modulation delay as well as the gain of the current control.

Passivity can be analysed using grid and converter impedance as described in [30]. Figure 15 shows sample passivity analysis results for a grid connection consisting of two parallel 1 km AC cables to a strong grid (left) and a converter system similar to the grid-side converters used in photovoltaic and wind generators. As expected, the grid system remains passive for all frequencies and provides a small amount of damping at low frequencies.

6.3.2 Example of a Harmonic Stability Problem

The converter system exhibits a low-frequency region of non-passivity up to approximately 55 Hz in the controller reference frame due to the action of the outer control loops and grid synchronisation, and a high-frequency non-passive region due to the time delay between 1.5 and 2.6 kHz.

The simulation results in Fig. 16 show a typical manifestation of harmonic instability following the disconnection of one of the parallel cables at 0.5 s. Figure 17 shows the corresponding Fourier transformed phase voltage in a 100 ms window before the switching (top) and 100 ms window after the switching (bottom). Before the switching, there are small and typical harmonic components around the PWM switching frequency at 3.5 kHz as well as small but noticeable fifth and seventh harmonics.

Following the switching, a strong and rapidly growing inter-harmonic at 1.7 kHz is superimposed on the fundamental voltage. As a secondary effect of the harmonic instability, the magnitude of the switching harmonics in the phase voltage is also amplified by the harmonic disturbance by about a factor of two. At this point, it is

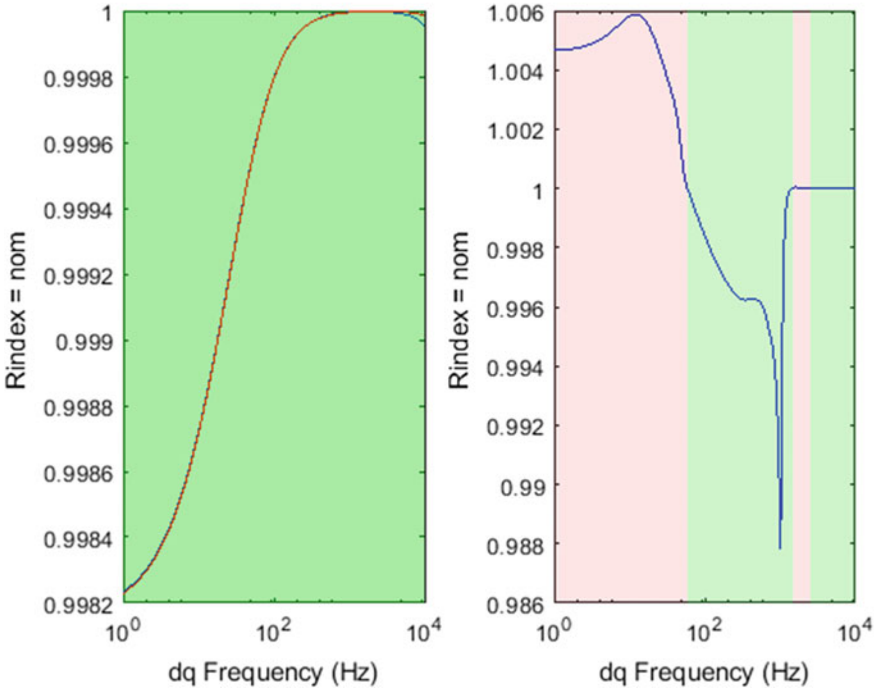


Fig. 15 Normalised passivity index for grid (left) and converter subsystems (right). The green areas correspond to passive frequency bands

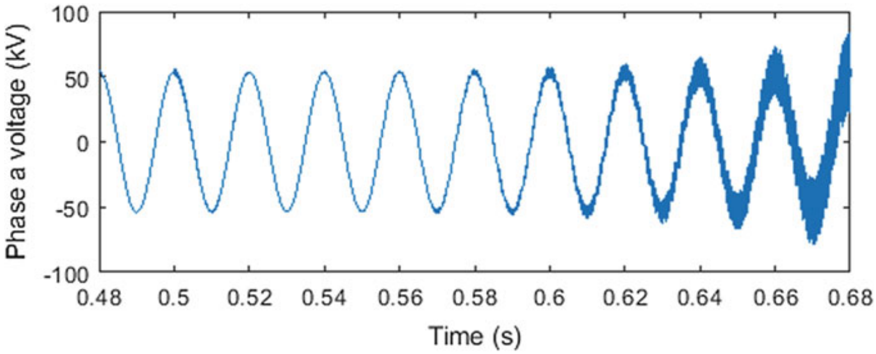


Fig. 16 Simulation of cable switching at 0.5 s

not unusual for converter systems to trip or restart due to internal protection functions [26]; however if not, the harmonic usually grows to a certain amplitude where the control system saturates and this condition will persist until the grid changes or the converter is manually disconnected.

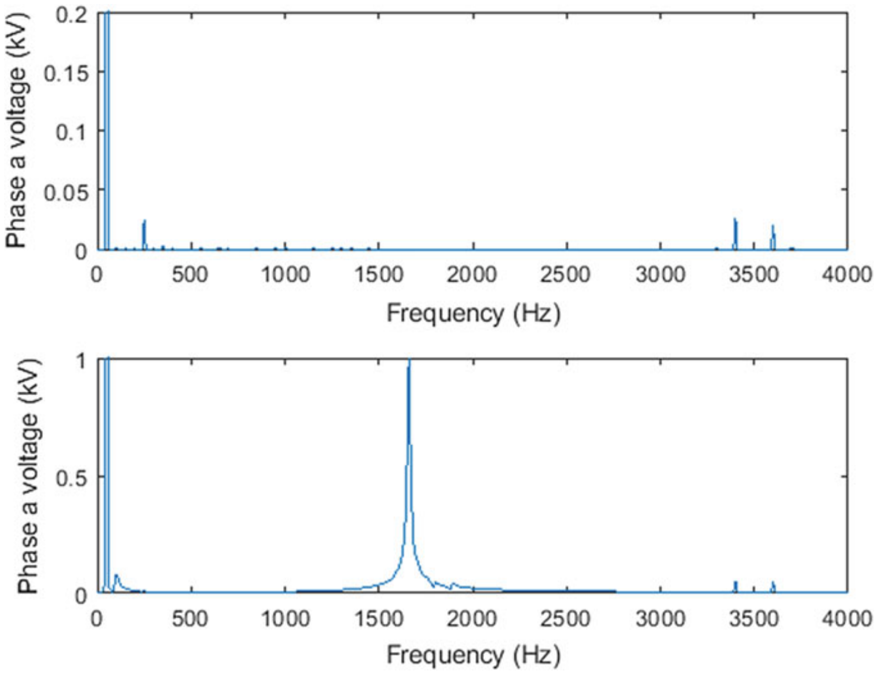


Fig. 17 Fourier analysis of phase voltages before switching (top) and after switching (bottom)

The mechanisms behind the harmonic instability can be explained as follows. Inspection of the equivalent impedance of the parallel connection of the grid and converter system which is given by

$$z_{\text{eq}}(s) = (z_{grid}^{-1}(s) + y_{\text{wtg}}(s))^{-1},$$

and shown in Fig. 18 reveals a poorly damped resonance at around 1.4 kHz with two cables in operation and 1.7 kHz with one cable in operation. With one cable in operation, the resonance falls inside the high-frequency non-passive region of the converter system which triggers the instability. In this frequency band, the converter system will amplify any variations seen in the grid voltages and currents due to its non-passive behaviour and continuously supply energy to the resonance with a growing oscillation as a consequence. On the other hand, in the case with two cables in operation, the grid provides enough damping in the passive region to counter the amplification by the converter system and the closed-loop system remains stable.

This example reveals a complex interaction of the converter system and the grid when it comes to determining the stability of the interconnected system that is not easy to intuitively understand without detailed analysis. For example, a change of the length of the cables to 300 m instead of 1 km would lead to the opposite conclusion that the system remains stable with one cable in operation but not with two. With one

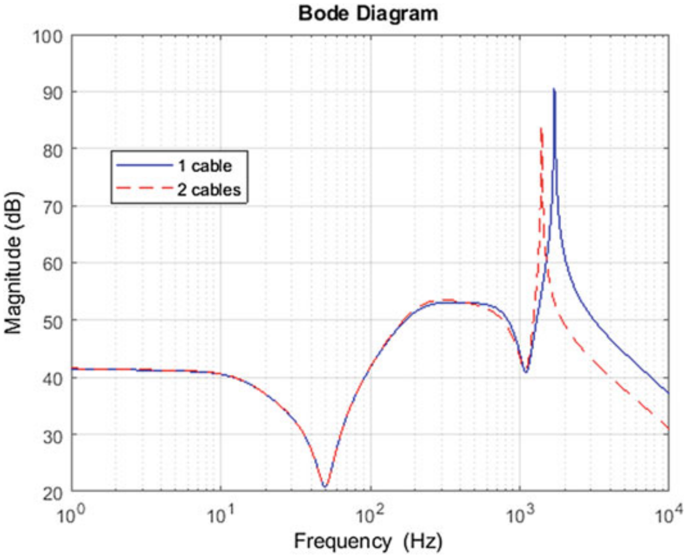


Fig. 18 Positive sequence input impedance of the combined grid and converter impedance with one and two cables in operation

cable, the resonance of the combined system would lie above the active region of the converter system and within it with two cables in operation. Thus, a small change in the topology or parameters can qualitatively change the behaviour of the system in an often non-intuitive way. This calls for structured approaches and screening procedures for assessment of harmonic stability.

6.3.3 Harmonic Stability Improvement

There are two different sources of the non-passive behaviour of converters, and both play an important role in harmonic instabilities. In general, both types result in extreme harmonic distortion at inter-harmonic frequencies.

Firstly, there is one related to the time delay in the converters which may cause high-frequency harmonic instabilities in a frequency range of the same order of magnitude as the converter switching frequency. The risk of this type of problems is larger in high-voltage networks with a large share of overhead lines whose inductance in combination with their own capacitance or shunt capacitors can create poorly damped resonances in the kHz range. These resonances are typically beyond the bandwidth of the converter control loops meaning that it is very hard to solve such problems by extending or adapting the tuning of the converter control system. For this type of problems, a solution may be to avoid certain switching configurations where resonances in known converter active regions can be foreseen. One may also consider additional damping resistors in converter filters (if installed) or control hardware upgrades that increase the sampling frequency to ensure converter system passivity or push the non-passive region to a higher frequency band. Simply shifting the non-passive region to a higher frequency band can be an effective solution since transformers and overhead lines can be expected to provide larger resistive losses at high frequencies, meaning that a stronger non-passive behaviour of converter systems can be tolerated at higher frequencies. Another solution that may be considered is grid-side passive filters. However, the design of these should be coordinated with converter control design to ensure that they do not introduce new resonances coinciding with active regions of converters. Also, passive filters may also add significant capacitance to the grid impedance, which in itself poses a stability challenge for current-controlled converter systems.

In other types of networks, such as microgrids, offshore wind or solar farms with long cable connections, grid resonances tend to appear in a much lower frequency range, in the order of a hundred or a few hundred Hz. In these grids, problems are more often related to the converter outer control loops and are referred to as low-frequency harmonic instabilities. These resonances are typically well within the bandwidth of the converter control system, and active damping strategies can be effectively used. This involves designing special control extensions to perform targeted or broad spectrum damping of resonances. Such methods are usually economically preferable since they do not require any new physical hardware and are also very effective in suppressing harmonic amplification of steady-state harmonics, even when no stability problem is present.

6.3.4 Challenges for the Future

Harmonic stability is most likely to be an issue in systems where the rating of converter-connected load and generation is large compared to the amount of directly connected resistive loads. This is already the case today for certain types of specialised grids. Several practical cases have been experienced, and active research is being performed for other types of specialised grids. Perhaps the next challenges will arise from the proliferation of electric vehicles that will lead to massive deployment of charging infrastructure in the low- and medium-voltage grids. Such charging infrastructure will add significant amounts of converters from different vendors and will highlight grid integration and inter-operability requirements for stable operation. This may force grid operators to do more detailed harmonics and power quality studies. Converter system manufacturers may need to take further steps, improve and tailor their control design for specific grid environments and more seriously consider the inter-operability of their converters with other manufacturers which will often be connected in parallel. Currently, grid codes do not consider explicitly harmonic stability although some proposals are under development for HVDC systems and offshore wind [31] and for rail power systems [32]. It is foreseen that future grid codes and study recommendations also for traditional distribution grids will need extension to incorporate harmonic stability and converter inter-operability as the degree of converter penetration increases on both the load and generation side.

Providing models that are good enough for harmonic stability studies while preserving the protection of intellectual property for converter manufacturers will be a major challenge. A promising approach is that manufacturers exchange impedance profiles as foreseen by [31, 32], but standardisation of measurement and computation techniques for such impedance profiles are still open topics.

Currently, analysis techniques for harmonic stability are a maturing field—a brief review of applicable methods is available in [23]. So far, most results have been based on impedance matching techniques, which are difficult to apply in practical cases where topologies become complex. The adoption of the modal analysis approach is more recent but shows some advantages, particularly related to its ability to pinpoint root causes of stability problem, universal applicability and scalability to grids with complex topologies and large number of converters.

7 Operation and Maintenance of Facts and HVDC Facilities

7.1 Challenges for Setting Up and Performing Operation and Maintenance of HVDC Facilities

There are certain challenges associated with a new FACTS or HVDC facility when preparing the facility for commercial operation that are typically not present when doing the same for normal AC transmission facilities. FACTS and HVDC facilities will have more complex control and protection systems and more auxiliary systems that are critical to the facility's operation (such as air conditioning, air handling and water cooling systems) than an AC transmission substation. They also will have solid-state power electronic equipment such as thyristors and IGBTs and in the case of HVDC may have long-distance submarine cable systems [33].

To be prepared to operate and maintain the new FACTS or HVDC assets upon completion of its construction, installation and commissioning, operation and maintenance (O&M) issues need to be considered as early as possible in the development of a new project. Late consideration can often lead to critical and costly issues, including being unprepared for various compliance issues and missing the unique training opportunities for the staff expected to operate and maintain the asset.

Early identification, engagement and involvement of the O&M team are important, in particular because training opportunities for O&M staff exist during the testing, construction, installation and commissioning of the HVDC facility, including:

- The factory testing of control and protection systems provides an opportunity for O&M staff to practise operating the system in a simulated environment without affecting the AC network. This can also allow an opportunity for feedback from O&M staff associated with the operator interfaces.

- During construction and installation, O&M staff can consider how the required O&M tasks can be completed. As the installation takes shape, O&M staff can identify potential issues for which solutions will be costlier to rework once the facility is completed.
- During the site works, custom O&M processes and procedures unique to the new facility can be developed by O&M staff in close cooperation with the supplier's specialist personnel, preventing potential issues on completion of the project.

Some key challenges for setting up and performing operation and maintenance for FACTS and HVDC facilities include:

- Location of control and monitoring
- Sourcing of operation and maintenance (O&M) expertise
- Spare part strategy
- Preparation of O&M documentation.

7.2 Location of Control and Monitoring

An owner and/or operator of a new facility will typically need to determine the location from which the new facility will be operated (e.g. dispatch of active and/or reactive power, operation of switches, etc.) and be monitored for alarms and events. The location options are typically from an existing manned network control rooms, at a new location, remote from the equipment or a manned control room at one or, for HVDC, multiple converter station locations. Some pros and cons of these options are provided in Table 2.

The owner and/or operator of the new facility will need to consider both capital and O&M costs when deciding on a location. Having a control location at one or more converter stations may save O&M costs, reducing the need to have local contractors or staff available close to the converter stations for first response and reduced reliance on high reliability communications, but will require additional facilities to be built at the sites and dedicated control centre staff.

Different utilities weigh different factors very differently and employ different options successfully. For example, a utility in Sweden (Svenska kraftnät) has no local operator in any HVDC station and fully depends on remote support, while the utility in India (Power Grid Corporation of India) has both operation and maintenance staff in every HVDC station.

7.3 Sourcing of O&M Expertise

The level of O&M expertise necessary for the successful operation of a HVDC facility can vary, from skills available readily such as the maintenance of the air-conditioning

Table 2 Control room location

Manned control room location	Pros	Cons
Existing transmission network control room	• No or minimal new staff • Low ongoing operating costs • Low cost and schedule impact	• Multi-skilling of operators • Less focus on the asset • Need to have arrangements in place for emergency response to site • Reliance on communication lines for visibility
New control room location remote from the asset	• 100% focus on the operation of the asset • Availability of qualified staff if remote control room is in densely populated area	• Need to have arrangements in place for emergency response to site • Reliance on communication lines for visibility • High ongoing operating costs • High cost and schedule impact
New control room location at one or multiple assets	• 100% focus on the asset • Emergency response to site can be covered by control staff • Non-reliance on communication lines (except inter-station communications)	• Need to have office accommodation facilities built on site with appropriate support facilities • High ongoing operating costs • High cost and schedule impact

units, through to rare technical skills, such as troubleshooting, replacement and repair of high-tech control and protection systems and power electronic switching devices.

Very often, a FACTS device or at least one HVDC converter station is located in a very remote location some distance away from large population areas, and in this case, the issue becomes that of sourcing this expertise and having it close enough to respond and attend the site in reasonable time.

Typically, some of the more common maintenance requirements, such as auxiliary power systems, air conditioning, water cooling systems and basic maintenance on high-voltage primary and secondary plant, can be sourced nearby. The difficulties lie in sourcing expertise in the more technical and specialised areas such as control and protection systems and power electronics (IGBTs and thyristors).

Some strategies that can be applied to manage these issues include:

1. Source local technical staff and invest in training.
2. Engage the supplier, or more specifically the OEM, for O&M activities.
3. Use local technical staff as first response with more specialised staff made available through options 1 or 2.

7.4 Spare Part Strategy

Some configurations of HVDC facilities have a degree of redundancy in their main circuit design. For example, many bipolar LCC HVDC facilities are capable of being operated at reduced power transfer with one pole out of service. However, most main circuit designs for FACTS and HVDC facilities are such that the loss of one major item of plant will significantly affect the power transfer capability. Some replacement items may have long lead times. The reliance of the facility's operation on many auxiliary systems, such as cooling and air-conditioning systems, means that the failure or reduced performance of these units can limit the equipment's operational capability as well. In these cases, easy access to spare parts and well-thought-out and pre-prepared replacement procedures can reduce the downtime in the event of failure and limit the effect of the failure.

The spare part strategy needs to be considered early in the project. The non-redundant items of main circuit equipment can usually be identified, in which case one or more spares should be specified to be supplied with the project. For the redundant items, items with either large quantities installed and with long lead times should have the appropriate number of spares specified with consideration to the anticipated failure rate, such as for thyristors and IGBT modules/units. The types and quantities of spare parts are heavily dependent on the reliability requirements of the HVDC equipment. It is seen that some utilities require spare transformers at each asset location. There are also utilities having common transformer spares for multiple assets.

In addition to considering the types and quantity of spare parts, other factors that should be considered in the spare part strategy include:

- Where the spare parts will be stored, including storage of large main circuit items (transformers, reactors, circuit breakers and capacitors) and controlled atmosphere spare part storage (sensitive electronics and power electronics)
- Possible future and short-term technical obsolescence, for example computers used for the human–machine interface. In this example, will similar specification computers and associated operating systems be available 'off the shelf' in a few years' time?
- Required shelving and method of storage, labelling, identification and retrieval of spare parts
- How will the larger spares be transported to their required location in instances where spare parts shared between converter stations or at a remote location.

7.5 Preparation of O&M Documentation

In a typical FACTS or HVDC project, the supplier will provide the necessary O&M documentation as detailed in the specification. However, there may be other O&M

documentation requirements which would not normally, or for various reasons could not, be provided by the supplier. The owner of the facility needs to prepare for this and implement a programme to ensure this documentation is developed prior to handover of the facility. Such documentation can include:

- OH&S documentation related to local codes, standards and guidelines
- High-voltage safety and access rules and switching programmes
- Documents to demonstrate compliance with statutory reliability requirements and/or requirements of the market operator
- Emergency response plans for the replacement of major items of non-redundant plant.

As a part of this process, and understanding that local OH&S requirements may differ to that of the suppliers' home country, it is recommended that O&M staff be present during the final stages of construction to identify any potential local OH&S issues associated with the troubleshooting, repair or replacement of equipment, for example requirements for working at heights or access to live electrical panels. Where issues are identified, appropriate documentation should be developed to manage the issue where a solution cannot be engineered.

The amount of owner-developed documentation required can vary from project to project and in some cases has been observed to be significant. There may also be a requirement for some of this documentation to be completed prior to first energisation of the facilities and before commissioning can begin in earnest. These requirements need to be scoped early in the project (preferably at a high level at least at the specification stage), and a process put in place in parallel with construction and installation activities to ensure these are complete when required.

8 Conclusions

Both FACTS and DC transmission have developed from a niche application within the AC network to a major element. This trend is expected to continue and even accelerate through the increased demand on both the transmission systems, through interconnection and the integration of renewable generation connected, through power electronic converters. The development of DC transmission is expected to develop into multi-terminal and HVDC grids to provide new corridors for power transfer.

The distribution system has, historically, been a passive interconnection between the transmission system and the load. However, with the increased integration of renewable generation at the distribution level along with new, active, loads this is no longer the case. To support this development, new applications of FACTS and DC transmission are being developed.

The integration of multiple power electronic converters into the AC grid is not without its challenges. These challenges will need to be addressed by both the owners and the suppliers over the coming years. One of these challenges, that needs to be considered, when specifying FACTS or DC transmission systems is the arrangements for operation and maintenance, and this must be factored into the project requirements.

Acknowledgment Photos/Pictures of equipment or HVDC installations are acknowledged (in alphabetical order) from: ABB Power Grids, GE, Infininon, Siemens

References

1. Schenk, M., Jansen, U., Przybilla, J., Koreman, C., Rathke, C.: “Power Semiconductors for Energy Transmission”, B4-106. CIGRE, Paris (2018)
2. Schenk, M., Przybilla J., Kellner-Werdehausen, U., Barthelmess, R., Dorn, J., Sachs, G., Uder, M., Völkel, S.: State of the art of bipolar semiconductors for very high power applications. In: PCIM Europe Conference, Nuremberg (2015)
3. Huang, H., Sachs, G., Schenk, M., Zhang, D.: HVDC Converter using 6 Inch Light Triggered Thyristors (LTT) for DC Currents up to 6250A 2016 International High Voltage Direct Current Conference (HVDC 2016). Shanghai (2016)
4. Heer, D., Domes, D., Peters, D.: Switching performance of a 1200 V SiC-Trench-Mosfet in a Low Power Module. PCIM, Nuremberg (2016)
5. Hierholzer, M., et al.: Characteristics of High Voltage IGBT Modules. IEE Colloquium on Propulsion Drives, London (1995)
6. Göttert, J. et al: 6.5 kV IGBT-Modules, PCIM, Nuremberg (1999)
7. Yu, J., Moon, A., Smith, K., MacLeod, N.: Developments in the Angle-DC Project; Conversion of a Medium Voltage AC Cable and Overhead Line Circuit to DC. CIGRE B4, Paris Session (2018)
8. Electricity NIC submission: SP Energy Networks—LV Engine, Nov 2017
9. Berry, J.: Network equilibrium. In: Balancing Generation and Demand. Project Progress Report Dec 2015–May 2016, 17 June 2016. [Online]. Available: https://www.westernpower.co.uk/docs/Innovation/Current-projects/Network-Equilibrium/EQUILIBRIUM_PPRMAY2016_V1.aspx
10. ABB: PRS SFC INCO EN, 4 Aug 2006. [Online]. Available https://library.e.abb.com/public/d20bc6e606717f9bc12576c40043ea95/PCS%206000%20STATCOM_INCO_EN.pdf
11. Liu, Y., Cao, X., Fu, M.: The upgrading renovation of an existing XLPE cable circuit by Ccof AC line to DC operation. IEEE Trans. Power Delivery **32**(3), 1321–1328 (2017)
12. Bathurst, G., Hwang, G., Tejwani, L.: MVDC—The new technology for distribution networks. In: 11th IET International Conference on AC and DC Power Transmission, pp. 1–5, Birmingham (2015)
13. CIGRE Brochure 533: HVDC Grid Feasibility Study
14. Barker, C.D., Whitehouse, R.S., Adamczyk, A.G., Kirby, N.M.: Urban Infeed Utilising Hybrid LCC Plus VSC. In: CIGRE paper 559, CIGRE Canada (2015)
15. Sharifabadi, K., Krajisnik, N., Teixeira Pinto, R., Achenbach, S., Råd, R.: Parallel Operation of Multivendor VSC-HVDC Schemes Feeding a Large Islanded Offshore Oil and Gas Grid. CIGRE, Paris (2018)
16. Marten, A.-K., Akhmatov, V., Stornowski, R.: Kriegers Flak Combined Grid Solution—Novel Double Use of Offshore Equipment. IET ACDC, Coventry (2019)
17. CENELEC - CLC/TS 50654: HVDC Grid Systems and connected Converter Stations—Guideline and Parameter Lists for Functional Specifications
18. Best Paths Deliverable D4.3 (public). First Recommendations to Enhance Interoperability in HVDC-VSC Multi-vendor Schemes. Available from http://www.bestpaths-project.eu/

19. TF-77—AC Fault Response Options for VSC HVDC Converters, CIGRE Science & Engineering, Vol. 15, October 2019
20. MIGRATE European Project: https://www.h2020-migrate.eu/
21. Best Paths Deliverable D9.3 (public). BEST PATHS DEMO#2. Final Recommendations For Interoperability Of Multivendor HVDC Systems. Available from http://www.bestpaths-project.eu/
22. Kundur, P., Paserba, J., Vitet, S.: Overview on definition and classification of power system stability. In: CIGRE/IEEE PES International Symposium Quality and Security of Electric Power Delivery Systems, 2003, pp. 1–4. CIGRE/PES, Oct 2003
23. CIGRE Brochure 754: AC Side Harmonics and Appropriate Harmonic Limits for VSC HVDC
24. Ainsworth, J.D.: Harmonic instability between controlled static convertors and a.c. networks. Proc. Inst. Electr. Eng. **114**(7), 949–957 (1967)
25. Mollerstedt, E., Bernhardsson, B.: Out of control because of harmonics-an analysis of the harmonic response of an inverter locomotive. IEEE Control Syst. Mag. **20**(4), 70–81 (2000)
26. Li, C.: Unstable operation of photovoltaic inverter from field experiences. IEEE Trans. Power Delivery **33**(2), 1013–1015 (2018)
27. Liu, X., Forsyth, A., Piquet, H.¸ Girinon, S., Roboam, X., Roux, N., Griffo, A., Wang, J., Bozhko, S., Wheeler, P., Margail, M., Mavier, J., Prisse, L.: Power quality and stability issues in more-electric aircraft electrical power systems. In: Host Publication, 9 (2009)
28. Ouroua, A., Domaschk, L., Beno, J.H.: Electric ship power system integration analyses through modeling and simulation. In: IEEE Electric Ship Technologies Symposium, pp. 70–74, July 2005
29. Dong, H., Yuan, S., Han, Z., Ding, X., Ma, S., Han, X.: A comprehensive strategy for power quality improvement of multi-inverter-based microgrid with mixed loads. IEEE Access **6**, 30903–30916 (2018)
30. Zhu, F., Xia, M., Antsaklis, P.J.: Passivity analysis and passivation of feedback systems using passivity indices. In: 2014 American Control Conference, pp. 1833–1838, June 2014
31. [B9] VDE: Technische regeln fur den anschluss von HGU-systemen und uber HGU-systeme angeschlossene erzeugungsanlagen, Draft guideline VDE-AR-N 4131, Aug 2018
32. [B10] CENELEC: Railway applications—fixed installations and rolling stock—technical criteria for the coordination between power supply and rolling stock to achieve interoperability—part 2: stability and harmonics. prEN 50388-2: Draft Standard for review, Aug 2017
33. CIGRE Brochure 697: Testing and Commissioning of VSC HVDC Systems

Carl Barker he holds a B.Eng. from Staffordshire Polytechnic and a M.Sc. from Bath University in the UK. He joined GE's Grid Solutions in Stafford, UK, in 1989, initially working on the design and development of individual HVDC and SVC projects then becoming System Design Manager, responsible for all technical aspects of HVDC projects. He is, at present, Consulting Engineer within the business providing technical support across many activities. He is Chartered Engineer in the UK, Member of the IET (UK), Senior Member of the IEEE, Regular Member of CIGRE B4 for the UK and Honorary Visiting Professor at Cardiff University.

Les Brand he is an experienced Electrical Engineer with over 25 years of experience in the transmission and distribution industry in Australia, Asia and the USA and is Managing Director of Amplitude Consultants based in Australia. He has held senior technical roles on the owner and operator side for a number of HVDC interconnection projects including Directlink (Australia), Murraylink (Australia), Basslink (Australia) and Trans Bay Cable (California, USA). He currently operates as a consultant providing technical advice on HVDC and FACTS projects under development and in operation. He is Fellow in Engineers Australia and Regular Member of CIGRE B4 for Australia and was convenor of the international working group B4.63 ‘Commissioning of VSC HVDC Systems’. He is the convenor of IEC TC99 JMT 7 responsible for the revision of IEC TS 61936-2 ‘Power installations exceeding 1 kV AC and 1.5 kV AC—Part 2: DC’.

Olivier Despouys holds a M.Sc. from engineering school ENSEEIHT and a Ph.D. from LAAS-CNRS in France. He worked for EDF in Paris, France, in 2001 as IT Project Developer and Manager, before joining RTE where he started to work in 2009 on specifications for HVDC interconnections, European grid code for HVDC and research projects related to DC technologies. He is, at present, R&D Project Manager for HVDC and Power Electronics, managing a portfolio of research activities at RTE. He is Regular Member of CIGRE B4 for France.

Robin Gupta holds a master in electrical engineering from IIT Kanpur in India. He is working in National Grid Electricity Transmission (NGET), UK, as Innovation Lead for HVDC and power electronics portfolio. In this role, he is leading the research efforts to mitigate the control interaction issues associated with a high penetration of power electronics converters. Before joining NGET, he led several engineering and R&D projects on converter control system design, power system simulation, and smart grid with GE and Siemens. He is Member of the IET (UK) and IAM certified in asset management.

Neil Kirby he graduated with a B.Sc. degree in electrical engineering and computing science at the University of Newcastle upon Tyne in England, began work with GEC Rectifiers in 1982, based in Stafford, England, and has remained with the company through many transitions since that time from GEC, GEC Alsthom, Alstom, Areva and now General Electric. He has worked in many areas of HVDC hardware and software, seeing projects from concept to detailed design, through manufacturing, testing and commissioning on site, for HVDC systems in UK, France, Canada, India and South Korea. In 2003, he relocated to Philadelphia in the USA to develop the HVDC business in North America, and his current position is HVDC & FACTS Business Development Manager for N America. He is Senior Member of IEEE, CIGRE US National Committee B4 Regular Member, and the IET, and has also been Member of ANSI and IEC. He has authored and co-authored many published papers on the subject of HVDC and is active on many IEEE, CIGRE working groups, as well as other standard institutions and committees.

Kees Koreman is currently working in the Asset Management Offshore Department of TenneT. He is in charge of the electrical design of HVDC interconnectors used for connection to neighbouring countries with cables in the North Sea. His particular interest is in converter station design with a focus on the protection and control systems. He was Chairman of the International CIGRE Working Group on protection and local control of DC grids. Currently, he is leading the electrical development team for the North Sea Wind Power Hub, an offshore wind project developed by an international consortium to increase the utilisation of wind power in the North Sea.

Abhay Kumar Jain holds a B.Eng. from IIT Roorkee and MBA from New Delhi, India. He joined NTPC Ltd. in India in 1982 and worked with the design of HVDC projects and many other EHV substations. From year 1995 to 2000, he worked for ABB Ltd., New Delhi, as Senior Manager at Power System Engineering and Business Development Department. Presently, he is working as Senior Principal Project Lead Engineer and Senior Project Manager at ABB HVDC, Sweden. He is providing technical support for design and execution of large HVDC projects. Lately, he has been involved with North-East Agra 800 kV multi-terminal and Raigarh–Pugalur 800 kV HVDC projects in India. He is Chartered Engineer in India, Member of the IE (India) and Active Member of CIGRE. He has been with CIGRE for more than last 3 decades including as Chairman of Swedish National Committee for CIGRE, Swedish Regular Member in CIGRE (B4), Member of Administrative Council of CIGRE and Member of overall Technical Council of CIGRE.

Longás Viejo Carmen holds a master's in industrial engineer from Zaragoza University in Spain. She is Senior Engineer of the Network Reliability Department, in Red Eléctrica de España (REE), the Spanish Transmission and System Operator. Since she joined REE in 2009, she has been involved mainly in renewable energy grid integration studies, in electrical network and generation modelling, in HVDC and FACTS device specification, control design and network integration studies, as well as connection network code development and implementation. She is currently Regular Member of CIGRE B4 Study Committee for Spain.

Dr. Larsson Mats is Senior Principal Scientist at ABB Corporate Research in Baden, Switzerland. He holds a Ph.D. degree in industrial automation and a master's degree in computer science from Lund University, Sweden. He has been with ABB Switzerland since 2001 and has led the research on wide-area measurement systems and power system stability. Recent research focuses on the analysis and control of harmonic stability, and he was a main contributor in troubleshooting the harmonic issues in the Bard/Borwin wind farm and HVDC system, and the subsequent development of an active damping concept for the HVDC converter. He has authored or co-authored more than 60 scientific manuscripts for leading journals and conferences as well as more than 30 granted patents and patent applications. In 2011, he was nominated by the European Patent Office Best Inventor Award, for inventions in the field of synchrophasor-based wide-area monitoring.

James Yu is Charted Engineer, Elected IET (Institute of Engineering and Technology) Fellow and Royal Engineering Academy Visiting Professor. He is the convenor of a joint CIGRE Medium Voltage DC Working Group: C6/B4.37. He is Deputy UK Regular Member of B4. He joined the UK electricity transmission/distribution industry after he finished his studies from Newcastle upon Tyne. He has taken various technical, commercial and managerial roles in the industry. He is currently accountable for the innovation project delivery at SP Energy Networks. His team are working on flagship innovation projects at national and European level, and pushing the innovation into business. He has been recognised by the Utilities Innovation Star Award in 2016. He is passionate about education and fully aware of its profound impact on young people's future. He has strong commitment in the engineering higher education in the UK. He is Ph.D. Supervisor and Visiting Professor at various institutes, including Glasgow University, University of Newcastle upon Tyne and the University of Manchester. He published over 50 academic papers covering electricity market, transmission network control, renewable generation and engineering education.

Protection and Automation

Iony Patriota de Siqueira

1 Introduction

Protection, automation and control systems (PACS) are an essential part of existing power systems and will continue to play a key role in the electricity supply systems of the future. From the control and protection of individual equipments like transformers, reactors, generators, motors, turbines, transmission lines, etc., to interconnected substations and power plants, PACS make the secure and automated operation of wide-area transmission and distribution systems possible, in a synchronized and harmonious form, while limiting the consequences and preserving their integrities during faults.

This chapter examines the current state-of-the-art and probable long-range directions of evolution of PACS, and their role in the electricity supply systems of the future. It is organized into three perspectives: State-of-the-Art, grid requirements, and future developments. Its content is based on data from two-structured surveys conducted by CIGRE: Functional Requirements of Power System Protection and Automation [1], with answers provided by 135 experts in 97 companies from 42 countries, and a specific questionnaire about Protection and Automation for the Electricity Supply Systems of the Future [2, 3] with contributions from 11 countries. Further contributions were received from members of the Strategic Advisory Group (SAG) of the Study Committee B5—Protection and Automation.

The "State-of-the-Art" perspective is a short description of the status of PACS, including its technology and know-how; standardization and interoperability; advanced metering infrastructure and sensor devices; engineering process including planning, specification, design and operational phases; development tools; hardware, software and telecommunication technologies; education and knowledge acquisition.

On behalf of CIGRE Study Committee B5.

I. P. de Siqueira (✉)
Study Committee B5, Tecnix Engineering and Architecture Ltd, Recife, Brazil
e-mail: iony@tecnix.com.br

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_9

The “Grid Requirements” perspective is a justified list of current or future grid needs not yet solved or poorly addressed by current PACS technologies, including concepts, techniques, education, standardization, practices, etc., as seen by stakeholders. This will cover requirements related to the power sector structure, prosumers, organization, cybersecurity, hardware, software, technology, islanding, education and knowledge acquisition, etc.

The “Future Developments” perspective is a justified list of topics, describing possible (long-range) scenarios of evolution of PACS. This will address the progress of wide-area distributed and centralized systems; software-defined protection and automation; cloud-based systems; remote monitoring, testing and maintenance; advanced user tools; application of formal methods; education and knowledge acquisition; research and development; standardization and regulation; etc., necessary to be pursued or developed, and how they will attain the above requirements. As this perspective is dependent on the evolution of the electrical network, but also on the parallel development of new technologies, methodologies, power electronics, telecommunication and software. It is expected that the scenario described in this chapter may change in the future, needing an update with time.

The summary and conclusions resumes the main directions expected for PACS evolution in the long-range future, with recommendations for stakeholders.

2 State-of-the-Art

The power industry is traditionally seen as conservative, but innovation is a characteristic of the current status of PACS, building on the new developments in hardware, software, and telecommunications. This section provides a summary of the state-of-the-art of PACS and their supporting technologies, covering the following aspects:

- Technology and know-how
- Protection
- Standardization and regulation
- Advanced metering infrastructure
- Engineering process
- Development tools
- Hardware technologies
- Software technologies
- Telecommunication technologies
- Advanced sensor devices
- Education and knowledge acquisition.

As PACS is based on many diverse technologies, just a short description of each topic will be provided with their current status of development and application and with emphasis on their positive and negative aspects.

Technology and Know-how

Although many existing installations still use PACS based on electromechanical or electronic devices, most of the new systems are based on digital technology and optical networks. Process computers use local area networks (LAN) to transmit signals internal to the substation and power plants, and wide-area networks (WAN) to exchange data among substations and control centers. Local components are mainly organized as Intelligent Electronic Devices (IEDs) performing protection and control functions, and interconnected by copper, optical fiber, or radio telecommunication networks. Most existing installations use a station bus but not a process bus near the field components. These are usually interfaced using bay cubicles hardwired to the high voltage (HV) equipment. Remote supervision is often based on RTUs (Remote Terminal Unit (RTUs) and not on full digital systems. RTU allows the remote access for failure and event analysis, supervision, command and control, but require dedicated software configuration management and continuous retrofit, resulting in user dependency on vendor for PACS evolution and patches.

Most PACS installed today implement multifunction numeric devices. As a result, they occupy less space and can be more cost efficient. However, multiple functions require many settings and programmable logic and hence, the configuration, asset management, and documentation effort can be significant. The scope for errors is increased. Some new PACS employ distributed physical devices for measuring and decision making, including phasor measuring units (PMU), merging units (MU), and control units (CU) for interfacing locally to the process equipment, while IEDs and phasor data concentrators (PDCs) are used for collecting, processing, and decision making based on the measured signals, with command messages transferred to control units and back to the primary equipment. This architecture typically adopts a two-layer network within a substation, with a process network for transmitting the measurands and control signals among the PMU, MU, and CU devices, and a station network for transmitting signals and connecting IEDs and PDCs within a substation. Figure 1 illustrates a typical PACS for a transformer bay in a substation, formed by a process network with two control units and one merging unit, and a station network with five IEDs for overcurrent and differential protection, bay control, operator console, engineering station, and telecommunication gateway.

This architecture is an example of the state-of-the-art of PACS being currently deployed in new substations.

Protection

The purpose of an electrical power system is to generate and supply electrical energy to consumers. The greatest threat to the security of a supply system is a short circuit, which generates abnormally high current flow and is accompanied by a localized release of a considerable quantity of energy that can cause fire at the fault location,

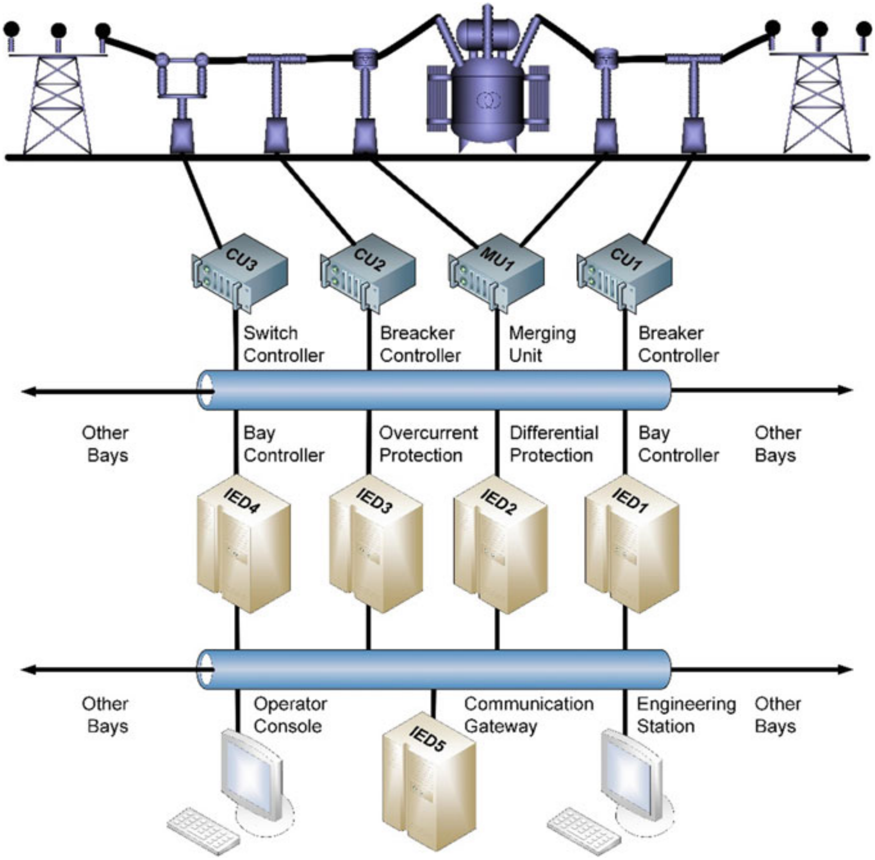


Fig. 1 Process and station network. *Source* The author

mechanical damage throughout the system, and an interruption in the supply of electrical energy.

It is important that on the occurrence of a fault on any part of the system, the faulted section or plant be disconnected as quickly as possible. It is equally important that unfaulted healthy sections remain in service or automatically be returned to service without delay. Protective relays detect system fault conditions and disconnect the faulted equipment from the power system through the operation of the appropriate circuit breakers. This is necessary in order to accomplish the following:

- Keep damage and consequent cost of repairs to the plant to a minimum.
- Reduce the possibility of system disturbance and supply disruption.
- Minimize the risk to personnel from explosion and fire.

The general philosophy to facilitate speedy removal of a disturbance from a power system is to divide the power system into "protection zones." Protection relays monitor the system quantities appearing in the power system "protection zones." If, for example, a fault occurs inside a zone, the relays operate to isolate the zone from the remainder of the power system. The operating characteristic of a relay depends on the input signals fed to it such as current or voltage or various combinations of these two quantities and also on the manner in which the relay is designed to respond to this information. The power system is divided into protection zones for generators, transformers, buses, transmission and distribution lines, and motors. Each protection zone is controlled by switchgear in association with protective gear. The location of current transformers (CTs) defines the edge of the protection zone. Because failures do occur, some form of backup protection is provided to trip out the adjacent breakers or zones surrounding the trouble area. Ideally, the zones of protection should overlap, with the circuit breaker being included in both zones, to avoid the possibility of unprotected areas.

Different types of protection relays are applied to protect transmission lines, power transformers, generators, motors, shunt capacitors, shunt reactors, and distribution lines. The most common protection principle used throughout the world for the protection of transmission lines is the distance protection principle applied either as a non-unit distance protection function or as unit protection based on distance teleprotection schemes. Distance protection devices are also applied for the protection of transformers and generators and to separate large networks into smaller ones to maintain their stability during major disturbances that cause out-of-step conditions [4, 5].

To assure power system integrity during fault conditions, one of the most important requirements is reliable performance of power system busbar relay protection. This requirement is further emphasized by the fact that an incorrect operation of busbar protection will result in loss of all connected lines, power transformers, and generators, which may lead to a power system blackout. Reliable performance of the busbar protection system must be preserved for both In-Zone and Out-of-Zone faults [6].

Standardization and Regulation

To implement these PACS, many new and advanced technologies must be ensembled in a complex network that must be interoperable. Many utilities are conservative in nature, being careful to fully adopting these new technologies and waiting until there is greater user experience. Additionally, in regulated and open markets, utilities can be heavily criticized/penalized for loss of supply or loss of opportunities, so they are naturally cautious and propense to use conventional solutions. But many new enterprises are also looking for standardized solutions to projects, reducing costs and engineering time, aiming mainly for interoperability for easy expansion and adaptability, even as a market impetus. Interoperability refers to the ability of two or more devices from the same vendor, or different vendors, to exchange information and use that information for correct cooperation. Currently, it can be viewed as a layered process that spans the entire corporate enterprise, as shown in Fig. 2.

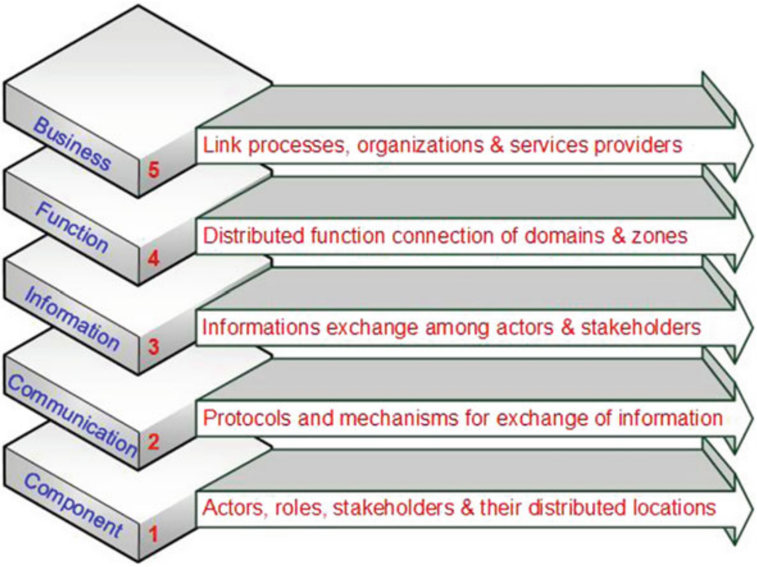


Fig. 2 Layered interoperability model. *Source* The author

Interoperability may be required at the lowest component level between actors, roles, stakeholders, and their distributed locations; at the next communication level using protocols and mechanisms for exchanging information; at the middle information level for exchanging data among actors and stakeholders; at, the upper functional level, for distributed connection of domains and zones; and at the external business level for linking processes, organizations and service providers.

Most of the PACS technologies used today are deployed at the component and communication levels, based on International Electrotechnical Commission (IEC) standards like IEC 61850 [7], IEC 61,499 [8], IEC 61131 [9], and IEC 13568 [10], using Object Management Group (OMG) Unified Modeling Language (UML) [11], and Systems Modeling Language (SysML) [12]. Specialized languages were developed for each of these standards, mostly based in eXtensible Markup Language (XML) or UML. Although the use of standards like IEC 61850 (for protection and automation), IEC 62351 (for Cybersecurity), and IEC 61869 (for Instrument Transformers) enable multi-vendor interoperable PACS, it requires a high level of training and involvement from PACS engineers. This is further complicated by the different implementation and interpretation of standard functions by different manufacturers (OEM), reducing their interoperability. For the upper layers of the interoperability, the current standards are based mainly on the IEC Common Information Model (CIM), as shown on Fig. 3. This set of standards provides an object-oriented representation of the power system, with specific communication profiles for interchange of information among control centers and with the market based on Web services and XML. Efforts are underway in IEC to harmonize the object-oriented representation of CIM and IEC 61850, as shown on green color in the picture.

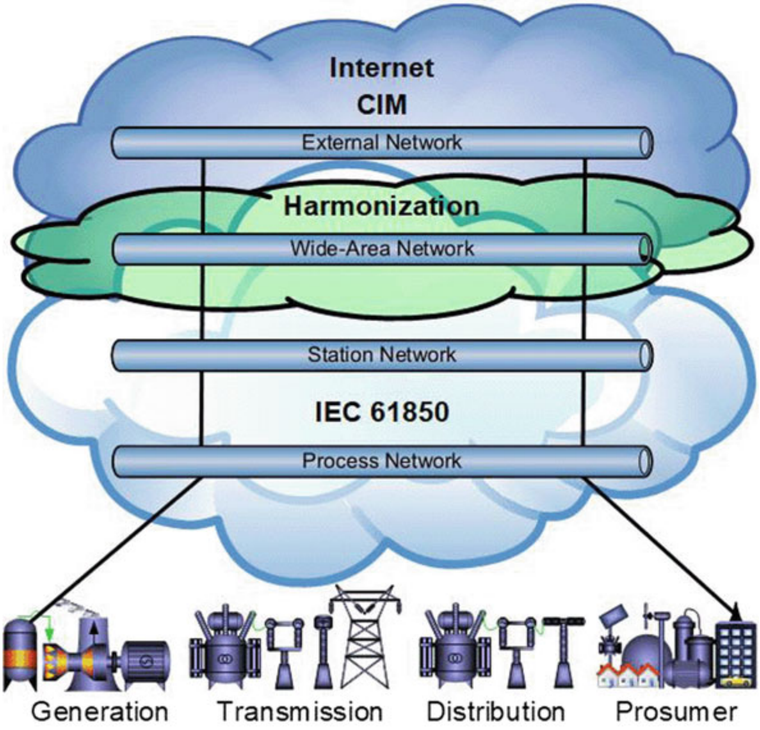


Fig. 3 Interoperability standards. *Source* The author

State-of-the-art PACS use currently standardized digital processing hardware with specialized firmware to store and perform multiple functions, according to the needs of each application. A similar movement has motivated the standardization of most functions used in PACS, now defined by software modules and object-oriented classes defined by interfaces in standards like IEC 61850. This tendency has been extended to protection and automation of most of the current resources used in power systems, like hydro power, wind power, etc. For development of PACS, the following standards and formats are currently applied in the engineering cycle [2, 13]:

- **NL**—Natural Language;
- **IEC 61850**—Protection and Automation;
- **IEC 61499**—Function Blocks;
- **IEC 61131**—Programmable Controllers;
- **IEC 13568**—Z Formal Specification Notation;
- **OMG UML**—Unified Modeling Language;
- **OMG SysML**—System Modeling Language;
- **CNL**—Controlled Natural Language.

With exception of the natural text (NL), the original language of users, owners, or stakeholders, all remaining formats are typically expressed in some scheme of eXtensibleMarkup Language (XML) and standardized by some international body like ISO, IEC or OMG, as a format for vendor-agnostic engineering and configuration of intelligent electronic devices (IED). Controlled Natural Languages (CNL) are currently vendor or application specific formats, based on macros and spreadsheets, or on syntax diagrams or Backus–Naur form (BNF) schemes used for internal design. To address this issue, the following findings were compiled from a recent CIGRE survey [2] about the state-of-the-art standard preferences for PACS applications, regarding aspects of applicability, implementability, testability, checkability, maintainability, modularity, expressibility, soundness, verifiability, usability, tools, looseness, learning, maturity, modeling, discipline as seen by different stakeholders:

- **All stakeholders**—IEC 61850 is the preferred format in all aspects except for Learning, where IEC 61131 is preferred; IEC 61499 is better than IEC 61131 only in discipline and modeling capabilities, for most stakeholders. UML is the preferable modeling language for requirement specification, but both UML and SysML are difficult to learn according to most users.
- **Manufacturers—**IEC 61850 is again the preferred language in all aspects except for learning, where IEC 61131 is the preferred standard; IEC 61499 is better than IEC 61131 only for modeling andmodularity. UML is the preferable language for modeling, except for looseness and testability. Both languages, UML and SysML, are seen with low applicability for requirement specifications of PACS by manufacturers.
- **Researchers**—IEC 61850 is the preferred format for all research work except for usability, tools, looseness, learning, and modularity; IEC 61131 is the preference for modularity, learning, and availability of tools, while IEC 61499 is the preference for looseness. UML is the preferable modeling language for requirement specifications, except for looseness; but both languages, UML and SysML, are seen with low applicability for requirement specification by researchers.
- **Users**—IEC 61850 is the preference in all aspects except for learning, where IEC 61131 is the preferred format. For the users, IEC 61499 is very similar to IEC 61131 as a design language. UML is the preferable modeling language for requirement specifications by final users, except for learning.

Specifically, for PACS functional requirements, the following current practices are preferable by stakeholders, according to [2]:

- **NL—**Natural Language is most preferable by manufacturers;
- **CNL**—Controlled Natural Languages are preferable by researchers;
- **IEC 61850**—Most popular among manufacturers;
- **IEC 61499**—Absolute preference among researchers;
- **IEC 61131**—Less used by users when compared with other stakeholders;
- **IEC 13568**—Mainly preferable format by researchers;
- **OMG UML**—No clear preference among stakeholders;
- **OMG SysML**—No clear preference among the groups;

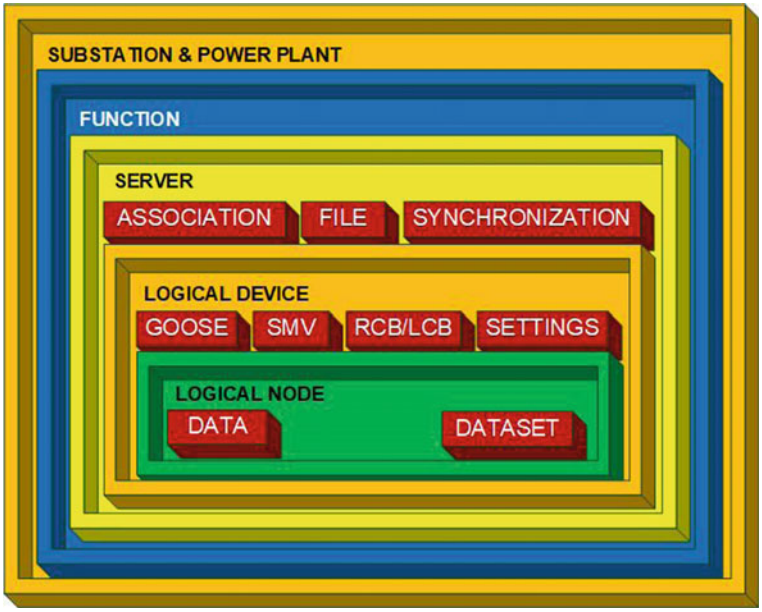


Fig. 4 IEC 61850 hierarchical organization. *Source* The author

Among these standards, IEC 61850 (Communication networks and systems for power utility automation) is the main reference document and the “de fact” standard for implementation of current PACS. The interfacing aspects and functional blocks needed by most applications are described in this standard, as well as the network architecture for building local and wide-area PACS. The standard uses an object-oriented approach to specify a hierarchical view of a PACS, as shown in Fig. 4.

At the lowest level, IEC 61850 defines all data and datasets that can be processed and transmitted by IEDs, grouped in blocks known as logicalnodes, defining the smallest piece of functionality that form a PACS. These nodes can be further grouped in logical devices that provide services for setting and exchanging messages among IEDs. The messages can be of high-speed type like Generic Object-Oriented Substation Event (GOOSE) and Sampled Measured Values(SMV), or slower client–server (C–S) messages for vertical communication. Logical devices can be grouped in servers that provide services for association, time synchronization, and file transfer among IEDs. These servers are used to compose the function objects that form a substation and power plant automation and integrated externally to a wide-area PACS.

Advanced Metering Infrastructure

In addition to PACS, parallel developments have occurred in the metering of electrical energy, with the expansion of intelligent meters and the advanced metering infrastructure (AMI). Figure 5 shows the main components of a typical state-of-the-art intelligent meter.

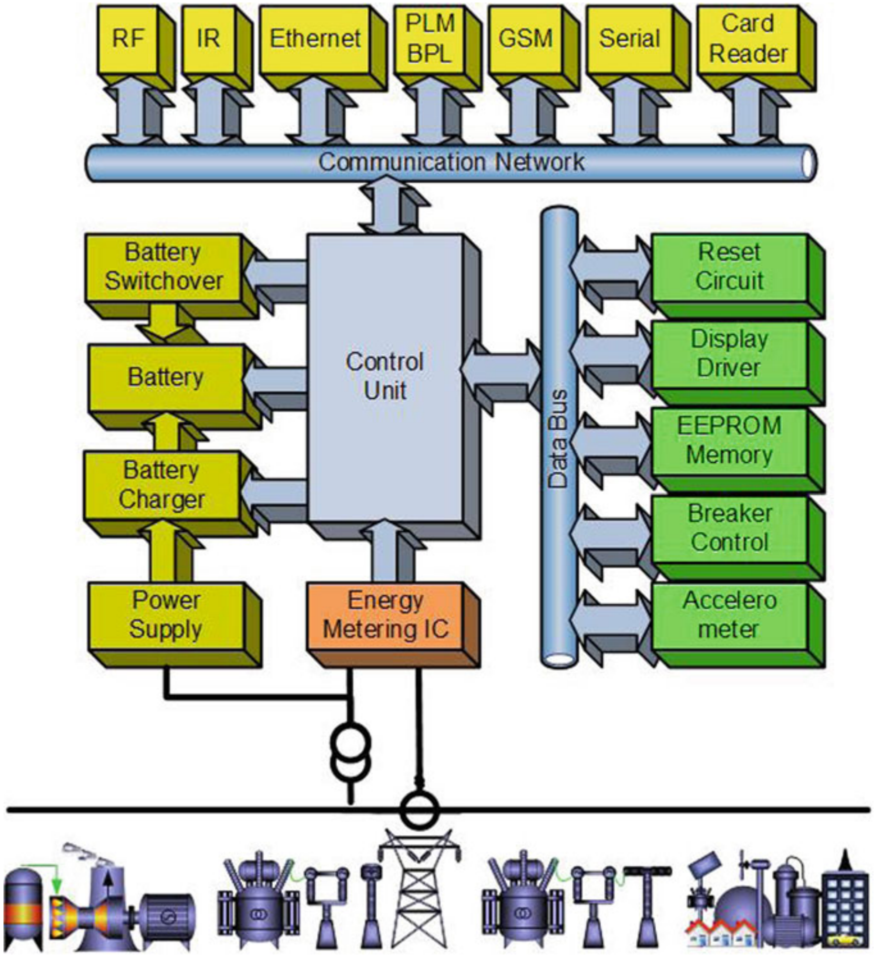


Fig. 5 Intelligent meter. *Source* The author

To support the requirements of AMI, intelligent meters now are full servers (IEDs) that not only perform energy metering, but supervise quality of service (QoS) at customer premises, with battery and power supply for autonomous operation; data bus for metering, display, resetting and local external control for distribution and home automation; and a full set of communication resources for integration to the utility's or energy trader's metering central. They are devices acting as a gateway or interface between the utility/trader and the home area network (HAN) or building area network (BAN), allowing the execution of telemetering and billing; remote disconnection and reconnection of loads; energy balancing and demand response control; fraud and loss detection; loss of supply detection; remote access to consumer meters by mesh networks; multimedia integration with consumption information; power quality monitoring; local visualization of energy consumption; remote consumer access to energy consumption; and local and remote control of house or business appliances.

Engineering Process

Parallel to the development of these devices, there has been an international effort to modernize and standardize the engineering process for developing PACS. Many international standards and proprietary methods are available to support their development, although this diversity results in some difficulties for the planning engineer. The following paragraphs review the current available tools and standards used in each phase of the engineering process for deploying PACSs, and analyze their advantages and disadvantages, and identify issues to be addressed in the future.

The traditional representation of the design cycle of a PACS mirror the engineering process of system engineering as shown in Fig. 6, as a cascade process with five phases: Planning, Specification, Design, Implementation, and Operation, followed by a description of the state-of-the-art.

Planning—The first step in the engineering process is dedicated to requirement definition. This definition usually contains a listing of the system, user, owner, or stakeholder requirements, including product functions and non-functional features. It is done by a *Planner*—the actor(s) that interprets the requirements from the users, owners, or stakeholders, generating a document with the *User Requirements* for the intended functionalities and performance levels of the system. As the start of the

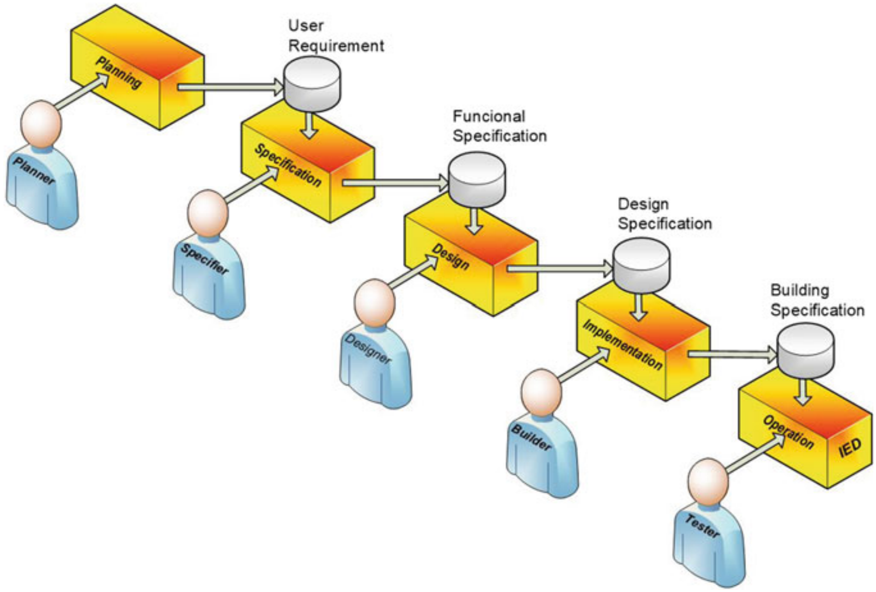


Fig. 6 PACS engineering process. *Source* The author

engineering process, a clear, unambiguous definition of the desired PACS is necessary. A design problem often begins as a vague, abstract idea in the mind of the user, owner, or stakeholder, or as the outcome of a formal planning process. Extracting a clear definition of a functional requirement is a difficult task, so that its definition may evolve through a series of steps or processes to the complete definition of the problem. Although PACS engineers are generally involved in defining the user requirements, they may not be the ones who initially recognize the need during the planning phase of a power system, nor the required performance levels of each function. Natural Language (NL) supported by free sketches, tables, or graphical drawings of the desired requirements is currently the usual method to write a user functional requirement. These requirements may be defined in some sort of proprietary Controlled Natural Language (CNL) to avoid the impreciseness and ambiguity of a Natural Language. Text processor is the most popular current tool for requirement specifications, with spreadsheets as the second most used tool for requirement definition, followed by IEC 61850 tools for requirement specifications. Lack of a standardized format and a mechanic compiler among these and other formats is a recognized deficiency of the current methods. There is clearly a need for a humanly understandable but formal format to force the description of unambiguous requirements, and to allow manual or mechanical compilation into selected technologies by suppliers and integrators.

Specification—In the next step, these requirements are translated into detailed functional specifications with relevant information for the design of the PACS. It is done by a *Specifier*—the actor(s) that translates the *Functional Requirements* from the planner into a document with the *Functional Specification* with the translated requisites of the *User Requirements*. Contrary to the planning phase, in the specification phase, the PACS engineer can select among a set of well-established set of standard languages, with well-developed tools to support their use. In this step, it is a good practice to choose a format that is vendor-agnostic, to allow the maximum freedom in the selection of suppliers. Depending on who oversees this phase, the selected format will depend on the intended technology of the final system. IEC 61850 is currently the preferable standard for this phase, due to its standardized Substation Configuration Language (SCL) based on XML, availability of modern tools, and its seamless integration with the remaining phases of the engineering process. IEC 61113 is also used due to its diversified support from many vendors; its interchangeable formats based on text, graphics, and ladder diagrams; and its easy-to-use and learning tools, and widespread acceptance by the process and power industries. UML and SysML are also used in these fields, to a lesser extent, mainly for generation of new software solutions for PACS. IEC 61499 and IEC 13568 are used mainly in theoretical and research projects with incipient use in the industrial applications. Both are good candidates for the development of tools for future PACS projects.

Design—In the third step, the final design that best fits the PACS functional requirements is selected, based on agreed design criteria and technologies. It is done by a *Designer*—the actor(s) that translates the *Functional Specification* from the Specifier into a *Design Specification* with the recipe for building the system using available modules and technologies. Depending on the language of the previous phase, the design step can be supported by modern automation tools, based on proprietary or supplier independent software. The main requirement related to this phase is the full integration of the language with the solution modules available from the selected technology. Good tools are available for this step if the same entity is responsible for the specification and design phases. Again IEC 61850 is the preferable standard, due to the integration of SCL to the previous phase, availability of modern proprietary and open tools, and its guaranteed integration with the remaining steps of the engineering process. IEC 61113 is also common due to the support from many vendors, its interchangeable text, graphical and logic formats, and intuitive tools used by the process and power industries. To a lesser extent, UML and SysML are also used in these steps mainly for design documentation and software implementation. Depending on the future developments, IEC 61499 and IEC 13568 may migrate from theoretical and research projects to industrial applications.

Implementation—In the next step, a solution is built, and final functional tests are performed to verify its conformance to the original requirements. It is done by a *Builder*—the actor(s) that translates the *Design Specification* from the Designer into a *Building Specification*, with the final as-built configured specifications and drawings of the system. As the final phase before deployment, the implementation phase is the most dependent on the technology used by the PACS manufacturer. Depending on the available modules, this step can be fully or semi-automated by suitable tools, by simply instantiating and connecting standardized modules to attain the design specification. This is a step most adequate for automation by software tools, as the industry is moving steadily to the adoption of standardized modules independent of hardware. This is the phase in which IEC 61850 excels as the preferable standard, due to the availability of a rich library of logical nodes for almost any application, the availability of modern proprietary and open tools, and its guaranteed integration with the previous steps of the engineering process. IEC 61113 is also adequate to this end by the same reasons. UML and SysML can also be used in these steps for documentation and software implementation. Modularity of the design is a strong treat of IEC 61499 and IEC 13568 for implementation purpose, favoring their application in the future implementations of PACS.

Operation—In the final step, the system is exercised during commissioning and maintenance to check its conformance to all previous specifications. It is done by a *Tester*—the actor(s) that test the built system is in accordance with the *Building and Design Specifications*, and these are in conformance with the *Functional and User Requirements* during the commissioning and operational phases of the engineering cycle. The quality and integration of all phases of the engineering process will determine the extent of conformance of the deployed PACS with the user requirements. The operational phase will require commissioning and maintenance testing during the lifecycle of the PACS. These tests will be eased depending on the technology and level of development of the standards and tools used for their design. If the system is based on IEC 61850, a rich library of logical nodes will be available for maintenance, with the availability of modern proprietary, open and independent tools, and its guaranteed integration with the previous steps of the engineering process. For the same reasons, IEC 61113 is also adequate to this end. UML and SysML can also be used in these steps mainly for training, documentation, and software maintenance. The same will apply to future PACSs developed in IEC 61499 and IEC 13568, depending on the development of new tools.

Development Tools

For designing and maintaining these state-of-the-art PACSs, specialized software tools are used by manufacturers, system integrators, and maintainers to configure standardized modules like IEC 61850 logic nodes to specific needs. These tools are usually proprietary of each relay maker but can also be from independent software houses. The entire engineering process from the user requirements to the final configured PACS devices can now be partly automated by software tools defined by the standard IEC 61850 as shown in Fig. 7.

Three engineering tools are currently defined by IEC 61850 to automate the design cycle, using standardized SCL (Substation Configuration Language) files based on XML (eXtensible Markup Language):

- SST—System Specification Tool
- SCT—System Configuration Tool
- ICT—IED Configuration Tool.

The SST tool is used to describe the process to be controlled at the level of a single-line diagram, with the process names and functions to be performed by the PACS. The SCT tool allows the designer to choose the components with functional assignments. Finally, the ICT tool supports the creation of parameter sets for specific IEDs used in the design. These tools generate and maintain a consistent set of standardized

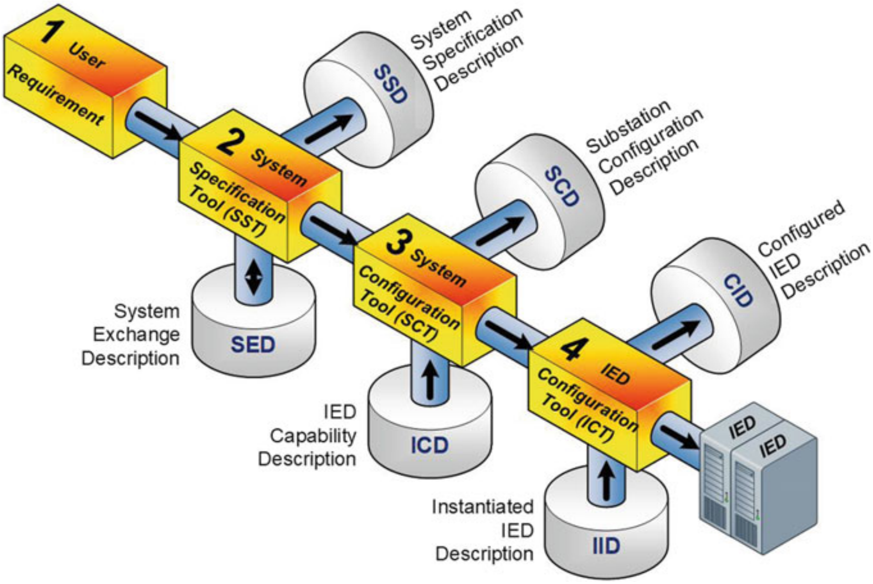


Fig. 7 IEC 61850 engineering cycle. *Source* The author

SCL files at different stages in the engineering cycle that can be exchanged among independent tools or different relay manufacturers (Fig. 7):

- IID—Instantiated IED Description
- CID—Configured IED Description
- ICD—IED Capability Description
- SCD—Substation Configuration Description
- SED—System Exchange Description
- SSD—System Specification Description.

In addition to the tools defined by IEC 61850 for the engineering cycle, PACS engineers use commercial software packages and dedicated (in-the-loop) hardware for performing simulations and relay settings, like short-circuit calculation, stability and dynamic simulation, and relay testing and simulation.

Hardware Technologies

Following the tendencies in other fields, the hardware of IEDs and PACSs is now being standardized in a few types, allowing the deployment of different applications and functions by just changing their software or firmware. This is already current practice by major manufacturers, and it seems to be the common direction of all IED makers. Currently, the differentiation among products from the same manufacturer is mainly on the embedded firmware of each IED, allowing its change with new versions of software. In the future, it is estimated that this will be done purely by software patches and versions.

The unbundling of hardware and software will be further enhanced by the possible introduction of optical processing units in substitution to traditional microprocessors, and the evolution and penetration of wireless communication inside the substations. This technology will be further employed when the current vulnerability to environmental interferences are resolved.

Software Technologies

Paralleling the development of hardware systems, software is evolving in its own lane and with a much higher speed. High-level functional and object-oriented programming languages are now available, directed to the final user, supported by powerful development environments. This status favors the implementation of highly-adaptative PACS, with agent-based standards modules that may be assembled in highly complex systems, but easily maintained and adapted to changing needs. The use of advanced systems based on artificial intelligence (AI) is now common in many fields and it is expected to be also used for design and maintenance of PACS.

Currently the use of these technologies requires a highly specialized crew and infrastructure, motivating a strong tendency in the Information Technology (IT) world to the outsourcing of these resources. These services are commonly referred to as cloud services and offered typically in three versions: Infrastructure-as-a-Service (IaaS) for utility computing data center providing on-demand server resources; Platform-as-a-Service (PaaS) as a hosted application environment for building and deploying cloud applications; and Software-as-a-Service (SaaS) for applications typically available via a browser. They are distributed systems based around the notion of externally provided services (Web services). A Web service is a standard approach to make a reusable component available and accessible across the Web, supported by the standard Simple Object Access Protocol (SOAP) for cross-platform inter-application communication, Web Services Description Language (WSDL) for description of services, and Universal Description, Discovery and Integration (UDDI) for finding available Web services. These are mainly directed for storage, database management, information processing, application use, integration, security, and management as a service.

All these technologies are motivating similar research and development in PACS, due to its strong reliance on software systems. Mainly in the off-line processing of relay data, many utilities are already using cloud-based services for PACS, for setting calculation and storage, remote monitoring, and auditing. All these developments are strongly dependent on fast and reliable telecommunication resources.

Telecommunication Technologies

The state-of-the-art of telecommunication offers many different technologies and media that can be used by PACS, ranging from copper, optical fiber and wireless nets inside the substations, to surface radio, satellite and optical fibers outside the utility. From a PACS point of view, these resources may be seen as a layered stack of specialized message buses that conveys the communication horizontally inside and across the installations, and vertically through and outside the corporate organization, as shown in Fig. 8.

Near the process level, a real-time event bus transports sampled values and other information acquired from the process interface of the process signals using a message-oriented middleware, storing their status, and using local monitoring and control processes. At the next station level, a logic message bus transmits Goose and client–server (C–S) messages using a procedural middleware, serving the automation processes of station components. At the corporate level, an enterprise data bus transports mainly C–S and Common Information Model (CIM) messages defined by IEC, using a transaction middleware serving the corporate processes and shared databases. Finally, at the upper level, a Web service bus transports business data based on generic interface definitions, using a Web service middleware connecting Web service repositories, and serving distributed cloud-based processes. The distinguishing feature of this architecture is the state-of-the-art standardized interface of each layer, abstracting the implementation of the services from the PACS user. This result is now possible with the widespread application of the standards IEC 61850 and CIM but requiring their harmonization by IEC.

Advanced Sensor Devices

Recent advancements in optical and magnetic materials have resulted in the development of new kind of sensors used by state-of-the-art PACS. In addition to the traditional current transformers (CT) and potential transformers (PT), based on the induction principle, many low-power linear-transducers and non-conventional instrument

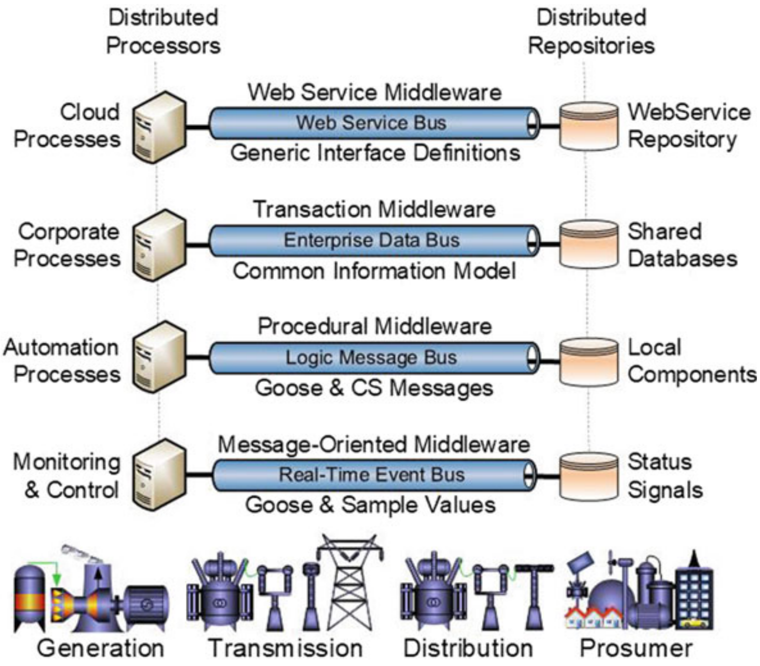


Fig. 8 Telecommunication state-of-the-art. *Source* The author

transformers (NCIT) are now available for application in protection and automation, practically free of harmonics and saturation effects. In parallel, new devices can sample and interface these signals to the message-oriented buses used for communication among IEDs. Merging and phasor measurement units are among the advanced sensor devices currently used by PACS based on these principles.

A merging unit (MU) is a dedicated device intended for sampling current and voltage signals from instrument transformers and merging them into the standard digital output format used in a process bus for use by other protection and automation processes. It is typically implemented using field-programmable gate array (FPGA), with a high-precision oscillator, signal conditioning, internal memory, human and communication interfaces with external networks as shown in Fig. 9.

Phasor measurement units (PMU) are among the major recent developments in PACS with a wide range of possible applications. Their usefulness extends beyond the immediate application as a sensor in substitution to simple local sampled-value signals, to wide-area transmission of synchronized phasor data, strongly impacting the future of all wide-area PACS. A phasor is a vector consisting of magnitude and angle that corresponds to a sinusoidal waveform at a given frequency. A synchrophasor is a phasor calculated from data samples using a standard time signal as the reference for the measurement, usually provided by a Global Positioning System (GPS) microwave signal broadcast from satellites. Synchronized phasors from remote sites have a defined common phase relationship. Figure 10 shows the typical

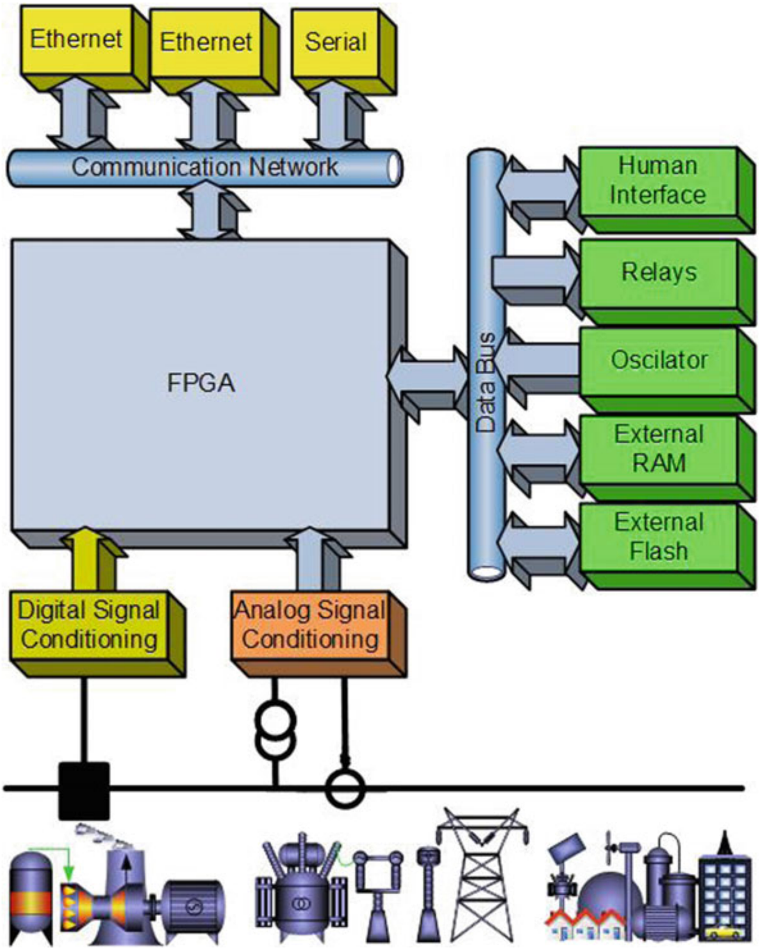


Fig. 9 Merging unit. *Source* The author

architecture of a phasor measurement unit, formed by input filters, analog-to-digital (A/D) converters, synchronized by a sampling clock and GPS receiver. A quadrature oscillator guides the extraction of the real and imaginary parts of the sampled signal to form the synchrophasor.

Many state-of-the-art IEDs already use an embedded PMU as the standard processing unit for sampled signals. This allows the broadcasting of synchrophasors in the station network and their use by other IEDs. The signals used by a standalone PMU can also be the result of a resampling of the samples provided by merging units as shown in Fig. 11.

Synchrophasors follow the standard IEEE/IEC60255-118-1 (Measurement and time tagging specifications for synchronized phasors, frequency, and rate of change of frequency). Current problems include cybersecurity issues like hijacking of satellite

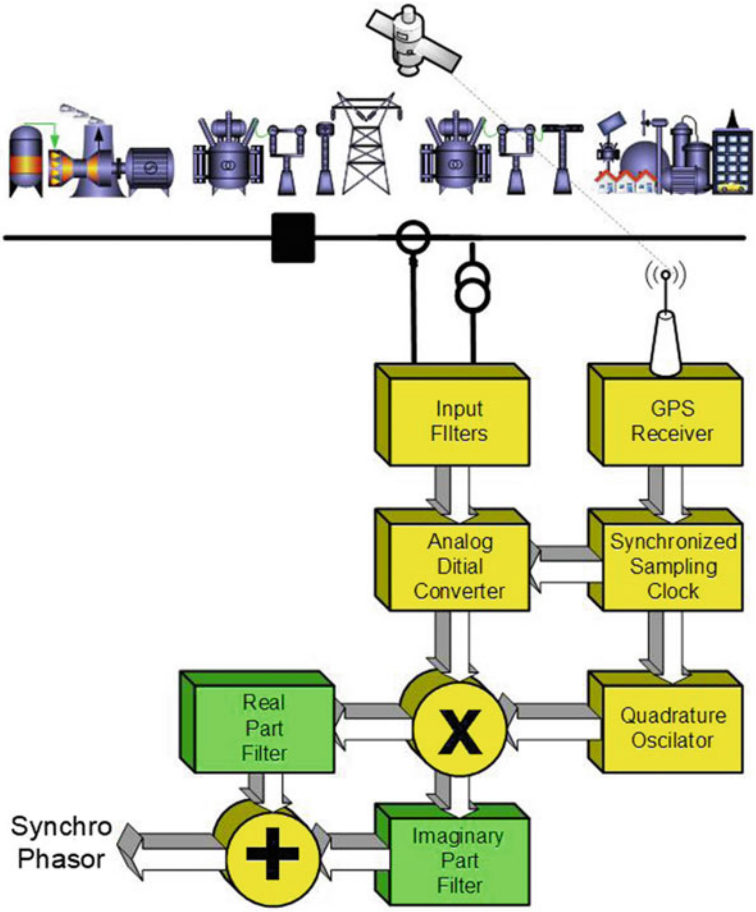


Fig. 10 Phasor measurement unit. *Source* The author

clock signal, satellite signal loss and quality, and communication issues like reporting rates and latency, jitter and reliability with data loss in the telecommunication network.

A Phasor Data Concentrator (PDC) is a function that collects phasor and discrete event data from PMUs and possibly from other PDCs (Super PDC) and transmits to other applications. PDCs may buffer data for a short time period, but usually do not store the data for a long time.

Education and Knowledge Acquisition

All these modern devices have a far greater number of functions than legacy electromechanical and analog static devices, posing new challenges to engineers to understand and be familiar with their capabilities and settings, in addition to power system expertise. The existence of many manufacturers adds to this burden. The impetus on

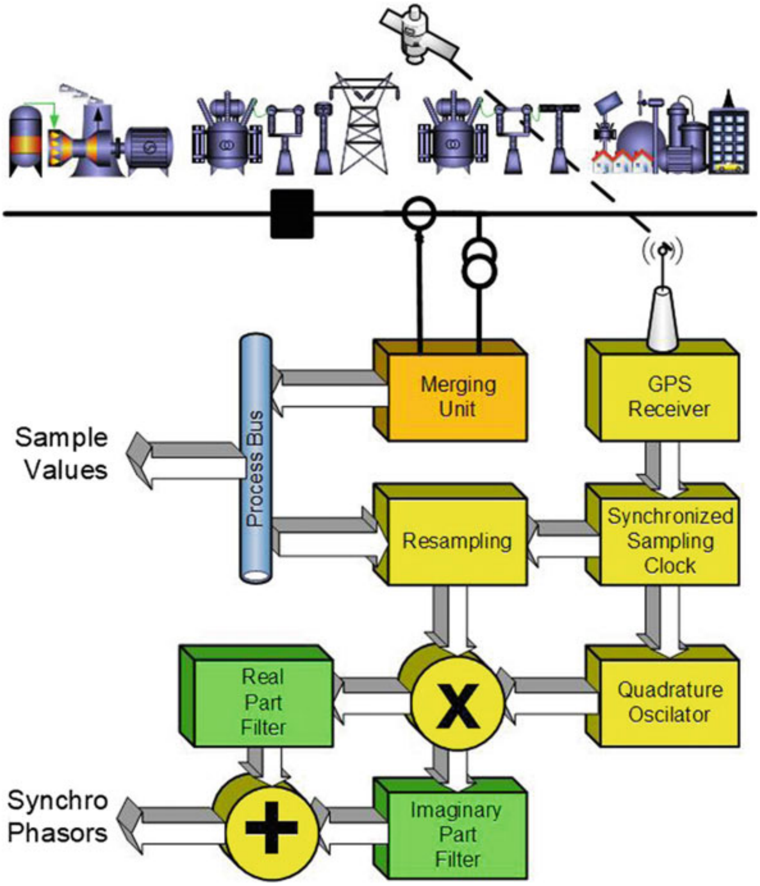


Fig. 11 Phasor measurement and merging unit. *Source* The author

digitalization and use of modern software-based systems is contrasted to the current lack of formal teaching of these technologies in the official education of protection and automation engineers in most universities and education centers. Few universities today offer a formal training on protection and automation in-line with the current needs of the industry. Most of them address only the basics of fault calculation, relay settings and coordination for major power system components [14]. Specifically, they often do not include in their curricula the needed knowledge about power electronics, computer science, protocols, and telecommunication necessary for the new PACS. This has resulted in an education gap between the practicing engineers in utilities, and the new type of technicians needed to cope with these technologies. Please refer to [15] Education, Qualification and Continuing Professional Development of Engineers in Protection and Control, a Cigre brochure from SC B5 related to education and knowledge. Some people even argue that the device suppliers are best placed for setting these devices, due to the increased complexity compared to older and more traditional devices. Therefore, rapid obsolescence is expected from the current generation of PACS engineers, as is observed in current legacy hardware-based technologies. This must be included as a requisite to attain the future grid requirements for PACS.

3 Grid Requirements

The profound transformations undergoing the electrical industry in this century bring new requirements for the power sector, and particularly to PACS. Many new demands are related to the changes in the structure, governance and ownership of the electrical grid, to the inception and penetration of distributed resources and power electronics, and the availability of new technologies in hardware and software.

The development of new technologies in electrical power systems must be closely followed by equivalent development in PACS. This relates mainly to the introduction of new generation, transmission, and distribution methods that require non-conventional methods of protection, control, and automation. Currently, these requirements come mainly from the development of DC/AC networks, microgrids, prosumers with distributed generation and storage, electrical transport, and physical and cybersecurity. This section resumes these requirements, and how they affect the future of PACS.

Structural Requirements

Distributed generation resources are now a reality in almost every region in the world, motivated by the search for renewable non-pollutant sources of energy. Most of these new sources are based on power electronics conversion, with limited short-circuit capacity. As most protection systems used in distribution networks are based on sensing the level of current during faults, this brings a new difficulty for these methods. This is further complicated by the reduced information about the implementation and internal functioning of proprietary converter systems; by the strict requisites for performance and faster response for information after system faults and to resolve protection issues; and by the early disconnection of many new sources of power, making it more difficult to detect the exact location of the fault by current PACS.

The traditional serialized organization of electrical power system, with unidirectional flow of power from bulk generation, through transmission and distribution to consumers is modified, thus changing the structure of the electrical grid. Distributed generation is now common in the high, medium and low voltage, and in the consumers (sometimes called prosumers), with a tendency to include personal home generation and independent Microgrids, resulting in possible reversal of power in many branches of the grid. For the protection systems, this means the need for detecting direction of flow, and low short-circuit capacity during faults. Many PACS in distribution networks were not designed for bidirectional flow, so they will have to be adapted. There could be insufficient fault currents to drive the protection relays, causing reduction on the Critical Clearance Time (CCT), requiring protection systems to operate more quickly. One of the major risks is the protection failure to operate, with consequent loss of stability or frequency control.

The automation of the distribution grid, with high penetration of distributed generation, faces two additional difficulties: (a) low inertia of these new sources, reducing their contribution to the frequency regulation and fault current; and (b) unpredictability of their non-dispatchable generation, dependent on weather conditions. The low inertia will also shorten the "first response" time after disturbances, creating difficulties for frequency control, requiring additional means to control frequency variations during disturbances, like simulated (virtual) inertia introduced by direct control of the converters, and adequate generation control for the fluctuation of wind and photovoltaic power. Reduced system inertia and fault levels may require new techniques for fault detection such as travelling waves, which do not rely on fault level. Hence, apart from plain protection schemes, special protection or microgrid protection schemes may also be required, as new prosumer requisites.

Prosumer Requirements

At the consumer level, the possibility of generating locally the electrical energy for their needs, to store or export the excess power brings another layer of requirements for PACS. The control of many small home generators (Nanogrids), with local storage and electrical vehicle charging stations, distributed in a vast geographical area is a challenge for the current operation and control of the grid. New requirements must be attained that involves advanced metering with massive need for exchange of information of new measured parameters, information architectures, communication technologies and algorithms. This requires the identification and standardization of the data to be exchanged, the introduction of analytics, disaster recovery strategies and restoration plans, and cybersecurity countermeasures in a massive population of prosumers, with new organizational requirements.

Organizational Requirements

The open market model for electricity has resulted in new architectures for PACS. It is now possible for a company to invest in a transmission line, or a generation source, with their terminals in existing substations owned by other companies. So, in many countries, there are stations with multiple owners, sometimes with concurrent PACS operating on the same LAN. This brings new challenges for the integration of different technologies, owners, and methods. Issues of cybersecurity and governance must be addressed, as there is no standard solution, and as PACS are not the central focus of stakeholders, with possible budget restrictions that may lead to PACS functions which do not meet all technical requirements.

The same challenge is faced for the integration of millions of active prosumers, using unsecure meshed networks and non-standardized interfaces and protocols. Requirements from new players like energy traders, electric vehicle chargers, virtual power plants, and association of prosumers complete the complexity confronted by future PACS.

Environmental factors in power systems also face increasing demand for PACS. There appears to be cumulative focus on developing protection mitigation measures and/or tools to prevent and locate faults as quickly as possible, not only to shorten the impact on consumers and producers, but also on the environment. Ground fault neutralizers are being examined to mitigate power line faults leading to bush fires in dry regions. Also travelling wave distance to fault plus geospatial map location is helping to more accurately find faults before manual reclose of the faulted line.

Cybersecurity Requirements

To attain all these requisites will expose PACS to even more cybersecurity attacks. Full digitalization, with the adoption of standard open protocols, wide-area, and meshed communication networks, opens the door for cybersecurity threats that were not present in legacy technologies. Due to the layered and distributed architecture of current PACS, these threats span vertically from field hackers in the substation and process local area network (LAN) up to corporate hackers using the wide-area network (WAN) and mainly to external hackers coming from Internet, as shown in Fig. 12. Note that the internal hackers by-pass the protection of existing firewalls, one of the main issues for PACS cybersecurity.

A full set of new tools and techniques, not specific to protect and control the power system, must now be introduced and managed by PACS engineers. Many technology changes will require to train engineers and field personnel on concepts foreign to their main objective. This brings a new dimension of complexity, forcing a review of the educational curricula of PACS engineers. Traditional PACS security has been based primarily on physical isolation and this approach will no longer work. PACS should comply with relevant cybersecurity standards to benefit from new technologies. This itself represents a completely new profession. A good risk management with efficient criteria and the selection of mature and probed technologies and practices is necessary as a cybersecurity policy. Effects on maintenance and test procedures and remote access capabilities must be addressed carefully to get the least possible impact on PACS. Improved practices are needed to prevent road blocks on protection work and information transfer imposed by global cybersecurity rules that have not considered protection implications or alternative solutions. An industrial-grade full-network security monitoring system is required with layered protection, self-learning, self-adapting, self-forming defense strategy, periodically audited by a regulating agency for compliance with national security of critical infrastructures. If not addressed correctly, the wide application of information and telecommunication technology will threaten the network security and proper control of the electrical grid.

Hardware Requirements

Aside from these issues, the application of standard industrial computers as the hardware for IEDs allows new functionalities but also facilitates the cyber-attacks, while requiring for more frequent updates. This is motivated by frequent evolution of the technology, with rapid functional obsolescence, and the need for additional functions. Sometimes, the processing of new functions and algorithms, like those for authentication, cryptography and cybersecurity protection, does not run in legacy

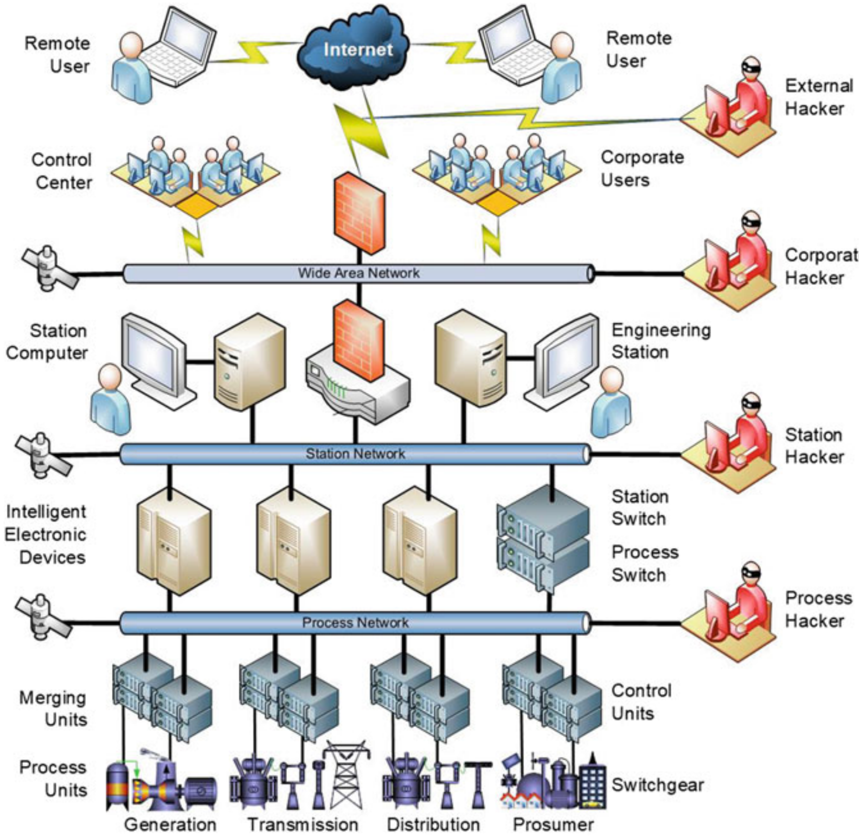


Fig. 12 Cybersecurity threats. *Source* The author

processors due to speed requirements, potentially demanding more frequent upgrades than in the past.

Furthermore, strong requirements are being placed on eliminating and safely disposing of environmentally damaging protection components such as printed circuit boards (PCB) and batteries, leading to new requirements regarding components, power consumption, decommissioning, recyclability, and used raw materials. This is contrasted to the long life of legacy PACS based on electromechanical relays. A different approach is needed for the asset management of PAC that includes also software configuration.

Software Requirements

The movement toward a standard hardware for PACS is closely followed by a continuous change in the software (firmware) that runs in these devices. This increases the difficulty of configuration management, resulting in many versions of the same function operating in different PACS. With computerized protection devices, firmware and scheme change to correct device issues or design issues appear to become more frequent and difficult/costly to deal with. This is further complicated by the frequent changes and releases of new versions by the manufacturers that must be kept updated. Configuration management is now indispensable for PACS asset management. Further development is needed for digital substation devices and scheme configuration tools catering for different vendor devices, interoperability, modularity, and free function allocation.

The intensive use of power electronics in direct current (DC) networks, in renewable sources of energy like wind and photovoltaic power plants, and in converters for distribution generation, brings in parallel the need for automatic control and protection methods compatible with these technologies. In many cases, the tripping of converter-based sources must act directly on the thyristor control and power electronics, instead of circuit breakers. This is not standardized like the control of circuit breakers, nor is the information ease to get from manufacturers, needing further standardization, research, and development. The further research is also needed for new technologies to recognize faults in systems with low inertia and a big amount of power electronic-based sources.

Islanding Requirements

The continuous evolution of HVDC transmission, and the introduction of converters and microgrids, has renewed the interest in DC networks as an alternative to the traditional AC networks. Multiterminal HVDC transmission systems will present specific challenges for their protection and require the development of DC breakers and DC transformers and the need for synchronized tripping and control of distant terminals.

The operation of microgrids and the possibility of part of the network to operate isolated from the rest of the grid have specific requirements for coordination of PACS. In addition to the automatic detection and management of the disconnection and reconnection to the grid, the PACS of a microgrid must keep it secure in isolated or connected condition. These two conditions involve different levels of short circuit, power flow, and information exchange conditions that further complicate their design, with strict requirements for coordination with fault ride through (FRT) and inadvertent and intentional islanding detection.

Microgrid operation requires the PACS to perform many new functions like metering and billing of energy transaction; transaction accounting and reconciliation; remote control of connection; setting of operating points; interchanging power at scheduled values; meeting system and equipment operating limits; correct islanding and resynchronizing; optimizing market participation; limiting circulating currents among parallel inverters; securing supply to sensitive loads; securing black start; emergency control and load-shedding; demand response to grid signals; and proper control of energy storage.

Education and Knowledge Acquisition

Based on the above requirements, it is widely recognized that a drastic change is needed in the training curricula of engineers related to PACS. In addition to the traditional engineering knowledge about power system, including transient and steady state behavior, PACS engineers need to be proficient in modeling and simulation of complex topologies likely to be found in the future, including mixed DC and AC grids. This includes short circuit, stability and power flow simulation, and specific packages provided by IED manufacturers, requiring an exhaustive formal and in-house training.

In addition, there is a requirement to learn the integrated engineering tools provided from independent suppliers to guide the entire engineering cycle and serve as a documentation tool. Laboratory structures are needed to simulate complex configurations likely to be found in the future wide-area PACS, mainly related to the evolving and highly flexible network topologies. This includes the availability of training software, based on real devices, with better and more specific models, both for protection functions implemented in relays and for primary devices to be protected (e.g., inverters). All these requisites should be part of the future development of PACS.

4 Future Developments

Driven mainly by the grid requirements of the electricity supply system of the future, and by new developments in hardware, software, and telecommunication resources, PACS are expected to change drastically in the long term. One main impetus will come from the need to cope with increasingly complex distributed network of functions, expanding wide geographical areas, and needing to operate in synchronism. This will motivate radical changes in the architecture of future systems with impacts in the engineering lifecycle and its methods. It is expected that the following areas will experiment paradigmatic changes in the long term:

- Wide-area protection and automation
- Centralized protection and automation
- Software-defined protection and automaton
- Cloud-based protection and automation
- Remote testing and maintenance
- Advanced intelligent tools
- Application of formal methods
- Education and knowledge acquisition
- Research and development
- Standardization and regulation.

Wide-Area Protection and Automation

While the need for local PACS will remain in the future, as the first layer of protection and automation for substation components, the need for advanced wide-area distributed functions will guide the development of future systems. This requirement is driven mainly by the systemic demands of the electricity supply and the need for decisions to be taken based on real-time data from wide-area locations. This is motivated by the penetration of distributed resources, and the changing of the traditional structure and unidirectional flow of energy to a multi-directional meshed flow and flat distribution of energy sources, with a need to mass transmission and processing of data, and a distributed responsibility for the network control. This concept is represented in Fig. 13 by a generic wide-area protection, automation, and control (WAPAC) system.

This architecture is currently based on a four-layer network that starts at the process level in the field layer, going up to the station network and to the wide-area network, and even to the external network connecting to remote users in the market, operation, and regulation entities, using the Internet. Typically, automatic decisions are taken locally in the substation by IEDs, regionally by phasor data concentrators

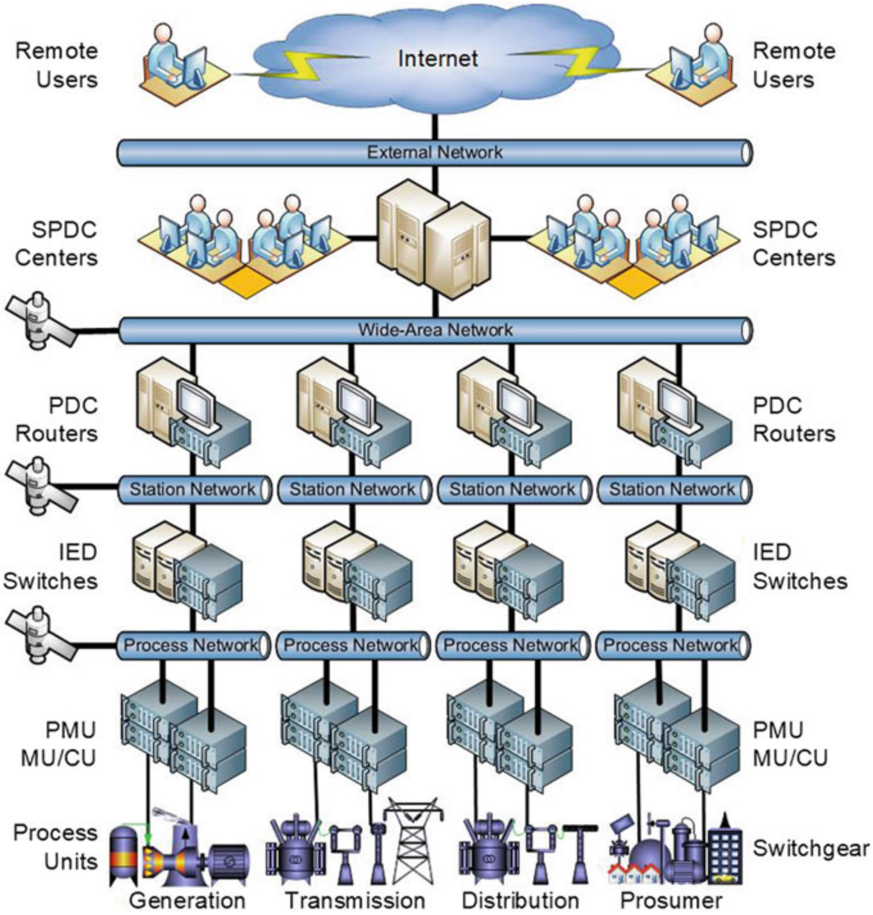


Fig. 13 Wide-area PACS. *Source* The author

(PDC), and globally by super phasor data concentrators (SPDC), or energy management systems (EMS) at corporate or national level. In a typical WAPAC system, data is sent from one or more PMU or MU devices to a controller located at a substation, control center, or other appropriate facility. WAPAC functions can include switching of capacitors, reactors or lines, generator and load dropping, SVC damping, and any other action including traditional special protection schemes (SPS) and automatic generation control (AGC). Among its main objectives are remote access to real-time sensors, centralized automatic protection, and control decisions, and remote tripping of equipment. Additionally, the device receiving the commands can use this information to adjust relaying parameters or settings, so the relay is making local optimal decisions based on the actual system configuration, adapting to changing grid status. Furthermore, it can automate the definition and deployment of relay settings, calculated based on real-time requirements defined by system simulations or regulatory authority, stored in a centralized data base or replicated in a distributed data base per station. Settings may be downloaded to local engineering stations or directly to the relay using IEC 61850 messages, while the installed settings are recovered automatically from a central database and compared to expected stored settings for auditing.

This architecture is supported by recent developments in telecommunication systems, with spread of wide-area networks (WAN) and satellite GPS signals, and the standardization of high-accuracy phasor measurements and advanced sensor devices. It is expected that synchronized phasor measurements will fully replace the traditional sensing of electrical signals in the substations and become the standard method of information exchange for wide-area PACS and supervisory control and data acquisition (SCADA) systems, replacing the traditional Remote Terminal Unit (RTUs). A change in paradigm that is closely related to the concept of centralized protection and control (CPC), as applied to local substation automation [16].

Centralized Protection and Control

In parallel with the development of wide-area PACS (WAPAC), a related development is underway in the direction of Centralized Protection and Control (CPC) systems in substation, as illustrated in Fig. 14, instead of bay-wise dedicated PACS. The architecture of a centralized PACS includes a high-performance computing platform that provides protection, control, monitoring, communication, and asset management functions for a full substation [17, 18]. Instead of employing several distributed IEDs embedded in proprietary physical devices, the software running in each IED is moved to virtual machines on a centralized replicated computer. The CPC collects the required data using high-speed, time-synchronized measurements within the substation.

The development of merging units (MU), control units (CU), and phasor measuring units (PMU) paved the way for the adoption of this architecture, with all sensor data now available in high-speed communication networks inside the substation. All these secondary devices could be installed locally in the field, reducing the need for control room space. Soon, it is envisioned that even the MU, CU, and PMU could be

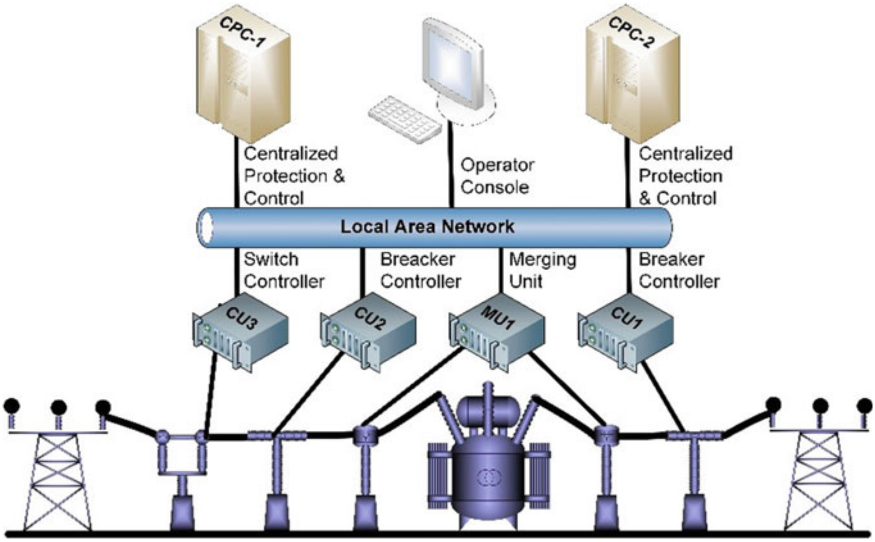


Fig. 14 Centralized protection and control. *Source* The author

embedded in the primary equipment, avoiding local cabinets, following the concept of Internet of things (IoT) for home appliances, applied to power equipment.

Reliability and speed are the main requisites for the sensor network and for the servers of a centralized PACS. Current network technologies like the Spanning Tree Protocol (STP), Rapid Spanning Tree Protocol (RSTP) and Media Redundancy Protocol (MRP) are among the possibilities for these networks, providing true zero-frame loss communication. Time-sensitive networks (TSN), deterministic-time networks (DTN), and software-defined networks (SDN) will further improve Ethernet networks by assuring deterministic behavior, easy-to-manage, and configure.

The concept of a centralized PACS provides several advantages over the current distributed processing architecture [19]. The limited number of physical devices requires fewer configuration tools and less (per bay) maintenance, with a limited number of access points. Mainly, configuration between IEDs is not required as it is done internally to the central system. This will eliminate the interoperability challenge common to distributed architectures, with easier configuration and PACS rollout but with possible common mode failures. Finally, the centralized system can also function as the gatekeeper or master intelligent node for substation-to-substation and substation-to-SCADA communication. Of course, this will require a paradigm shift in the way of designing, manufacturing, installation, testing, operation, and maintenance of PACS.

In addition, CPCs can perform power quality analysis of local phenomena like voltage sags, swells, interruptions, harmonics, impulses, flicker, switching transients, and notches, etc. State estimation-based protection can also be processed by comparing the measured signals with the simulated behavior of each component and topology, based on substation models. Pattern classification-based protection can explore advanced AI algorithms to classify the signals into preselected types of disturbance signatures and taking appropriate actions.

Software-Defined Protection and Automation

Complementary to the movement toward a centralized PACS, software-defined protection and automation (SDPA) systems will rely strongly on software modules to execute the essential protection, monitoring, and control functions. Instead of a set of hardware boxes, PACS could be structured as a set of interconnected software packages running in a centralized or distributed processing system. Contrary to the current modular structure of hardware-based PACS, SDPA can be totally programmable and modular, allowing the dynamic remote changing of software, parameters, and location. Like SDN, SDPA separates the control layer from the data layer, providing flexible communications through the provision of a centralized controller. This opens entirely new perspectives on asset management, as the blocks can be moved as intelligent agents from different hardware locations and adapted according to changing requisites. The concept is illustrated in Fig. 15, where a farm of standard distributed servers support the control layer, and the running of software-defined modules or IEDs that can be executed in any of the available servers.

This architecture signals the possibility of an entire network of standard processing units, connected by high-speed wide-area networks, where the distributed functions implemented in the PACS are entirely defined by software, and can be changed and moved remotely. As a natural consequence, the wide-area network of processing units

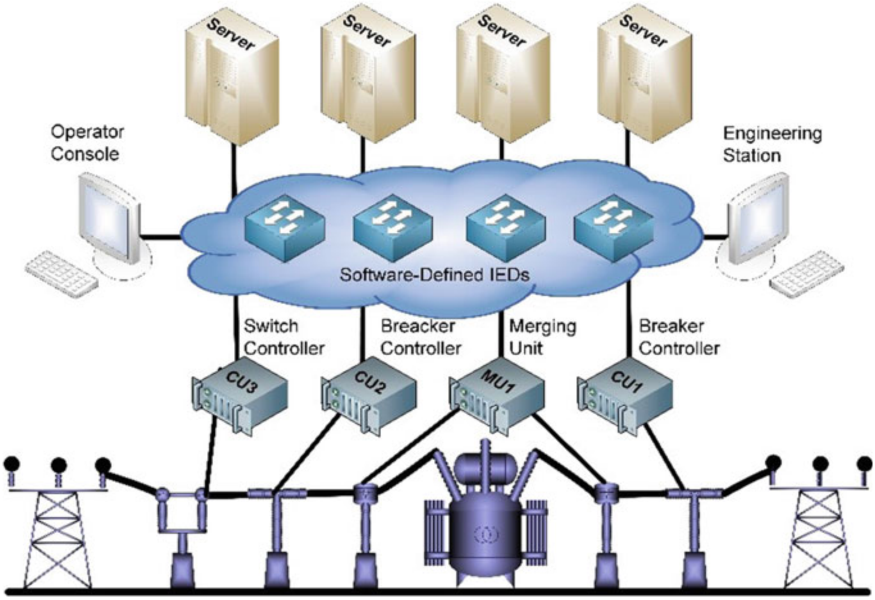


Fig. 15 Software-defined protection and automation. *Source* The author

can be physically located in the premises of the substations, or located somewhere in the Internet, which brings the possibility of a cloud-based protection and automation systems.

Cloud-Based Protection and Automation

Cloud-based protection and automation (CBPA) is a natural consequence of the evolution of cloud-based information processing services. Mirrored in the current Information Technology (IT) services available through Internet, it will be possible in the future to deploy PACS using Infrastructure-as-a-Service (IaaS) as servers in the cloud acting as IEDs;Platform-as-a-Service (PaaS) as a hosted application environment for building and deploying CBPA applications; and Software-as-a-Service (SaaS) for PACS applications typically available via browsers or thin clients. Figure 16 illustrates these concepts as applied to a substation.

Although the concept is easily transferred from IT to PACS, many issues must be solved before their full adoption by utilities. The main aspects are related to cybersecurity, as the strategic PACS functions will be located outside the utility domain, and the speed and real-time requirement of protection applications.

Remote Testing and Maintenance

As the IEDs will be based on digital hardware, and their input and output signals are formatted network messages, the process of testing and maintenance of a PACS resumes now to generating input messages and gauging the output messages for

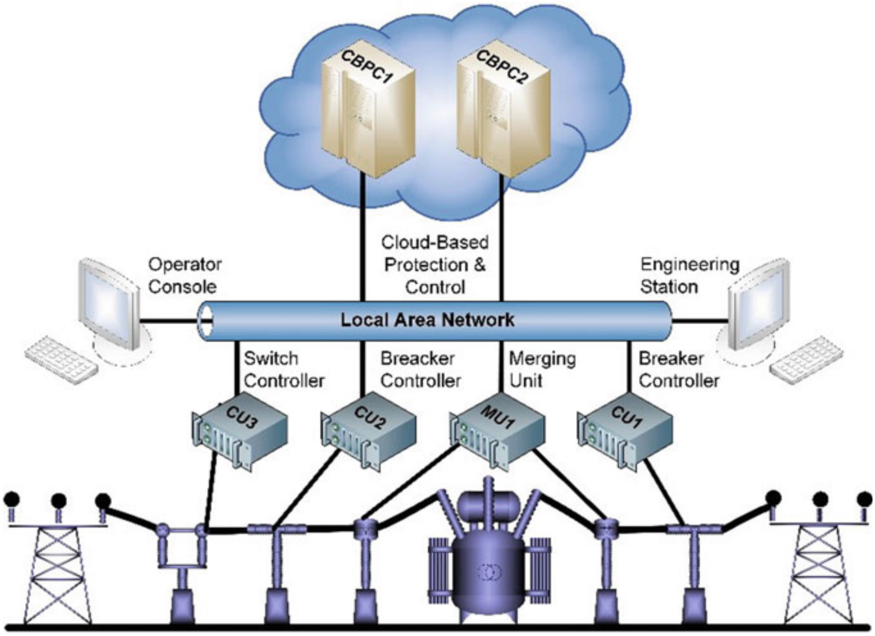


Fig. 16 Cloud-based protection and automation. *Source* The author

typical use cases, while comparing with expected results. This applies also to the PACS settings, as this is deployed today by client–server (C–S) messages exchanged with the IED, with IEC 61850 offering the isolation means required for testing. The possibility of sending and receiving these messages from a remote location, using a communication network, introduces the concept of remote testing and maintenance.

Automatic verification of relay settings can be performed by unattended checking of relay conditions and remote test of relays. In these systems, test scripts are developed based on the requirements defined by asset management or regulatory authority. The scripts can be stored in a centralized data base, replicated in a distributed data base per station, and downloaded to locally installed test-sets. The results are sent automatically to the central database and compared to expected stored results, using advanced intelligent tools.

Advanced Intelligent Tools

Despite all recent developments, several non-standardized graphical tools have been in use to ease the development of PACS, most of them being specific to each technology, standard, or proprietary formats. Functional requirements, at the start of the engineering cycle, have not been fully standardized by any of these standards, raising questions about how to validate any solution against its functional requirements. These requirements are currently defined in natural text (NL), subject to the impreciseness and ambiguity of such format. To be precise, there is a need for a human-understandable but formal format to force the description of unambiguous requisites, and to allow its manual or mechanical compilation into selected technologies by suppliers and integrators. The format should allow also the early application of formal verification and validation methods to such systems, before design decisions are taken, as well as during conformance testing of the final system to the user requirements, and across all stages of the engineering process. A recent CIGRE survey about the preferred future language for functional PACS requirements showed a convergence of stakeholders [2] to using languages based on formal methods. A large fraction of manufacturers sees Controlled Natural Language (CNL) as the preference language among producers for future requirement specification, while researchers prefer the language Z and CNL for new developments; Natural Language is the smallest fraction of preference among these stakeholders for future requirement specifications, except if formal methods or artificial intelligence (AI) methods are developed capable of unambiguously interpreting every Natural Language requirement.

With the advancement of Information Technology (IT), the complexity of new solutions will require more sophisticated tools to design and maintain these systems. Intelligent tools are critically necessary as an enabler, freeing the engineer to work specifically with PACS, avoiding the details of telecommunication, electronics, interoperability, etc. Formal methods of design verification are required to model-check the entire engineering cycle, preventing errors to propagate in the process, and increasing their safety and reliability. The development and standardization of a Domain-Specific Languages (DSL) [20] for human interaction with PACS is a possible direction, mainly at the initial phase of the engineering cycle, for functional

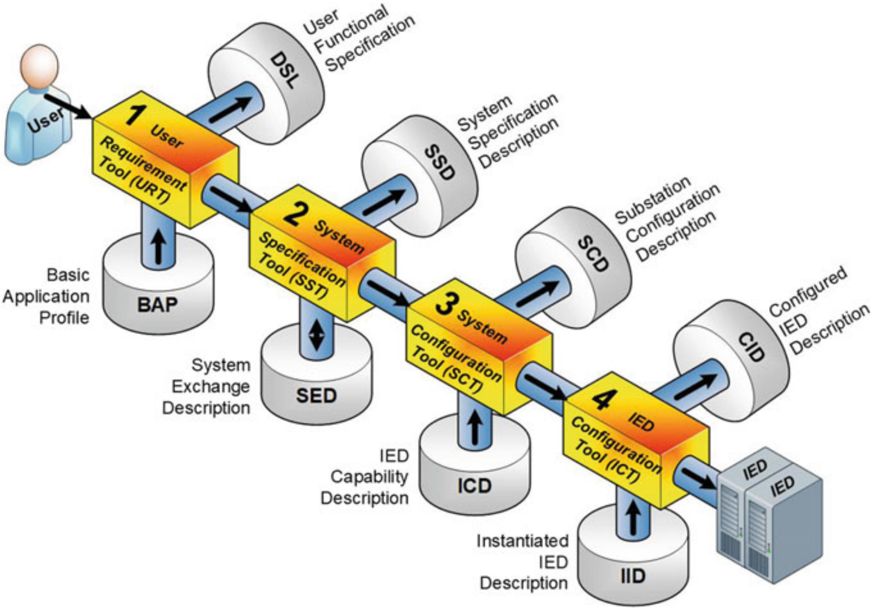


Fig. 17 Advanced user-requirement tool. *Source* The author

specification and for testing. Figure 17 shows the intended function of a user requirement tool (URT) in the engineering design cycle proposed by IEC 61850, using a DSL as the format for user interaction.

Note that the DSL is just a human-understandable view of the requirement, based on Controlled Natural Language (CNL), with a formal syntax and semantics, supported by a graphical integrated development tool that could be automatically translated to XML for computer processing. The tool for functional requirement specification would possibly access a database of standard recommended solutions or basic application profiles (BAP) expressed in the same DSL, and produce a functional requirement expressed again in DSL. This is standard technology already used for developing AI systems, language compilers, and games that can be adapted to PACS, allowing the application of formal methods to the entire engineering process, and integrated to IEC 61850 tools. This concept is currently being researched by a CIGRE Working Group B5.64 (Methods for Specification of Functional Requirements of Protection, Automation, and Control) [21], among the application of other formal methods to PACS.

Application of Formal Methods

New developments are expected to occur with the introduction of formal methods into the design and engineering cycle. In addition to automatic compilation of high-level design languages (DSL) to low-level implementation modules, formal methods can be used to define the semantics of existing technologies like IEC 61850, and model-check the correctness of implementation of a given user requirement or design

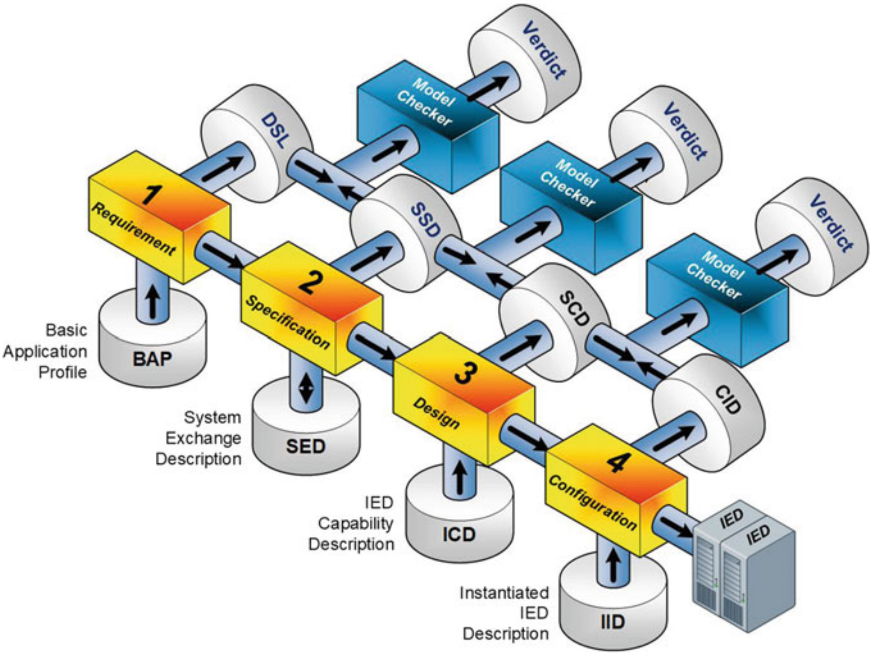


Fig. 18 Application of formal methods. *Source* The author

specification. Figure 18 shows a possible insertion of formal model checkers into the engineering design cycle of IEC 61850 based PACS, with the user requirement expressed in a formal DSL.

Each phase transition of the engineering design cycle can use a model checker to verify the correctness of the implementation, providing verdicts about design flaws. The model checker verifies that each stage produces a set of artifacts that is logically coherent with the previous stage. This is possible considering that every stage of the engineering cycle is now translated into a set of formal representation of the design in SCL, the Substation Configuration Language of IEC 61850.

Education and Knowledge Acquisition

To cover this wide-spectrum knowledge required from future PACS engineers, a systemic approach to education will be needed. Part of the education should be dedicated to learning high-level PACS languages, systemic views and methods, leaving the implementation and interoperability details to development tools. From a PACS point of view, development will be based mainly on simulators and formal languages, that will mimic and model-check all aspects of a new system. This tendency is already seen in other complex fields like aeronautics, nuclear power and medicine, where pilots, engineers and physicians are educated and tested on complex simulators.

A strong emphasis should be placed on training using specialized software as most PACS in the future will be software-defined systems. Application engineers should focus mainly on the assembly of complex systems based on available software modules (expressed in DSL), produced by software houses or relay developers, and not on the details of their implementation or interoperability. New and modern academic curricula need to be developed, aligned with the evolution of PACS technologies to cope with future grid requirements. With dispersed workforce and reduced downtime requirements, focus should be placed on increased online education methods, particularly for pre-work/study where interaction/practical aspects are not required, forging a continuous learning and improvement ability, with free dissemination of technical information to promote interest in the career. This will only be possible with a radical change in education curricula, supported by investments in Research and Development (R&D).

Research and Development

With the fast evolution of digital systems, the total unbundling of hardware and software of PACS is expected in a near-term future. This includes the introduction of new players as solution developers that are not suppliers of hardware. Third-party PACS services seems to be the next evolution in these systems, following the tendency already seen in the telecommunication and software industries. It is not difficult to imagine also the advent of a new kind of market of service providers of PACS services, as seen for ancillary services in the power industry and cloud services in IT and software industry. This tendency will be the result of a future movement from traditional large suppliers of solutions based on hardware to small and start-up software companies that produces tailor-made solutions and PACS based on software. Research and Development (R&D) should now be focused on centralized protection with separation of hardware and software, possibly located in the cloud, and supported by intense use of formal mathematical methods. New business models need to be established with server providers and software houses for deploying these future PACS.

In-line with the current tendency to wide-area PACS, remote testing and setting of relays and IEDs are not only feasible with current technologies and standards but also a prerequisite to lower the costs of maintenance, and to allow the implementation of adaptative PACS. Its widespread use is limited only by security and grid procedure restrictions. Many intelligent and formal tools are expected to be developed soon for testing, setting, and validation of the design of PACS. Utilization of modern optimization techniques such as neural networks, Petri Nets, fuzzy logics, and wavelets shall be considered as candidates. Analytics and tools for automated fault analysis (AFA) are rich research areas as the number of installed digital fault recorders (DFR) increases, and synchrophasors are available from wide-area systems. For protection and fault location, time-domain functions based on signals digitized at higher sampling rates will offer a promising field of research. These R&D initiatives should be followed by corresponding efforts in standardization and regulation.

Standardization and Regulation

Many tools and languages have been used in the specification, design, implementation, and operational phases of the engineering of PACS, with varying levels of success. The only phase of the design cycle not yet standardized is the planning phase. The standardization of a unique Domain-Specific Language (DSL) for human interaction with PACS, mainly at the beginning of the engineering cycle, for functional requirement; at the end of the cycle, for testing and maintenance, and in the intermediate phases for formal checking, is a requirement for the future of PACS. This is motivated also by the huge size of IEC 61850 dedicated mainly to the syntactical communication aspects of PACS. Lack of a formal semantics for the functional blocks and logical nodes (LN) demands much effort for its understanding and application, resulting sometimes in interoperability problems among different IED manufacturers.

Closely connected to the need for a formal DSL, performance requirements and statistical collection and evaluation of PACS behavior need to be standardized, easing the regulation, benchmarking, and maintenance of these systems. The information transfer between manufacturer and utilities also needs to be standardized for accurate modeling of fault contribution for renewable generation. Sometimes, there is a lack of clarity of protection methods relating to how protection functions work and are applied, and this can lead to unintended power system consequences. The focus should perhaps be on less paper standards and more online documentation systems for easy access from PACS engineers.

Formal Methods

Except for the planning phase and testing, all remaining steps of the engineering process of PACS are currently supported by standardized formats and languages, with suitable proprietary and independent tools. The previous discussion shows that there is clearly a need for a formal language specifically designed for the description of functional requirements from a user, owner, or stakeholder point of view. This language should use a vocabulary and grammar close to the way a user expresses the desired functionality of a PACS, while being easy-to-learn and independent of the implementation technology. To be precise, it should also use formal syntax and semantics to allow unambiguous definitions and computer-aided processing and be easily integrated to the common standard IEC 61850 used by the industry for the design cycle of PACS.

The answers obtained from the CIGRE survey [2] constitute a rich picture of the status of standardization of the engineering process of PACS, and the specific needs for a standardized format for functional requirement specification. The following general conclusions are derived from the survey, and represent the current view about the turning point of evolution of PACS:

- IEC 61850 is the de facto standard for designing PACSs for the power industry;
- Any new Requirement Language should be integrated to IEC 61850;
- Any Requirement Language should be easily readable by humans and computers, like Natural Language (NL) or Controlled Natural Language (CNL); this precludes specifically XML for human interaction;
- The Requirement Language should be understandable by non-expert users. Again, this favors Controlled and Natural Languages (NL or CNL);
- The Requirement Language should be formal and mechanically translatable (by a compiler) to standardized design languages like IEC 61850, IEC 61131, IEC 61499 or IEC 13568.

In summary, this language should use a vocabulary and grammar close to the way a user or power system planner expresses the desired functionality of a PACS, while being formal, easy-to-learn, and independent of the implementation technology. Based on the results of this survey, the need for a Domain-Specific Language (DSL) oriented for the specification of functional requirements of PACS was identified. Using a formal syntax and precise semantics, the language shall help users to describe and exchange the structure and desired logic of PACS, without delving into the technological details of its implementation. It could also pave the way for the definition of a formal semantics for the entire IEC 61850 standard.

For specification of future PACS, complex temporal logic (TL) need to be described using simple linguistic constructs near the natural language. A set of use cases should be possible to exemplify its application to typical PACS in substation and control centers, like the basic application profiles (BAP) under development by IEC. The format will allow also the early application of formal verification and validation methods to such systems, before design decisions are taken, as well as during conformance testing of the final system to the user requirements, and across all stages of the engineering process.

5 Summary and Conclusions

To take the right decisions with focus into the future, it is recommended that utilities, regulators, and planners develop their technological roadmaps, to support the decisions about education, and investment in new technologies, with comparison between technological options, demonstration of benefits, compliance with national policies for infrastructure protection and account for public views. A PACS roadmap should define the future state for this area, the gaps in reaching the target state, other organizations working in this area, the stakeholder´s role and strategy in working in this area, its design standards and priorities for R&D projects. Pilot projects should be scheduled in order to evaluate the advantages and disadvantages of implementing new technologies with existing network. It should envision the future and current state-of-the-art; provide the implementation strategy for creating the IT and communication infrastructure to support the future vision; identify needs for management changes and issues, and plan workforce training and education. In the future, probably, there will no longer be separate protection and control staff—those roles will merge (as they are already starting to) into application system engineers, and staff will need to deal with an integrated assemble of protection, control and communications.

Acknowledgements The author would like to acknowledge the contributions received from Study Committee B5 chair and members from the CIGRE National Committees of Norway, Australia, Brazil, China, Colombia, France, Great Britain, India, Japan, Saudi Arabia, Spain, and Thailand, that provided answers to the survey [3] for writing this chapter, as well as the 135 experts in 97 companies from 42 countries that provided their view about the future of Functional Requirements of Power System Protection and Automation [1].

References

1. Siqueira, I.P.: Functional requirements of power system protection and automation—CIGRE Task Force B5.02, Paris, France, 2018
2. Siqueira, I.P., Faarooqui, N.U., Nair, N.-K.C.: A Review of International Industry Practices for Specification of Functional Requirements of Protection, Automation and Control. CIGRE Science & Engineering, N. 11, Paris, France, June 2018
3. Siqueira, I.P.: Electricity Supply Systems of the Future—Protection and Automation—Green Book—Chapter Survey. CIGRE, Paris, France (2018)
4. CIGRE: Modern Distance Protection Functions and Applications, Brochure 359, Paris, France
5. CIGRE: Modern Techniques for Protecting and Monitoring of Transmission Lines, Brochure 465, Paris, France
6. CIGRE: Cigre Modern Techniques for Protecting Busbars in HV Networks, brochure 431, Paris, France
7. ISO/IEC TC57: IEC 61850—Communication Networks and Systems for Power Utility Automation. IEC, Geneva (2003)
8. ISO/IEC TC65: IEC 61499—Function Blocks. IEC, Geneva (2005)
9. ISO/IEC TC65: IEC 61131—Programmable Controllers. IEC, Geneva (2003)
10. ISO/IEC JTC 1: IEC 13568—Information technology—Z formal specification notation. IEC, Geneva (2002)
11. OMG: UML—Unified Modeling Language. http://www.omg.org/spec/UML/
12. OMG: SysML—System Modeling Language. http://www.omgsysml.org/
13. Siqueira, I.P.: A review of standards and tools for the engineering process of protection automation and control systems. In: International Conference and Exhibition, Relay Protection and Automation for Electric Power Systems, Saint Petersburg, Russia, 2017
14. Brahma, S., De La Ree, J., Gers, J., Girgis, A.A., Horowitz, S., Hunt, R., Kezunovic, M., Madani, V., McLaren, P., Phadke, A.G., Sachdev, M.S., Sidhu, T., Thorp, J.S., Venkata, S.S., Wiedman, T.: The education and training of future protection engineers: challenges, opportunities and solutions. IEEE C-6 Working Group Members of Power System Relaying Committee. EEE Trans. Power Delivery **24**(2)
15. CIGRE: Education, Qualification and Continuing Professional Development of Engineers in Protection and Control, Brochure 599, Paris, France
16. Bo, Z.Q., Lin, X.N., Wang, Q.P., Yi, Y.H., Zhou, F.Q.: Developments of power system protection and control. In: Protection and Control of Modern Power Systems, Springer Open, 2016
17. IEEE PES, Looking into the Future Protection, Automation and Control Systems, Working Group K15 on Centralized Substation Protection and Control. IEEE Power System Relaying Committee

18. IEEE PES, Centralized Substation Protection and Control, Power System Relaying Committee, Report of Working Group K15 of the Substation Protection Subcommittee, December 2015
19. Das, R.: Looking into the future protection, automation and control systems. Presentation on the at the Power System Relaying Committee of the Substation Subcommittee about Working Group K15 on 'Centralized Substation Protection and Control', EPCC 14 Workshop, Wiesloch, Germany, May 16, 2017
20. Fowler, M.: Domain Specific Language. Addison-Wesley Professional (2010)
21. CIGRE: Methods for Specification of Functional Requirements of Protection, Automation, and Control, CIGRE Working Group B5.64 Term of Reference, Paris, France, 2018
22. Siqueira, I.P.: A layered hierarchical object–oriented view of IEC 61850. In: PAC World Conference. Dublin, Ireland (2011)

Iony Patriota de Siqueira holds a D.Sc. and B.Sc. in Electrical Engineering, an M.Sc. (honors) in Operations Research, an MBA in Information Systems, and more than 40 years of experience in consulting, operation and maintenance management for infrastructure sectors. He is an Honorary and Distinguished CIGRE Member and former Chairman of Study Committee on Protection and Automation, Chairman of Brazilian Technical Committee of IEC TC 57 and ABNT, an adviser for the Brazilian Maintenance Association, President and CEO of Tecnix Engineering and Architecture, Director of Brazilian Maintenance Institute, Permanent Member of the Brazilian National Engineering Academy, and a post-graduation visiting teacher at four universities. A recipient of CIGRE Technical Committee Award, Brazilian Engineering Premium, CIGRE-Brazil best Paper Award, Vote of Praise from the Brazilian Chamber of Deputies and CIER Special Award. He has authored four books about Maintenance, Management Science, Power Plant Automation and Critical Infrastructure Networks, and co-authored two books on Operations Research and Power System Resilience.

Power System Development and Economics

Konstantin Staschus, Chongqing Kang, Antonio Iliceto, Ronald Marais, Keith Bell, Phil Southwell, and Yury Tsimberg

1 Introduction

Study Committee C1 (SC C1) deals with system development and planning, work which routinely looks far into the future. Today, the view on the system of the future is even more holistic, as well as its role in society. Therefore, next to the ten technical issues and challenges listed in Sect. 1 of the Introduction,the following aspects need to be taken into account:

1. The COP21 **Paris Agreement on climate protection** and Europe's national and EU-wide energy and climate plans which address full decarbonization of the energy system for a horizon of 2050 or soon after, mean that many countries already plan for a CO_2-free power system for a closer time frame than typical

---

On behalf of CIGRE Study Committee C1.

K. Staschus (✉)
ENTSO-E, Brussels, Belgium
e-mail: Konstantin.Staschus@ext.entsoe.eu

C. Kang
IET, London, UK

A. Iliceto
TERNA RETE ITALIA, Rome, Italy

R. Marais
Eskom, Sandton, South Africa

K. Bell
University of Strathclyde, Glasgow, UK

P. Southwell
Australian Power Institute, Canberra, Australia

Y. Tsimberg
Kinectrics Inc., Toronto, Canada

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_10

power plant and network equipment depreciation times. This decarbonization goal brings aspects of a clear and common target into system planning which did not exist before, and also of increased risks of stranded assets.

2. Since greenhouse gas emissions including CO_2 do not only come from the electricity system but also from transport, heating/cooling, industry, and agriculture; many countries aim at complete **decarbonization**. Because of the efficiency of electricity use in transport, heating, and many industries, this implies planning and investing for a system for the **coupled sectors of electricity, gas, transport, and heating**, i.e., a system of systems. Electricity grids could come to be considered the backbone of the entire energy system (see, e.g., ETIP SNET Vision 2050).
3. Because our use of electricity, heating/cooling, and transport together makes up a much bigger part of our daily lives than that of electricity alone, this **holistic energy transition will affect and interest many citizens very strongly**. It has the potential to unite and positively excite us, as our cities get quieter, our air cleaner, and climate catastrophes are kept at bay. But, it will likely also lead to heated discussions, for example, about distributional effects.
4. Both continental-scale international interconnections and microgrids have made progress, and for both, trading and balancing rules are important, meaning that aspects of electricity trading and of markets have entered most electricity systems. This means the number of potentially active participants in electricity markets and in the coupling with gas, heat, and mobility markets is enormous. Many countries have concluded that only a **market approach** can lead to good solutions when so many actors need to be coordinated.
5. The **balance between the three traditional goals of electricity supply, reliability, economics and the environment, and the character of the respective goals are changing**: Until the 1980s, reliability was a hard constraint, the environment was captured in certain constraints without very extensive influence on planning decisions, and economics was optimized usually from the perspective of a single, integrated electricity utility. Today, the environment and in particular climate protection imposes the most important constraints, reliability becomes a function of economics with demand response and price-elastic loads, and the optimization of economics occurs in a market environment.

Looking at the combined effects of the above concepts, system development, asset management, and system economic analyses will have to evolve strongly from their past and current state of the art:

- to deal with much broader analyses of costs and benefits,
- of a wider range of investment and efficiency alternatives,
- with changes in expected useful equipment life due to varying loading conditions,
- with stranded asset risks from technical, economic, and climate change developments,
- in a “system of systems,”
- under strong and multi-dimensional technical, economic, and political uncertainties,

- but with a newly clear common worldwide goal of climate protection.

Section 2 describes the state of the art of electricity system planning, asset management, the economics of investments, and the interconnections between different countries, voltage levels, and energy sectors. Here, planning and decision support methods are especially important; technology developments on equipment and control systems are covered by other SCs' chapters, and this chapter only needs to address how new technology affects the planning and decision support methods. Similarly, the important aspects of standardization concern software, data exchange standardization, and interoperability issues, while educational aspects relate to promulgating a good understanding of the holistic power and energy system as a system of systems. Section 2 also includes descriptions of how the aspects of the system of the future listed above, and thus the new societal and grid requirements, are dealt with by this state of the art, but leaves identifying gaps for which new methods will need to be found for Sect. 3. Finally, our methodological approach for Sect. 2's planning problem descriptions uses generic high-level formulations of the objectives pursued and constraints considered, albeit without symbols but with easier-to-follow words. This approach aims to better clarify the differences between different planning problems and their evolution over the past and into the future.

Section 3 then points out innovation needs for new societal and technical needs and challenges not fully addressed in the state of the art. Sections 4 and 5 summarize the resulting future and research issues, and provide conclusions.

2 State of the Art and Degree to Which It Addresses the New Societal and Grid Requirements

2.1 Overview of Current System Planning Methods

The current electricity system planning environment requires consideration of new technologies, customer participation, and therefore, new planning methods at multiple levels. In response, electricity system planning is becoming more holistic, i.e., addressing generation, transmission, distribution, and demand flexibilities increasingly together, because computing power begins to make that possible, and because the need for this increases due to distributed energy resources and empowered customers. In this section, the generic high-level formulations of generation, transmission, and distribution planning subproblems are described separately, each with a brief sketch of the current worldwide state of the art of system planning. The treatment of uncertainties, externalities, and of market decisions versus central system planning, deserves special attention in these descriptions.

2.1.1 Generation Planning

Of the components of the value chain of electricity supply, generation planning has the longest history of formal optimization approaches to investment planning.

Over the past decades, the monopoly structure of utilities has been questioned and evolved toward markets in many countries. Ideally, all market participants, consumers, generators, storage operators, prosumers, would make their own assumptions based on market price signals and their own forecasts and preferences, and invest with the expected risks considered. Several markets in Europe, North and South America have become quite sophisticated in their market price signals including not only prices per market time unit on kWh energy but also on capacity or reliability, and on many different kinds of ancillary services. Nonetheless, it is hard to achieve full consistency between the price signals for all these markets, with the incentives for clean generation, and with the price signals in gas, oil, combined heat, and power and transport fuel markets.

Understanding the future supply requirements (incl. load growth) and available resources (incl. disruption from new technologies) is among the most important inputs into generation planning. The objectives are influenced by many factors including political, climate change, innovation and efficiency factors, and many inputs and influencing factors are subject to strong uncertainties. Therefore, along with the examination on how markets can affect the formulation of objectives and constraints of generation planning, the effects of uncertain parameters are also examined through scenario evaluation. This makes the state-of-the-art generation planning a multi-criteria analysis.

Generation planning with uncertainties and through multiple regions or subsystems

With the operational uncertainties considered, the maximum unit generation becomes stochastic. These uncertainties can be caused by the full or partial outages of generation units, or by wind speed, solar irradiation, or water availabilities. Furthermore, the unit operating costs can be modeled depending on unit loading. With generation unavailabilities modeled, the constraint that all loads must be covered becomes one of meeting minimum loss of load expectation (LOLE) or loss of load probability(LOLP) standards. Expected system operating costs and LOLE/LOLP can be evaluated for a given set of units resulting from investment decisions, by chronological stochastic simulations. Chronological simulations are state of the art as the traditional equivalent load duration curve approach based on convolution of load and unit outage distributions does not work with strongly correlated unit availabilities, such as for solar and wind generation within a region subject to the same weather. To integrate the uncertainties into the planning optimization model, several modeling methods of uncertainties have been applied. Generally, common optimization models involving uncertainties include chance constraints models, risk-based models, robust models, and stochastic models. Uncertainties impose a huge computational burden on problem solving, which can be addressed only by modern computational power and algorithms.

Generation planning with competitive or market frameworks

Beginning in the 1980s, competition was introduced into the generation sector in Chile (1982), the UK (1989), and then in Europe, and many other parts of the Americas and Oceania. This was done by separating the natural monopoly networks from competitive generation and supply, and it altered the generation company's investment portfolio problem. System load and emissions constraints are replaced by contractual values, and rather than minimizing costs, a generation company maximizes profits. The price at which the company sells the energy to different kinds of customers for different products (e.g., energy, capacity, and different kinds of reserves), at different times and in different market areas, is in principle not regulated, but depends on the competitive situation. Price forecasting for all different kinds of energy, capacity, and reserve products thus becomes a major determinant of generation and storage investment decisions in competitive electricity markets. For the price forecasting, it is ideal to perform a full system investment portfolio optimization which includes not only the generation company's own units but all existing and new units of all companies.

The overall system constraints do not appear in market party's optimization, but do appear in their price forecasting. Furthermore, the state or the system operator will assess the generation adequacy [1–3], i.e., whether there is sufficient generation capacity among all generation companies to meet reliability constraints. If the state or the transmission system operator agrees that the capacity available within the network is insufficient, capacity mechanisms [4, 5], generation capacity auctions, or similar measures may be taken. These scenarios further complicate the price forecasting mechanism for generation companies. They also present a difficult challenge for the overall market design, where national strategic planning aiming at public benefits (e.g., national climate-energy plans in Europe in conjunction with national capacity mechanisms) does not lead to direct state action but needs to be enacted by private investors. This challenge is even more difficult considering the long deployment time of transmission investments, compared with much shorter deployment times of some kinds of generation, storage, demand flexibility, and distribution investments. These challenges will be addressed in Sect. 2.1.2 on transmission planning below.

Generation planning with flexible demand and monetization of reliability and externalities

The flexibilization of demand and the monetization of environmental and safety externalities described in the introduction tend to lead to an alternative formulation where costs, reliability, at least some environmental externalities like CO_2 emissions, and even safety, can all become part of the objective of planning an integrated system. All of these being treated in parallel in the objective function means that tradeoffs among them are made very explicit, e.g., based on conversions of reliability and environmental externalities into the same currency as costs and profits. Such monetization is an extreme example of making these tradeoffs more explicit; nearer-term planning, which does take multiple criteria into account, often prefers to leave making the tradeoffs to politicians rather than to those planners who define the input data for an optimization program.

This approach especially to reliability requires very sophisticated price forecasting mechanism, not only for scenarios and hours where there is sufficient adequacy but also for other scenarios or hours with insufficient adequacy (i.e., scarcity in at least some products). For such scenarios and hours, balancing energy cost but also possibly the price achieved for energy or reserves, approach the value of lost load [6]. Value of lost load or VOLL is used to describe the per kWh cost of a blackout, which varies between customers, time of day or season, and the usage of electricity. VOLL also changes based on the duration and geographic scope of a blackout. Similarly, the future price of emission certificates depends on political decisions in many countries and is hard to forecast.

Recent CIGRE work addressing generation planning

CIGRE and especially SC C1 have provided various technical brochures (TB) on the key issues mentioned above, in the evolving generation planning environment. In recent years, SC C1 work examined roles and responsibilities of the electricity industry actors with reference to the system development aspects, identifying the extent of their influence on the electric industry in relation to system development, based on effective physical boundaries between generation, transmission, and distribution.

2.1.2 Transmission Planning

For a generic high-level formulation of transmission planning, the traditional objective was to avoid any equipment overloads in any contingency scenario (usually an outage of a single piece of equipment from a pre-defined contingency list). A security analysis based on AC power flows was the traditional approach, with a nodal representation of the system generation portfolio and of loads as inputs. Because of high computational requirements and strong nonlinearities of these power flow analyses, usually only a few critical cases were simulated for a target year, e.g., winter peak and summer minimum load cases for 5 or 10 years in the future. If an equipment overload occurs in one of the simulations, equipment is added or reinforced until the overload does not appear anymore. A master program which tries out different additions or reinforcements of equipment can be placed above the security analyses to automate the process of finding least cost reinforcements of the system which satisfy all security constraints. This cost minimization (min) objective function and the constraints it is subject to (s.t.) can be summarized as follows:

Min sum over years and reinforcement options of reinforcement capital costs,
plus sum over years and hours of system losses
s.t. all pre-defined contingencies do not lead to equipment overloads, incl. if needed
dynamic security constraints
all constraints of the AC power flow

Despite its challenging computational complexity, this approach ignores several important issues:

- With higher penetration of renewable energy with limited capacity factors, cases where equipment overloads might occur become harder to identify. They may be more dependent on sunshine and wind than on load level, and the traditional few peak and off-peak load cases may become insufficient.
- Equipment overloads might be cheaper to remedy by demand response than by reinforcements.
- Driven both by international electricity trade and by renewables with limited capacity factors, the benefits from exchanges between different areas or countries become economically more important than the avoidance of equipment overloads. For example, a country with wind resources in the North and strong load in the South might be able to operate securely by curtailing wind energy and running gas-fired plants in the South, but the additional cost of running the gas units—or of foregoing trade between North and South—can be much higher than the cost of additional transmission.

Therefore, transmission planning has evolved into a value-based assessment, similar as generation planning. For example, the security benefits are captured partially through applying values of lost load (VOLL, see above) in a market-related simulation, and partially through AC network simulations; these complement a market simulation with a DC approximation of the network. In the problem formulation below, the word "node" is used to mean either a node in an AC or DC network simulation (e.g., in the North American ISO approach to transmission planning [7]), or a region or zone with several or even many nodes within which there is no congestion (e.g., in the European bidding zone approach to ENTSO-E's Ten-Year Network Development Plans [8]):

Min expected value over scenarios of
(sum over years, hours and nodes
of equilibrium nodal costs of generation * nodal energy served,
minus sum over years and all reinforcement options
of capital costs of reinforcement options,
minus sum over years, hours and nodes
of nodal energy demand not supplied * VOLL,
minus sum over years, hours, units and pollutants
of emissions * price of emissions certificates)

s.t. maximum unit hourly generation

maximum unit storage energy injection with consideration of unit storage efficiency
maximum storage unit energy content with consideration of storage efficiency
technical constraints on units (e.g., ramp rates, min up and down times, startup costs, voltage and frequency ranges)

remaining environmental constraints not captured in emissions certificates

all network and security constraints of the (AC) power flow, incl. if needed dynamic security constraints

The ideal key tool for such analysis would be a security-constrained optimal power flow [9–11]. However, for large networks with several scenarios, these analyses are often solved via security-constrained economic dispatch (SCED) [12, 13] models with DC network approximations due to computational considerations, accompanied by traditional AC security simulations and if needed dynamic analyses for certain cases. In ISOs in North and South America, nodal representations of a transmission grid operated by one (independent) system operator are analyzed under different scenario representations of load and generation in SCED studies, in chronological simulations over the target year and with different weather conditions affecting renewable energy output. Analyses of the expected nodal price differences are used to determine the value of additional transmission infrastructure between different pairs of nodes. AC power flow and dynamic studies complement these economic analyses to indicate technical requirements for new investments. The value estimates from the nodal price studies and the importance of the technically required reinforcements are compared to estimates of the cost of the additional infrastructure. Where benefit/cost ratios are large enough in a relevant majority of scenarios, and where other, non-economic criteria do not reduce benefits strongly, infrastructure investments are proposed in public and stakeholder consultations. After taking into account comments received, a completed ISO investment plan is checked for internal consistency and published. Finally, the transmission owners in the relevant grid areas, and possibly additional independent project development investors, are encouraged to seek regulatory approval for the investments and sign contracts with the ISO.

In Europe, a similar approach is used for multi-national coordinated planning in ENTSO-E's Ten-Year Network Development Plans (TYNDPs): 44 transmission system operators (TSOs) from 36 European countries cooperate to update a continent-wide plan every two years. Instead of nodal economic analyses, the chronological stochastic simulations are performed over Europe's wholesale market bidding zones, to arrive at expected bidding zone price differences which are translated into values for additional transmission capacity between each pair of neighboring bidding zones. AC power flow and dynamic studies complement these economic analyses to indicate technical requirements for new investments, especially also for internal reinforcements within the larger bidding zones. A formal multi-criteria cost-benefit analysis[1] is performed on the basis of the economic and technical studies as well as several other well-defined criteria, for each candidate infrastructure project which has been proposed by the TSOs or by other project developers. The criteria are socio-economic welfare (incl. fuel and emission cost savings), CO_2 variations, renewable energy integration, societal well-being, grid losses, adequacy, flexibility, stability as benefits, capital, and operating expenditures as costs, and environmental, social, and other residual impacts. In ENTSO-E's experience [3, 14], reliability constraints force only a small fraction of network investments, most are suggested by the economic analysis and other criteria.

The ENTSO-E TYNDPs have also evolved the state of the art of scenario definition, lately defining common scenarios for European electricity and gas transmission planning,[2] and building consistent sets of scenarios of the planning horizon which for the 2018 TYNDP reached 2040. Each scenario is characterized most importantly by a so-called storyline: Sustainable transition; Distributed generation; Global climate action. 26 different parameters are varied across three scenarios to be consistent with the respective storyline. These include for example climate action, economic conditions, electric and gas vehicles, demand flexibility, heat pumps, industrial demand, the growth or decline of different generation options, power-to-gas and biomethane. The 2020 TYNDP is to refine the scenarios further and take them to 2050.

The 2040 European electricity network resulting from these TYNDP analyses can be considered a target network. It is thus an example of a methodology that has recently become more commonly applied for extra-high, high, and even medium voltage networks, where a master program steps through combinations of reinforcement options, and subproblems evaluate equipment overloads and calculate economic benefits from market price differences. Some countries apply estimates of the value of unserved load VOLL and trade off costs of reinforcement, losses, and unserved energy in the evaluations of combinations of reinforcement options, leading to a

---

[1] https://tyndp.entsoe.eu/Documents/TYNDP%20documents/Cost%20Benefit%20Analysis/2018-10-11-tyndp-cba-20.pdf.

[2] https://www.entsog.eu/sites/default/files/entsog-migration/publications/TYNDP/2018/entsos_tyndp_2018_Final_Scenario_Report.pdf.

target network. For distribution but also in an aggregate way for transmission planning, distributed energy resources such as batteries, PV, and demand response can be traded off against network equipment reinforcements (to capture what is called non-wire alternatives in North America).

The scenario-based, multi-criteria planning process aims to justify the increasing attention received by grid investments in politics and the population [15]. This leads to the transmission and system planning process involving many more actors than just system operator planners. In several countries, at the end of a very lengthy planning and consultation process involving system operators, utilities, regulators and the public, the resulting needed infrastructure investments are listed in national laws, aiming to minimize further controversy or delays with their permitting, financing, and construction. But despite the sophistication of scenario definition and multi-criteria cost-benefit analysis, the European approach still cannot stochastically optimize decision points for infrastructure projects, i.e., optimize the expected net present value of the lifetime of a project as a function of its installation date and in conjunction with the effects of all other projects. This is partly for reasons of complexity and computation time, and partly because the permitting time for new infrastructure projects continues to be on the order of 5–10 years. To truly react to evolutions in the many stochastic parameters, the bureaucratic permitting process and also the communication to stakeholders would need to be constantly adjusted, both of which appear practically impossible. Despite the strong enabling role of additional transmission infrastructure for integrating large amounts of fluctuating wind and solar energy into the energy system without having to curtail much of it, planning and permitting remain big challenges.

Recent CIGRE work addressing transmission planning

CIGRE and especially SC C1 have provided various technical brochures (TB) on the key issues mentioned above, in the evolving transmission planning environment.

TB 564 describes international practices and processes of access and connection to the transmission grid including grid code, system planning, and administrative processes.

TB 579 investigates an innovative approach to address the key issues faced by power system planners, namely high efficiency, high reliability, low carbon emissions, and high flexibility.

A joint working group from Study Committees B3, C1, and C2 developed TB585 which provides criteria to provide high-level guidance for evaluating and comparing substation configurations and the impact that different applications may have on the characteristics of the substation performance.

International utilities' best practice approaches for developing electricity load and energy forecasts are provided in TB670.

As the trend of new HVDC technologies and project unfolds, TB 684 provides a guideline to system planners in making analyses on HVDC system parameters and solutions.

TB 701 provides insight into investment in transmission infrastructure in the context of increase in renewable generation penetration.

TB 715 recommends changes to the definition of reliability and especially system adequacy in light of increased use of generation technologies (e.g., PV) by individual customers, of demand response, and of different values customers place of different uses of electricity.

2.1.3 Distribution Planning

With some delay, distribution planning is undergoing a similar development as transmission planning. The traditional formulation was:

Min sum over years and reinforcement options
of reinforcement capital costs,
plus sum over years and hours of system losses

s.t. all pre-defined contingencies do not lead to equipment overloads

all constraints of the AC power flow

In practice, as distribution networks at low and medium voltage are significantly less meshed than transmission networks, simplified decision rules often governed distribution system reinforcement (e.g., assumption of peak load and simultaneity factors per household or type of commerce, combined with standard size steps for conductors, breakers, transformers, etc.). Over the last decade, however, tools have appeared which analyze MV + LV distribution networks by stepping through combinations of reinforcement options in a master program and evaluating equipment overloads in a subproblem. More advanced approaches evaluate unserved energy at VOLL and trade off costs of reinforcement, losses and unserved energy, in order to evaluate combinations of reinforcement options both technically and economically. A master program can then cycle through different reinforcement combinations to find the economically most attractive one, which a subproblem evaluates economically and against equipment overloads. A further step for such target network methodologies (see also section above on transmission) is to model distributed energy resources such as batteries, PV, demand response, etc., so that network equipment reinforcements can be traded off against local congestion management (called non-wire alternatives in North America). These methods can culminate in calculating nodal market price equilibrium values for each distribution node, similar to the most advanced transmission planning approaches, in order to construct a target network toward which the current network can evolve over time.

Tradeoffs of demand response or customer price elasticity against the cost of generation and network equipment are also central to the planning of microgrids, which aim to be able to operate without connection to a larger distribution and transmission grid, either for standalone applications in remote sites, or for continued service during larger system blackouts. Both in rural electrification applications, e.g., in Africa or in reliability- and resilience-oriented applications, e.g., in North America, a microgrid may not include sufficient generation and storage capacity to satisfy all its loads. Therefore, microgrid controllers, which have recently become commoditized, not only need to manage the electrical microgrid parameters within the allowable ranges of, e.g., frequency and voltage but also its active power balance. Loads may be prioritized in classes, or might be prioritized according to their economic value or VOLL, so that balance can be achieved by adjusting schedules of the available generation sources, any available storage, and the different priorities of loads. TB 715 on the Future of Reliability, cited above, sheds light on these balance issues.

Planning of distribution networks, in cases where no important interactions with the transmission grid need to be considered, is handled in CIGRE SC C6, and recent CIGRE SC C6 Technical Brochures (TBs) are described in the respective chapter. Below several TBs are listed which address the interface between transmission and distribution system operators (TSOs/DSOs):

TB 733 focuses on two main aspects of the TSO-DSO relationship, namely the operational changes resulting from the presence of distributed energy resources (DER), and the impact of DER on frequency management, voltage control and system restoration.

The CIGRE and CIRED joint Working Group Technical brochure (TB) 727 reviews and reports on the latest developments relating to the modeling of inverter-based generation (IBG) for power system dynamic studies.

In the context of high penetration of variable renewables, technical, and functional interoperability between distribution and transmission systems is particularly important for ensuring service quality and system reliability. TB 711 provides insights on how DSOs are conducting different tests to move from a “blind” exercise of the network to a more and more monitored and controlled one.

TB 527 examines the impact and assesses the readiness of industry to cope with high levels of renewable penetration.

2.2 Recent Developments to Integrate the Different Planning Subproblems

The generic formulations in Sect. 2.1 show growing overlap. Whereas in the past, transmission and distribution planning were focused on technical analyses of potential network equipment overload, they now include full economic simulations of the system of generation, load, storage, and networks. At the same time, the generation and storage investment optimization need to more and more include network modeling: Since it is not optimal to expand network capacities so much that every potential generation from any node can reach the highest value load anywhere in the network, the value or price a generation unit can achieve depends on the node where it is located, and the network congestion around it.

Furthermore, the planning for the transmission and distribution systems, which are natural monopolies [16], requires its major input, like future generation capacities, to include their locations. In an integrated electricity monopoly, this means generation, transmission, and distribution should be optimized together. Especially in China, the integrated optimization approaches [17–20] employed toward this goal will consider ever more parameters and uncertainties. In an electricity market, the TSO may need to simulate expected or optimal generation additions not because the transmission monopoly would invest in them, but to derive the most realistic assumptions for these important input data to its transmission plan optimization. Similarly, in a market, each generation company needs to assume not only how much and where its competitors will build new generation capacity but also how much additional transmission and distribution capacity will be available, in order to forecast nodal prices for its own most realistic estimate of profitability of its generation investment.

And finally, transmission and distribution planning depend more strongly on each other, as distribution-connected resources tend to account for the majority of the total generation investments in many countries recently, as demand becomes more flexible and responsive to price signals, and as heating and transport are electrified. In the EU, the 110 kV level is not only planned together with the 230 and 400 kV levels in countries where the TSO operates all networks down to 110 or even 90 or 63 kV but also increasingly in countries where so far, 110 kV was considered distribution and is operated by the DSO. The EU network codes [21] require intensive data exchange between TSO and DSO about the 110 kV level. Another example of mutual dependency of transmission and distribution planning comes from EV charging: If DC fast charging at 150 or even above 500 kW becomes commonplace, and if it occurs in concentrated spots like garages or “mobility hubs” at the edges of downtowns, charging stations could easily reach capacities for which an HV connection needs to be considered. Network reinforcements need to be planned individually for each such charging station, by TSO and DSO together, and indeed in very close cooperation with city planners, as such mobility hubs will play decisive roles in the look and feel and quality of life of cities.

For these reasons and inter-dependencies, modeling would ideally integrate distribution, transmission, storage, demand flexibility, and generation at all voltage levels, with millions of deciders and of decision variables. It would take different perspectives depending on the decision maker. And it would utilize quantities of data several orders of magnitude bigger than in years past, based on smart meters and smart grids (see Sect. 3.1). Even for today’s powerful computers and algorithms, this is too large to handle with integrated modeling. Today’s algorithms and tools are expanding beyond traditional scopes step-by-step, but will likely not reach the full integrated distribution, transmission, and generation scope anytime soon. But on the other hand, given the different decisions for which different market parties are responsible (customer versus network operator versus generation investor), full integration of modeling should not be necessary. An important part of the reason for introducing markets in those parts of electricity supply which are not natural monopolies lies in the basic theory of markets: That many actors, each considering their own limited data and pursuing their own goals based on market price signals, will together make such decisions that the overall results for society are good. With perfect competition, with no externalities, and with good market price signals, economic theory even shows that the outcome for society is optimal. For the purposes of this chapter, it can be assumed that competition only gets introduced where market power can be controlled, and that externalities may be internalized, perhaps through monetization of CO_2 or pollutants. The realism of the hope that market outcomes are optimal for society, then hinges on appropriate market price signals for the coordination of the many different actors' separate decision making.

The electricity markets introduced in parts of the world since the 1980s were originally based on traditional generation technology with rotating synchronous machines, and had market price signals appropriate to that history, often only for the kWh generated and consumed in a given hour. Current systems often feature high penetration of converter-based, asynchronously connected generation and storage resources, such as solar, wind and batteries. They require already today a decoupled valuation of system services such as frequency or voltage control, and will required market signals to appropriately price more diverse market offerings and options. Where traditional technology combined capacity, energy, inertia, voltage support, system strength, synchronizing power, etc., from a single source, i.e., synchronous generators, new technologies allow for decoupling of these services resulting in greater commodity optimization of service and spatial location. The market signal and service will need to transform and adapt to the system and customer requirements, and to customers' ability to participate in the provision of different services with their consuming, generating, or storage equipment. Sector coupling of electricity, heating, and mobility further increases customers' ability for participation for the diverse service markets in the energy system.

The two recent CIGRE TBs which have addressed aspects of this evolution are TB681 on planning criteria for future transmission networks in the presence of a greater variability of power exchange with distribution systems, and TB715 on the future of reliability, mentioned already.

2.3 Overview of Current Asset Management Methods

Electricity system Asset Management is also becoming more holistic: It attempts to address all equipments in a given system together, and it gets more and more integrated with system planning. This development is fully in line with the growing sophistication which asset management in undergoing for all industries, in particular in the ISO 55000 series of standards.

Asset Management as a discipline is fairly recent and is continuing to mature. The ISO 55000 series of standards is based on the four fundamental concepts, namely:

- Value
- Alignment
- Leadership
- Assurance.

What also differentiates Asset Management from other management systems are the two key considerations:

- Analysis based on the entire life cycle of assets
- Continuous improvement of decision-making process.

These four concepts and two considerations are interdependent and provide the basis for the current Asset Management principles and methodologies. Following is a brief description of these six “pillars” of Asset Management:

Value

“Value” in the Asset Management context means that physical assets serve a purpose and, thus, have value to an electrical utility which is not only measured in monetary terms but also includes other aspects based on the corporate business values, such as safety, environment, customer service, societal impact, brand image, etc. As such, “value” derived from assets could include both tangible and intangible components and encompass value to other stakeholders, e.g., owners, general public, regulators, etc.

Alignment

Asset Management requires organizational alignment, i.e., understanding at all levels of the organization what corporate objectives are and how they are translated into specific corporate policies which, in turn, are used in developing Asset Management strategy and resultant objectives. To be effective, these objectives need to be Specific, Measurable, Achievable, Relevant, Time-limited (SMART).

Leadership

To be successfully implemented within an organization, a commitment to break traditional silos and commit to Asset Management principles should come from the very top of the organization, i.e., it is not possible to implement Asset Management in one division or department; the Asset Management approach entails cooperation and participation from all organization units in the decision-making processes.

Assurance

In order to ensure that the Asset Management process is properly implemented and utilized to achieve the defined objectives; it is essential to put in place a mechanism to regularly monitor and verify on-going Asset Management activities.

Life Cycle of Assets

The asset life cycle starts at the design stage and includes procurement, commissioning, operation/maintenance (the longest portion of the life cycle) and removal/decommissioning at the end of life. To properly manage large fleets of assets, it is imperative to not only consider capital costs associated with asset acquisition but also maintenance costs throughout the asset’s life.

From a strictly financial perspective, properly managing assets involves optimizing Total Life Cycle Cost (TOTEX) which is to say that there are both Capital Expenditure (CAPEX) and Operational/Maintenance Expenditure (OPEX) costs associated with each asset throughout its life. The ratios of CAPEX to OPEX vary depending on the specific asset category and even within the specific asset category for individual assets.

A more complete way of optimizing life-cycle management of assets incorporates Total Business Impact (TBI) which in addition to TOTEX takes into account other business measures, such as impact on reliability, system performance, probabilistic risk cost, and other corporate business values.

Decision-Making Process

Asset Management approach to decision making is based on three major sets of tradeoffs:

- Risk versus cost versus performance (triangle trade-off)
- CAPEX versus OPEX
- Short term versus long term
- "Top down" versus "bottom up" (not really a trade-off but rather complementing areas which could be conflicting at times).

Since proper decision making has to balance strategic needs with equipment-focused requirements, and in most cases, different organization units within a utility are involved with different aspects of investment planning, a prudent Asset Management approach involves three levels of planning using different set of tools:

1. Strategic Asset Management (AM) linked with corporate policies and objectives which define decision-making criteria
2. Tactical AM which typically deals with portfolio level, mid- to long-term CAPEX and OPEX planning
3. Operational AM which typically addresses specific assets.

To summarize, effective AM regimes should incorporate all the above elements and will enable utilities to greatly improve their decision-making processes.

AM has developed toward full risk consideration, whole-system consideration, monetization, and even successively stronger integration with the system long-term planning processes, as the timeframes and the required data are similar. This involves risk assessment at both unit and investment portfolio levels using quantitative assessment of condition and effective assessment of consequences using either monetized approach or other means, e.g., risk scoring. AM also facilitates better integration across the corporation, specifically between sustaining existing asset base and adding new assets to address planning needs.

Monetization of reliability, safety, and environmental objectives appears earlier in AM than in planning in general perhaps because sometimes, needed fast decision making do not allow for lengthy deliberations of the weights of various objectives, and because external stakeholders are significantly less affected by and interested in AM decisions.

A number of TBs dealing with Asset Management were produced by SC C1, specifically TB309 on AM of transmission systems, TB367 on AM performance benchmarking, TB422 on transmission asset risk management, TB541 on AM decision making using different risk assessment methodologies, and TB597 on transmission asset risk management's progress in application.

The two above-referenced active WGs, C1.34 "ISO Series 55000 Standards: General Process Assessment Steps and Information Requirements for Utilities" and C1.38 "Valuation as a Comprehensive Approach to Asset Management in View of Emerging Developments," are nearing completion of their work. The work is also underway to publish a Green Book on Asset Management in Summer 2020. Finally, the TOR for a new C1.43 "Requirements for Asset Analytics data platforms and tools in electric power systems" has been approved by the CIGRE Technical Council and the work has started in the first half of 2019.

Asset Management also plays an important role in CIGRE's equipment and subsystem SCs where Asset Management state-of-the-art practices are described in more equipment-related detail.

2.4 Drivers and Economics of Investment Decisions

The system economics part of SC C1's work complements its system planning work with specific analyses of whether and how individual investments can actually be made and infrastructure be built in order to implement the grid development plans. Indeed, each intervention described in a comprehensive network development plan needs to be individually and publicly assessed through codified metrics, in particular the cost-benefit analysis (CBA). CBA is evolving both to include in a quantified (possibly monetized) way fundamental aspects beyond pure monetary costs and profits, and toward standardization methodologies, in order to better compare very different paths to satisfy the system needs (wire and non-wire options, as well as investment in other coupled energy sectors such as heating/cooling or transport).

All aspects of the system of the future mentioned in the introduction are in principle relevant to these investment decisions, in addition to market and regulatory aspects which are more in the scope of SC C5:

- **Active distribution networks** and bidirectional flows mean that investments in transmission can depend on those in distribution, and both have cross-dependencies with generation, storage, and demand response investments. If there is unbundling, the separated investment responsibilities can bring additional risks to the investments.
- **Advanced metering** more data available for planning, active customers, and demand response mean that the system could be planned with less reserves than might be needed in the case of having less data availability and less demand response. Conversely, there are risks of stranded investments, if system reinforcements would be planned without assuming data-enabled demand response and such demand response would develop later, with less need for infrastructure.
- The **Economics of HVDC** and power electronics embedded into the AC transmission system, the potential for HVDC grids with DC circuit breakers, or even

the potential for DC low or medium voltage grids, means new investment options which require new investment decision approaches. Also, new technologies can progress very fast and costs can drop very fast from initial commercialization to maturity; this can bring about explosive short-term growth, such as for wind power and PV in China as well as several other countries. This can strongly affect the economics of investments planned or already made in other types of generation and transmission.

- **Business cases for energy storage** investments are a very active field of investigation, partly because of the strong cost decreases of batteries, and partly because of the sector coupling needed for decarbonization of the entire energy system. The regulatory treatment of storage is still in flux, and investment risks and opportunities are especially large.
- **Stakeholder and citizen engagement** and support can make or break many kinds of infrastructure investments; nuclear power plants, wind farms, and overhead transmission lines are notorious examples where negative citizen engagement often delays or even stops investments. This affects the economics of those projects massively, and also of the system as a whole.
- Perhaps the most important aspect of infrastructure investment economics lies in the combination of **regulation and finance**: The clearer the regulatory treatment and the rate of return on capital allowed by regulation for an infrastructure investment, the easier the financing becomes (assuming the projects does show a sustainable rate of return). If the rate of return is unattractive in general, or too low in comparison with the risks, financing will be difficult and the planned infrastructure might not be built. At the interfaces of different companies and jurisdictions, there can be lack of clarity which company should invest, whether it is a regulated or competitive investment, and what regulation applies.
- **CAPEX-only assets** (i.e., with zero or low OPEX cost component) are becoming more dominant in the value chain of power systems. Especially, renewable energy generation with no fuel costs are CAPEX-dominated, but so is storage in its various forms, as well as the grids themselves. The economic analysis and the methods for comparing different investment options may need to adjust to this. For example, market price differences between bidding zones or nodes as an important driver in the transmission planning approaches described above, may become even smaller during large parts of the year when zero operating cost renewable energy is sufficiently available. At times of (renewable) energy scarcity, however, market prices could spike, and could differ enormously by nodes or region. While investment optimization approaches which deal with several future timesteps or even a year-by-year formulation should be able to handle this issue, a target network methodology which just looks at a future year for an optimal network may have difficulties with it. An approach oriented to LCOE (Levelized Cost of Energy) might need to be combined into target network analyses, which requires deeper considerations and shared assumptions on financial modeling and parameters: cost of capital becomes the dominant financial factor; in some cases, it alone can determine the viability of a new investment; also important are

the equipment's useful life expectation, discount factors, the way to account for externalities and financing options, and net present value methodologies.

- Related to these considerations and also to asset management and sustainability, a **life-cycle approach** is becoming more and more important when assessing investment options. Such an approach includes impacts and costs incurred in the stages prior and after the traditional project phase. For example, concerning the technical assets involved in a project under assessment, economic, and environmental footprint of the manufacturing stage, starting from raw materials, and the recycling/waste management after the end of the useful life should be considered. This is particularly true when strategic options are compared, like the substitution of a transport fleet with Electric Vehicles (EV), which have different environmental and climate change footprints according to the source of electricity used by EVs, and according to manufacturing processes/materials and recycling policies in place, especially for the batteries.
- The urbanization taking place in almost all parts of the world until 2050 makes land resources near metropolises more and more scarce. The investment of power system projects often involves land expropriation (for the development of new transmission corridors). The cost of land usage in the process of urbanization may soar in the short term. Consequently, delaying investment decisions may bring even greater future costs.
- The above concepts translate directly in the application of **Cost-Benefit Analysis** (CBA), already highlighted above. This now standard methodology for assessing projects and investment options has recently been subject to remarkable developments both in methodological rigor and in comprehensiveness of impact analysis. Given the large increase in system complexity and inter-dependencies of energy subsectors, it becomes paramount to take investment decisions in the most rational way, applying certified and approved methodologies and relevant criteria; the same applies in order to feed the policy-making debate with sound and quantitative business cases, impact analyses, or what-if simulations.

Also, the additional aspects 1–5 listed in the introduction bring new questions to the economics of infrastructure investments:

- Climate protection often uses subsidies of clean generation units, but the existence, financial level, and structure of the subsidies or support schemes evolves and changes over time. This affects the economics of investment in clean and CO_2-emitting generation and even of existing plants, and of transmission and distribution investments needed to connect all such generation plants.
- Sector coupling is a relatively new concept inserting new uncertainties into infrastructure investment decisions. Sector coupling involves multiple energy systems, so the benefits of an investment will not be fully reflected in the power system alone. In addition, for an investment decision in a power system, there may be alternative, more economic solutions in the cross-energy system, e.g., electricity versus thermal storage. Other examples of sector coupling-related uncertainties are how much electricity loads grow and how load shapes change with electrification of heating and transport; how much distribution reinforcement is needed to

accommodate EVs or heat pumps, and how soon it should be installed; whether electrolyzers for power-to-gas become very much cheaper, and how that affects the economics of electricity versus gas transmission and distribution.

- The distributional effects of the energy transition mentioned in point 3 in the introduction have a direct relationship to investment decisions: For example, how to share the costs of investment spanning more than one jurisdiction (e.g., cross-border cost allocation of between TSO and DSO). For another example, if the energy transition brings benefits to some and disadvantages to others, this can create strong opposition to energy transition-related investments. Such a dynamic can lead to delays or cancellations of projects and has the potential to even derail the entire world's climate change mitigation strategy.
- Continental-scale international interconnections, and microgrids, have their own special effects on investment decisions and system economics. Household consumers may use very different economic investment rules than companies, and financing conditions can vary greatly within a country, and between countries.
- Monetization of reliability and environmental effects of infrastructure investments obviously aims to affect investment economics and decisions, but depends on regulatory, governmental, or even global decisions taken outside the company that makes the investment. This brings uncertainties into the future use of generation but also of grid investments.

Several recent CIGRE TBs addressed aspects of the above economic and investment issues:

TB 701 reviews the drivers for transmission investment decisions and identifies the growing trends in investment drivers.

Focusing on renewable energy, TB 666 describes possible technical and procedural solution to face the challenge of large surpluses or deficits of renewable energy and high gradients between system conditions.

Since a considerable part of the renewable energy growth is currently being seen in distribution networks; these distributed energy resources are changing how electricity transmission and distribution work together. A CIGRE/CIRED joint working group produced TB 681 which investigated the planning criteria for future transmission networks in the presence of a greater variability of power exchange with distribution systems.

2.5 Overview of State of the Art in Horizontal and Vertical Interconnections

This recently added field of SC C1 work focuses on the continental-scale international horizontal interconnections and the vertical TSO-DSO interfaces, where subsystems are often handled by different jurisdictions and companies and may be subjected to very different regulation.

Regarding “horizontal” interconnections, TB 775 is addressing large-scale intercontinental options for linking the presently isolated power systems of different continents in the world. The concept of a global electricity network would address the challenges, benefits, and issues of unevenly distributed energy resources across the world, as they can affect the goal to achieve overall sustainable energy development. A global electricity network can be envisaged to consist of intercontinental and cross-border backbone interconnections as well as the power grids (transmission and distribution networks) in all interconnected countries at various voltage levels. The global electricity network would take advantage of diversities from different time zones, seasons, load patterns, and renewable energy intermittent availability; thus, supporting a balanced coordination of power supply of all interconnected countries.

To date, few studies of such a future global network [22–24] have been undertaken, and barriers for its realization would be paramount, including political vision and worldwide collaborative mood. However, the potential high rewards of such a concept deserve a scientific, expert-based and truly international effort, well matching CIGRE’s distinctive character of unbiased vision and worldwide excellence.

This study shows that, within the limits and boundary conditions adopted (such as a CO_2 price/carbon tax), the added value of interconnecting the continents in comparison with keeping separated regions emerges clearly, in all the considered cases. A global electric network, compared to non-interconnected grids, presents these major improvements:

- significant increase of Wind and PV production, replacing an important portion of gas-fired power plants that would otherwise be needed, both of base load and mid-merit production;
- non-negligible reduction of total system cost (sum of annualized CAPEX and OPEX for transmission and generation);
- enabling a substantial increase of renewable energy share accompanied by a drastic reduction of CO_2 emissions in absolute terms.

This first-of-a-kind quantitative study has provided a possible geographical and technical configuration as well as preconditions for a global electricity network’s economic feasibility. Some of the assumptions and methods are themselves a first-of-a-kind result, e.g., the worldwide load pattern (at weekly, daily and hourly level) and the quantification of complementarities between today’s separate power systems.

The realization of large-scale interconnections heavily depends on non-technical preconditions to be met:

- technical interoperability and standards, as well as operational issues;
- envisaging market rules and business models for efficient exploitation of the interconnections;
- setting up business models for financial viability and construction challenges (project finance and project management);
- setting up legislation and regulation frameworks necessary to authorize, own, build and operate such strategic infrastructures;

- political support from all stakeholders, i.e., a global or at least multilateral, robust cooperation mood and mutual trust.

As a follow-up, CIGRE WG C1.44 is considering more thoroughly the impact of storage and demand response, introducing it in the trade-off equation between transmission and generation.

The realization of international interconnections, not only at intercontinental but also at regional level, typically faces extra hurdles on top of those characterizing any large infrastructure with visible territorial footprint and technical complexity. Such extra hurdles derive from their nature of being multi-jurisdictional and multi-party. This calls for deeper consideration of the evaluation principles and allocation criteria for costs, benefits, and related risks on both sides of the link. In particular, where the cost-benefit analysis shows an asymmetry of advantages for the involved parties, this also calls for asymmetric burden sharing for which no clear consensus rules have emerged yet, neither in a horizontal dimension (TSO-TSO projects) nor in a vertical dimension (integration between TSO, distributors and other grid operators). In Europe and elsewhere, the "merchant lines" concept is applicable for fully private investments, but is not the only option, especially when a mixed approach to private-public-partnership or multi-party links is considered. The intrinsic flexibility of the merchant line mechanisms and the possibility of asymmetric cost/benefit sharing between investors in interconnection projects give rise to innovative and case-tailored implementation schemes, and some existing projects already present innovative examples of such business models.

The key determining characteristics which shape the business models are nature of investors; prevailing direction of energy flows and related benefitting actors; capital intensity; geographical and topographical distribution of the assets (in particular, when transit territories or international waters are involved); technology—HVDC and/or submarine cables necessarily imply a unitary approach for the whole link regarding design, engineering, procurement and construction).

While costs (CAPEX and OPEX) are relatively easy to estimate, the assessment of benefits differs very much according to the point of view and the subject under consideration: investing company (looking for profitability), TSO (looking for system performance), electric system as a whole (with possible external factors), end-consumers (looking for energy price reductions), and transmission tariff payers. This adds to the already challenging and controversial exercise of benefits evaluation, since operational issues (like security of supply/system stability) and social issues (like social acceptance/environmental impact) are difficult to quantify and have no uniform metric.

WG C1.33 is addressing the above topics, to infer general principles as useful guidelines for the design of future cross-jurisdictional projects, and to analyze innovative models.

Regarding "vertical" interconnections, the paradigm shift of distributed generation and the consequent consumer evolution into "prosumers" who not only consume but may also produce electricity, provide energy storage and demand flexibility, call for a tighter cooperation in planning grids at different voltage levels in the same area. This will likely lead to an integrated TSO-DSO planning process, at all stages, starting from scenario definition.

When considering the complexity of the integration between TSO and DSO systems and planning activities, there is a clear need to develop improved planning approaches for more investment efficiency. With changing economic conditions, evolving technology, and renewable energy integration, integrated solutions and better-defined processes can create significant customer benefits.

On-going WG C1.40 is addressing such issues, for example:

- How are plans coordinated and costs allocated between different network owners?
- Do different rules at network ownership boundaries lead to suboptimal connection locations and network investment?
- How are bottom-up and top-down approaches integrated in forecasting (e.g., DSO on lower voltages and TSO on higher voltages)?
- How are renewable energy source and distributed energy resource forecast in line with rapidly changing technology?

3 Research and Innovation Needs for Gaps Between State-of-the-Art Planning Methods and New Societal and Grid Requirements as Well as New Technologies

This section reflects to what extent the state of the art described above does justice to each of the new societal, grid, and technological aspects to system planning and economics listed in the introduction as requiring a more holistic view.

3.1 Active Distribution and Big Data

This is the biggest opportunity but also challenge for system planning, economics, and asset management, as it increases the scope and the data available for optimization. For the reasons and inter-dependencies described above, the new scope should ideally be modeling which integrates distribution, transmission, storage, demand flexibility, and generation at all voltage levels, with millions of deciders and decision variables. Furthermore, this modeling needs to take different perspectives depending on the decision maker and his decision, e.g., monopoly societal-interest-driven transmission planning, or competitive profit-driven generation investment. And, most importantly, the quantity of data available and relevance for this kind of modeling is several orders of magnitude bigger than in years past, as smart meters with hourly or even higher resolution of each customer's demand as well as a multitude of distribution system sensors ("Internet of things" IoT or "Internet of Energy" IoE) get installed, to ensure observability and controllability of nested networks toward higher level ones.

The challenge and opportunity for system development and economics arising from more active distribution system management with many kinds of distributed energy resources are to model the new demands, new flexibilities, new decision variables controlled by customers, prosumers, and system operators appropriately in load forecasting and network planning. Therefore, the next paragraphs address how this complex, whole-system planning problem can be reasonably split into manageable parts.

The first focus is on the scope in system modeling, which needs to be over the lifespan of new equipment on whose investment decisions need to be made. Generation and network equipment in most cases can be expected to have lifespans of 25, 30, often typically 40 or even more years; only batteries may have lower lifespans of less than 10 years. The benefits of new equipment can vary over its lifespan, especially in times of global energy transition with entirely new demands (e.g., EVs), strong but uncertain progress in energy efficiency, unclear price elasticity of demand, huge changes in costs of different generation and storage technologies, sector coupling and last not least new network technologies (e.g., UHV transmission or DC distribution grids).

But current practice is to plan transmission for a target year 10–20 years in the future (i.e., for the first max 10 years of new equipment lifespans, as permitting takes up to 10 years), and to plan distribution for a target year about 5 years in the future (i.e., for even less years of new equipment lifespans). This risks suboptimal investment decisions especially in three kinds of situations: Either if investments are lumpy or growth in network loading might be strong, then it can be better to expand capacity by more than necessary for the target year and to partly anticipate future needs beyond the target year. Or if there is a risk that network loading might decrease after the target year, in which case it could be better to expand capacity less than necessary for the target year and manage the resulting increased distribution network congestion with flexible demand. For example, if low voltage network capacities are expanded to accommodate strong EV growth, but ride sharing, autonomous vehicles, fast and/or smart charging lead to less EV charging peak loads in the future, or to almost all EV charging stations being connected at MV rather than LV.

Perhaps most important is the third reason why a gliding 10- or 20-year planning horizon is no longer sufficient, i.e. the COP21 Paris Agreement on climate protection, which more and more countries worldwide are interpreting as a goal of complete climate neutrality by about 2050 (net zero greenhouse gas emissions). This crucial goal for mankind to avoid a climate catastrophe brings a clear common anchor into all power system planning. Many countries, utilities, and TSOs have recently performed quantitative scenario studies how their energy system could be climate-neutral in 2050, and they are using the results to guide their 10- and 20-year system planning studies onto a clear path toward climate neutrality, rather than just following arbitrary technological and load developments which their statistical forecasting methods might indicate. This third reason also implies that in addition to a target year, in this case, 30 rather than 10 or 20 years in the future, the path toward it is also crucial.

Advanced generation plan optimization approaches have handled such target year difficulties by modeling the evolution over the years explicitly, and as transmission planning evolved from eliminating technical constraints to economic cost-benefit analyses, it also started using 3 or 4 target years in sequence rather than just a single target year (e.g., evolution of the biennial ENTSO-E TYNDPs from 2010 to 2018). This evolution has not yet occurred in distribution planning, partly because distribution planning is still driven by technical constraints. But considering the many different reasons why benefits can vary over the equipment lifespan, distribution system planning needs to evolve into economic analyses and needs to include at least several different target years in sequence (see Sect. 2.1.2).

From the Asset Management perspective, proliferation of EVs could affect asset maintenance and replacement strategies as it will increase average loading on LV and MV assets and in some cases, depending on managed charging, also peak loading. Additionally, daily loading curves would look differently and could have smaller variations between daily maximum and minimum loads but larger fluctuations in the short term. This changing loading pattern is expected to shorten useful life of assets whose rate of degradation depends on their electrical loading. Additionally, some of the replacements will be required due to functional obsolescence, i.e., assets in good condition would have to be replaced due to loading exceeding their rating. Finally, it may be more difficult to schedule maintenance outages needed to achieve the desired useful life as the window of low loading periods is expected to shrink, and this will require system enhancements to allow for better system operability. As a result, in some cases, utilities may be forced to skip some maintenance activities or defer them until system enhancements are put in place, thus shortening useful life of certain assets and increasing replacement rates.

For long time scales, the capacities of integrated DER and the growth of electrical load show great uncertainties for future distribution systems, and thus cast the investment into a high-risk environment. Probabilistic forecasting and simulation of peak load, charging behavior of EV and storage, demand response behavior of consumers, etc., are effective ways to model future investment risk and promote a better planning. How the distribution system works in the short term also influences the investment risks and planning. For example, coordinated control of DER in short time scales can help reduce the uncertainties in the long investment and planning time scales; data analytics can be used for consumer behavior modeling so that the consumers are more willing to provide flexibilities to avoid sudden risk and thus reduce the investment cost. In short, various data such as weather data, consumption data, economic data, etc., can be fully analyzed to model or reduce the uncertainties and risks.

The well evident need of coordination of system planning among TSO(s) and DSO(s) in a same dispatching area, even when fully recognized, is not straightforward to enact, for many reasons: roles need to be established (who has decision power or at least leads the coordination?); cultural barriers need to be overcome when comparing consolidated planning and asset management methods, all of which function well on their own, but are not compatible among them, i.e., differing in: planning horizons, scenario settings, regulatory constraints/tariff remuneration/quality of service requirements, tools and calculation methodologies, risk adversity, prioritization criteria, etc. On top of that, company strategy and vision—in general and in particular for the investment decisions which so profoundly affect company profitability—may differ profoundly, as well as local stakeholders' sensibility. TSO/DSO coordination for system planning can improve via the steps of definition of standards for information sharing, for planning process steps, and for scenario assumptions; all this implies a potentially high degree of negotiation from different perspectives, or equitable rulings by competent regulation bodies, aiming at the primary interest of the final customer.

Unbundling and liberalization have unavoidably ushered in the multiplication of actors entitled to develop portions of the power system, raising a serious chicken-and-egg problem: shall grids be developed before (in anticipation of) new generation plants/load changing patterns, or vice versa? Traditional good practice was to address users' connection requests with progressive network expansion; this is no longer possible due to the fast and often erratic pace of change, not to mention the possibility of unrealistic connection requests; in some cases, this has been solved through the grid operator's subjective evaluation on the feasibility of many connection requests in the same area, or imposing an onerous compliance guarantee together on submissions of connection requests. These off-line solutions are not satisfactory, and a new process/business model has to be shaped, also to safeguard the non-discriminatory nature of fulfilling the final users' requests.

Moreover, grid performance varies also without new connection requests, as in the frequent case of a consumer becoming prosumer, or a DER producer enhancing its generation capacity, in both cases, modifying completely their profile of power exchange with the grid. The correspondent information is not always available to the DSO, and almost never to the TSO, who would need the aggregated value; to make things worse, this information could be split in several DSO in the same dispatching area, showing a subissue of DSO-DSO coordination within the issue of TSO-DSO coordination.

3.2 Modelling of DC, Storage, New Operations, and Control Tools

Optimizing system operations for transmission and distribution security and losses, and also for generation dispatch or redispatch costs, gets more complex with more DC lines and FACTS devices like phase-shifting transformers embedded in AC transmission systems. Modeling this complex optimization of DC lines and FACTS devices in planning studies and investment analyses presents both algorithmic and computational challenges, partly because of the wide range of new options and the many potential places in the network topology where they could be used.

DC, storage, and some FACTS devices, such as UPFC, are improving in cost but currently still expensive compared with other devices. Generally, it is difficult for these devices to be economic when economic analysesof investment is assessed. The benefits of these devices are system-wide and composite. Therefore, how to evaluate the input and output of these kinds of equipment is an unsolved critical problem. For example, storage units typically can be used to provide several grid services. They can be stacked and co-optimized depending on how it will be used after it is built. Underestimating or overestimating its economic impact of such storage units would greatly affect investment decisions.

These issues are quite important for system planning on many continents as DC lines and phase-shifting transformers embedded in a large AC system tend to be especially prevalent choices when different TSOs cooperate in a large synchronous system: Typically, under one jurisdiction the whole meshed grid is planned, realized, operated, and maintained by the same company, thus ensuring consistency and interoperability of the asset base both over geography and over time. Historically, the expansion of the electric system has taken place gradually and in form of meshed grids, so AC technology has been chosen, at voltage levels which are standard in that region. Only in particular cases, for high capacity and very long distances, DC links have been chosen, normally for connecting large renewable plants (hydro dam) in isolated areas (Brazil, China, and Congo) to distant load centers. In recent years, the boost of exploiting very large RES potentials (windy lands, solar in desertic areas, off-shore wind farms) has increased the number of DC links [18, 25, 26], but still in point-to-point configuration. DC links are an obliged option also for submarine interconnections and for asynchronous areas.

Once a system is endowed with several embedded DC links (like Western China), or vast off-shore regions are being developed (like Europe's North Sea), point-to-point DC links can become inefficient. Therefore, meshed DC grids are being investigated, for which some technological problems need to be solved in a reliable and cost-efficient manner: E.g., the DC breaker [27, 28], which ensures the indispensable feature of protection of grid elements from short circuit and other faults. In this perspective, new and challenging options for grid architecture and topology arise, which deserve expert efforts in modelling and assessing the multiple planning options.

Another prominent application of DC links is among different jurisdictions, and therefore different grid operators, who appreciate the versatility of controlling the power flows of DC links. AC grids, on the contrary, do not easily allow to pre-define the power flows, which arrange themselves only according to the electric parameters of the grid elements (Kirchhoff laws, in steady-state); in these cases, planning (and consequently operation) follows an approach of two strong systems connected via a relatively weaker DC link, which thanks to its controllability can be used to enhance the degree of control of active power flows. The above applies as well to reactive power flows, if the DC technology is VSC, whose converters can work in all 4 quadrants of the capability scheme, and to other devices acting on the phase angle (FACTS, PST, etc.).

For the future, an increasing combination of the approaches (embedded links and point-to-point links) and of the devices will require more sophisticated planning analyses and modeling.

3.3 Climate Protection, Environmental Constraints, and Multi-criteria Tradeoffs

As described in the above sections on generation and transmission planning, the consideration of environmental and other non-economic issues has moved from simply including clear legal constraints into explicit and systematic analyses of costs and benefits according to multiple criteria. Section 2.1.2 described the European Ten-Year Network Development Plan process as a state-of-the-art example of multi-criteria cost-benefit analysis. ENTSO-E's second cost-benefit analysis procedure provides more detailed descriptions of the types of costs, benefits and criteria. Those benefits include the important economic criterion of socio-economic welfare, i.e., the economic surpluses of electricity consumers, producers, and transmission owners (congestion rent), for which the most important part is the reduction in total variable generation costs (fuel savings and avoided CO_2 emission costs) achievable through the additional trading that becomes possible with new transmission infrastructure. Further benefits include renewable energy integration (minimizing curtailments), a separately displayed variation in CO_2 emissions, losses, security of supply (expected energy not supplied and a GDP-based estimation of the lost economic value caused by it), and system stability. Costs include estimated total project expenditures. Furthermore, external impacts are described: Environmental, social, and other impacts.

But the technical, economic, environmental, and other multi-criteria objectives and constraints so far are often inconsistent across countries or across different energy sectors. For example, different parts of the world assign drastically different values to CO_2 emissions, even within geographies which have already committed to including CO_2-related restrictions in their electricity system planning (e.g., EU, Canada, and USA). Different energy sectors deal with different constraints or values for CO_2, $SO_{x,}$ and NO_x, e.g., electricity production versus automotive transport versus heating versus agricultural greenhouse gas emissions; industry versus commerce versus households; EU-internal flights versus EU-external flights, etc.

This makes consistent planning for the benefit of the national, continental or global society at large very difficult. For utilities of both network and generation operators, a realistic approach is to take into account at all times the currently applicable constraints and values, and most utilities have been and are taking this approach. However, there are exceptions, e.g., the 2011 WECC non-binding 10-Year Regional Transmission Plan for the Western USA [29] assuming in some scenarios a CO_2 price of $33.07/Metric Ton despite the USA at that time not having any CO_2 price in effect. The reasoning can be that a planning study or investment decision evaluates benefits and costs over several decades in the future, and should simulate realistically the CO_2 prices, relative taxes and environmental constraints in effect in the future years analyzed. Just because a CO_2 price is currently zero or another environmental constraint does not exist, does not mean that it is likely that it still will not exist 15 years in the future, i.e., only a part into the lifespan of the equipment to be decided on. It may well be realistic to assume a CO_2 price, and will likely be appropriate to vary the assumed price over the different scenarios analyzed.

3.4 Sector Coupling

For the decarbonization of the entire energy system, including electricity, transport, heating/cooling, industry and agriculture, electricity systems and markets play a central role (see ETIP SNET Vision 2050 [30] which inspired much of this section). The versatility of electricity, the energy efficiency of its application in transport and heating compared to the use of fossil fuels, the relatively low cost of decarbonizing electricity generation with low-cost solar and wind energy, and last not least the fact that its value changes in very short time intervals, mean that its value will affect market equilibria naturally in all sectors. In the past, fossil fuels had that role, and electricity prices as well as prices for heating and transport were forecast based on coal, oil and gas price forecasts. Except for renewable and nuclear electricity generation, only biofuels can contribute to the carbon-neutral post-2050 future which the Paris Agreement demands. But biofuels are limited in quantity due to land availability and competition with food production, even if second cropping can lead to more biogas availability than assumed in the past.[3] However, for important parts of the world where heating dominates annual energy use, seasonal storage [30] will likely need to play a major part in carbon-neutral supply of all energy needs. Heat storage or power-to-hydrogen/power-to-gas can transform summer renewable electricity surpluses into energy available also during windless winter weeks. This also is best driven by electricity price signals: Low electricity generation costs and prices—due to surplus zero operating cost renewable energy—signal that some of the surplus energy should be injected into seasonal storage because its value in a different season is higher, even after energy losses, and vice versa for withdrawals from seasonal storage during high-price periods. For the system planning and economics problems of interest to us, the investment in storage, in generation, and in demand flexibility can all be driven by these price signals, of course including consideration of the respective capital costs.

In order to frame the broad sector coupling topic, methodological progress is still needed [31], which can be sketched as follows:

---

[3] See, e.g., Gas for Climate—The optimal role for gas in a net-zero emissions energy system, March 2019, Navigant for the Gas for Climate Consortium; https://www.gasforclimate2050.eu/files/files/Navigant_Gas_for_Climate_The_optimal_role_for_gas_in_a_net_zero_emissions_energy_system_March_2019.pdf.

- ***Planning***: power system planning must cater for the **progressive electrification** of different energy sectors like heating and transport. Some of these processes are already underway (EVs, heat pumps), and the challenges are to correctly forecast the pace of change (depending not only on technological advancements but also on incentives from policies/tariffs), the impacts on peak demand (GW) and on energy supply (TWh), and to properly take into account all direct and indirect effects.
- ***Operation***: the electrification of transport & heating provides **new opportunities of flexibility** for the operation of electricity grids, complementary to the existing means: flexible generation, hydro pumping, grid configuration, electric storage, demand-side management; the increased load of this collateral energy subsystems makes it possible to adjust the conversion rate and their inherent storage capability, in order to balance out surpluses or deficits of RES generated energy, as a much sought-after alternative to their curtailing.
- ***Optimization of energy carriers***: bidirectional conversion and storage of electric power can be extended not only to non-traditional electrical loads (EV, heating) but also to other traditional energy fluids: methane, hydrogen, green gases, fuels, which have their own transport infrastructures (pipelines, ships, tankers)and storage infrastructures (tanks, reservoirs, flowing stock). This allows storing **energy in form of molecules** (e.g., hydrogen or ammonia) and therefore with no intrinsic energy losses as well as transporting large amounts of energy economically, due to their intrinsic high energy density.

One key issue is to reach at some future time, convergence on externalities evaluation across sectors, which are today silos due to their legacy of totally separated approaches.

Also SC C6 is addressing various aspects of sector coupling, especially from a distribution system viewpoint: WG C6-1.33 (joint with SC C6) is addressing these issues, trying to set harmonized and consistent definitions in order to shape the topic and its opportunities to optimize the entire energy system in a structured way. Its TB is planned for 2020.

3.5 Stakeholder and Citizen Engagement

As explained in the introduction, and as exemplified with numerous planned infrastructure projects around the world, stakeholder and citizen opposition can lead to serious delays or cancellations. A state of the art is emerging [15] how governments and utilities should engage and communicate with stakeholders and citizens so that their input enriches the decision making at all stages of project development and especially in the early stages before capital has been spent or before the system security need for the project becomes overwhelming. This state-of-the-art features early and strong transparency toward stakeholders and citizens, as well as open-minded discussions with them about different options.

Nonetheless care must be taken that this approach does not lead to paralysis where society at large suffers (from low reliability or high cost of electricity service) because the particular interests of a vocal minority block all progress. In Germany for example, local opposition in a few districts within the state of Bavaria against important overhead lines needed for the continued energy transition, has first led to the state government adopting the arguments of overhead line opponents, and then to a Federal German decision to give preference to underground cabling four corridors of DC North-South lines of 2 GW transfer capacity and over 500 km length each. This has led to severe increases in the cost of the transmission system and of the energy transition as a whole. Beneficiaries of this decision are relatively few (primarily inhabitants in the villages from which the overhead lines would have been visible), but all 82 million Germans pay the higher costs. There seems to be no systematic quantitative comparison between the additional cost of undergrounding the lines versus the number of people who avoid a view on a new overhead line.

The effects of good stakeholder and citizen engagement on the planning process take different character:

- The modeling must not unduly appear like a black box, but it must be possible to explain and discuss model results with laymen. Also the tools need to be simple enough to modify inputs and to re-run with changed assumptions or options.
- The multi-criteria approach described in the previous section can also include a criterion capturing likely opposition, leading to likely delays or increased costs.
- Monetization can appear as the best approach to economists but remains unlikely to reduce controversies substantially. It might help to focus discussions on the most relevant disagreements.

CIGRE TB 548 described above addressed some of these issues. But the engagement of citizens in electricity and energy markets and in energy policy decisions is one of the largest uncertainties affecting the energy transition. A successful energy transition can secure a livable world for all citizens' children and for young citizens today (witness the Fridays-for-Future movement), but it also affects citizens' mobility, the comfort of their homes and neighborhoods, and last not least their wallets. How optimistically and how flexibly they will deal with their energy demand in the more integrated energy markets of the future will determine whether the energy transition brings strife and high costs, or cooperative spirits and good economics for everyone even while mitigating climate change and maintaining system reliability. Studies which examine existing experience with citizens' reactions to and engagement with an advanced energy transition can be especially valuable for system planners and energy policy makers.

3.6 Planning, Regulation and Economics in Energy Markets with Shifting Roles of Environmental and Reliability Constraints

Multi-criteria and multi-stakeholder decision processes can in principle be managed well both in market and in monopoly electricity system structures. However, demand response, price elasticity, local storage and distributed generation depend in their use quite a bit on individual customer day-to-day decisions, and all these can be important aspects of a future low-cost, carbon-neutral, sector-coupled and reliable energy supply system. This will likely be easier to coordinate well with the needs and economics of the distribution and transmission networks and the overall system if small prosumers are fully empowered participants of an energy market rather than being entirely dependent for their energy needs on a monopoly supplier. Also monetization of reliability as well as environmental and climate change externalities relies on price signals which tie millions of customers and prosumers together with the energy supply companies, and may also function with more trust and better effects in a market. But independently of the choice of a country for a monopoly or market structure of electricity supply, correct price signals, incorporation of multiple planning criteria, well-chosen degrees and fields for monetization of externalities, and transparent and open-minded interactions with stakeholders and citizens will be important.

It is likely that many countries will need to transition to new models to comply with the needs of the changing power system described above. This will lead to changing boundaries among central planning, regulatory oversight and the role of markets. Careful management of these changes will be critical as market participants do not like changing rules, and communities do not trust markets or central planners when prices rise rapidly or reliability is called into question.

The extent, and the way in which DSOs play their role in managing DER, varies in different utilities, and in different countries, mainly according to the existing regulations. While cooperation with the TSO is essential, economic incentives can play a role in optimizing cooperation.

The power system stakeholders all share the ambition of a more economically efficient system and a lower environmental impact. Demand response (DR) refers to the ability of the demand side to respond in a coordinated manner to market and power system conditions using a short-term perspective. Optimal DR development lies more in combining several possibilities than in selecting a single option to determine a value for DR. It is important to ensure that there are no entry barriers to DR participation, i.e., that DR is allowed to compete fairly with products based on generation capacities for the market, to drive optimal investment and operational decisions. There are also enablers whose absence can constitute a barrier to DR development including measurement, verification and market access mechanisms. Further work should focus on the link between DR and distributed energy resources and on the constant evolution of the DR related regulation that may have to be adapted to the new consumption patterns (e.g., electric vehicles) and to next generations of DR and storage technologies.

With the development of DER and microgrids, in some areas, demand increase is no longer the main driver of transmission investments. In these cases, transmission networks are viewed by some as an insurance against local shortages. The explicit valuation of the many different services that come together through the grid for stable supply, described above in Sect. 2.2, will be crucial to handle this challenge appropriately, as will be coordination between neighboring grids and between generation and transmission.

The above-mentioned TB 692 by CIGRE SC C5 defines the role of various entities involved in planning and investing in transmission. The complementary roles played by market prices, network tariffs and regulatory schemes in transmission planning are investigated. Appropriate and complementary signals can be delivered by market organization and network tariffs. However, regulatory consistency must be ensured between neighboring markets in order to facilitate building of interconnectors in a timely and optimized manner. Further, the risk profile of transmission investments must be correctly reflected in the tariff regulation.

As emphasized in the introduction, the balance between the three traditional goals of electricity supply: reliability, economics and the environment is evolving. The tradeoffs are becoming more and more explicit in many countries' system planning approaches. Reliability has been considered as a hard constraint with utilities held accountable for their part in the overall result. The environment has been captured in certain constraints in relation to the physical, societal and environmental impact of the infrastructure as well as the operating impact in terms of emissions. Economics was optimized usually from the perspective of a single integrated electricity utility. In the future, the environmental concerns in regards to climate change are imposing an overarching driver to minimize greenhouse gases. In addition, market-based options are evolving to help drive the most economic solutions as the power system. Reliability is becoming a function of economics and is supported by demand response and price-elastic loads. The optimization of economic outcomes is more often occurring in a market environment with many more participants across different countries and sectors and in an environment of growing uncertainties. In addition, market mechanisms such as CO_2 prices are being introduced. These changes require the system planning criteria to be modified in order to account for the impact of new generation technology and monetization of externalities. While technical planning criteria are still cited as the primary drivers of system reinforcement, planning will need to address multi-criteria tradeoffs and the use of probabilistic criteria.

With joint evaluation and optimization attempted for economics, reliability and environmental effects, making optimal investment decisions under growing uncertainty which was described already in Sect. 1 becomes even more important. This requires for example

1. An understanding of the impact of uncertainty factors on the reliability, economics, stability and sustainability of power systems, and the interrelationship among the various factors.

2. Development of widely accepted mechanisms and robust planning methodologies under uncertainty, such as generation planning with a high share of intermittent renewable energy, risk-based transmission network planning.
3. Further enhancement of probabilistic planning criteria under uncertainty. This will cover aspects such as the typical operating state chosen, required safety margins and capacity reserve requirements.

4 Research Issues

4.1 Opportunities from New Planning and Economic Approaches

This section summarizes and puts into perspective the various needs and opportunities for new approaches described and derived above. The opportunities from rapidly developing capabilities in cooperation between different power system actors and in the support which more and more sophisticated software brings, are fortunately improving. One challenge for electric system planners worldwide will be to leverage cooperation and software improvements fast enough to keep up with the evolving challenges and complexities, or as CIGRE SC C1's strategic plan states it, to make the best from such change.

Below, the summary of needs and opportunities for new planning and economic approaches hierarchically is given, both for ease of understanding and evaluation, and to support electric industry actors in realistic planning and timing for their methodological, cooperation and software evolution. The needs and opportunities are grouped under four headings:

1. Processes within the electricity sector.
2. Changes within the electricity sector.
3. Considerations beyond today's electricity sector.
4. Decision making.

Regulators and governments need to have confidence that the investments a system operator plans for and pursues are necessary, effective, and efficient. What a TSO does in respect of investment is therefore concerned with optimality, under multiple criteria and the difficult and uncertain changes described in this chapter. Improvements in data storage capacity and computing power promise to make the solution of such large optimization problems easier in the future, but much work is required to make these practical, often involving the use of appropriate approximations, decomposition approaches which ideally mirror the respective responsibilities of different companies in the electricity sector, and advanced data analytics. However, such approaches depend on improved access to data, appropriate characterization of costs and, in market environments, potential pricing and contractual arrangements.

Table 1 Needs and opportunities: processes within the electricity sector

High-level challenges and needs	More detailed challenges and needs	Near-future state of the art	Longer term needed evolution
Transmission (T) and distribution (D) grids planned together	Distributed energy resources and active distribution system management important to both T & D planning	Iterative process, e.g., master/subproblem based on common scenarios and data; respective responsibilities clarified	Joint-process, at all stages: time-horizon, scenario definitions, assumptions, analysis tools, sector coupling involvement
Optimal use of data	Correct and efficient data access management: who/why/how needs which data and who/how is entitled to access/handle which data	Data hubs give controlled access to permitted data to TSOs, DSOs, suppliers, customers, aggregators GIS systems developed and made available including representation of environmental impacts	Appropriate overall framework for big data management (for raw data plus for statistics/filtered/analyzed data) about: customer behavior, electricity/ancillary services prices with high resolution in time (less than hourly) and space (nodal)
Integration asset management—planning	Asset data-based system planning	ISO 55000 advanced data analytics used in characterizing the condition of assets value (monetization)-based asset management, i.e., asset replacement optimized in light of asset condition, system risk, reinforcement needs and outage opportunities	Integration of planning and asset management data and processes in both T and D

(continued)

Table 1 (continued)

High-level challenges and needs	More detailed challenges and needs	Near-future state of the art	Longer term needed evolution
Stochastic modelling/uncertainties	Short- and long-term uncertainties about RES and new demand (e.g., EVs) and active prosumers	G, T, D uncertainties modelled in scenarios with storylines for LT, and with Monte Carlo simulations for ST uncertainties; paradigms adopted for stochastic development paths (identification and management of investment options; intermediate years toward target year; to avoid stranded invests)	Stochastic optimization over decision trees applied in G, T, D, and integrated planning
		Assumptions in G, T, D planning on demand flexibility based on observed data (incl. surveys, data from other countries), considering customer incentives for flexibility and demand price elasticity at system level	Price elasticity of demand modeled (ideally appliance-specific) in G, T, D planning
Planning to consider more options and complexity	Enlarge and at same time, deepen the options considered and the services needed to keep the system secure, in a multi-level, multi-criteria planning process	Electrical and economic models of new devices and services, e.g., batteries, demand response	Extend probabilistic approach to all planning aspects (adequacy, asset management, operational planning, system services, etc.)
		‘Services’ from third parties considered as alternatives to network reinforcement	Commercial and risk arrangements for third party services defined

Table 1, on processes, introduces some of the major directions of foreseen methodological improvements.

Table 2, electricity sector changes, shows how the above and further methodological improvements are foreseen to address current and future challenges.

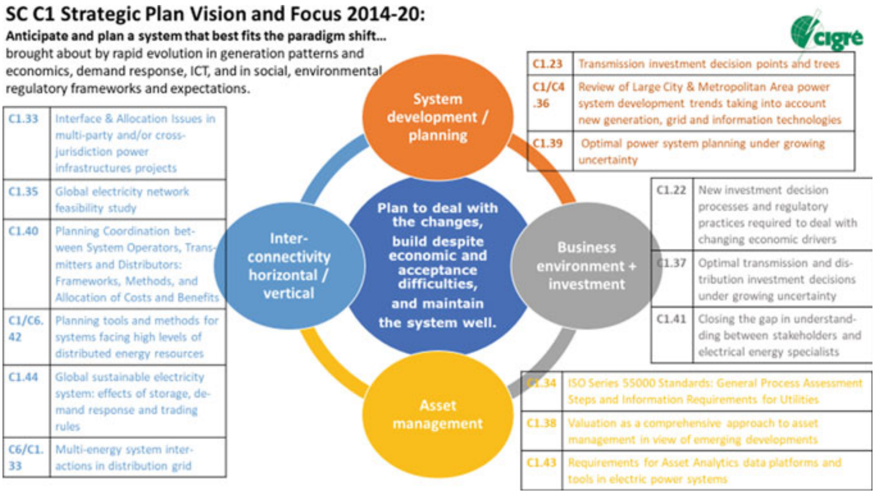
Table 3 looks beyond the electricity sector toward sector coupling and a potential global grid and describes how methodological improvements mentioned above combine with others to address these strong increases in complexity.

Table 4 broadens the view at system development and economics beyond utility and regulatory decisions into stakeholder and customer engagement, and into what this may come to mean for reliability and the balance between market and central planning processes.

Although the above tables list a multitude of challenges, opportunities and solutions, we can identify eight key themes that are key to and enable many of the needed evolutions. These eight key themes are described in Sect. 4.3 on suggested RD&I priorities below, and will be already referred to in the following Sect. 4.2.

4.2 *How CIGRE and Global RD&I Address the Challenges and Opportunities*

Within the context of the SC C1 strategic plan and its four main topics displayed in the graph below, several recently completed SC C1 WGs addressed important parts of the above research directions; their TBs are described and listed in the above sections. In this section, it is described how new and on-going WGs keep building on the prior work to address more and more of the RD&I needs and challenges in a prioritized step-by-step fashion; their titles are listed in the strategic plan graph.



SC C1 Strategic Plan Vision and Focus 2014-20:

Anticipate and plan a system that best fits the paradigm shift... brought about by rapid evolution in generation patterns and economics, demand response, ICT, and in social, environmental regulatory frameworks and expectations.

C1.33	Interface & Allocation Issues in multi-party and/or cross-jurisdiction power infrastructures projects
C1.35	Global electricity network feasibility study
C1.40	Planning Coordination between System Operators, Transmitters and Distributors: Frameworks, Methods, and Allocation of Costs and Benefits
C1/C6.42	Planning tools and methods for systems facing high levels of distributed energy resources
C1.44	Global sustainable electricity system: effects of storage, demand response and trading rules
C6/C1.33	Multi-energy system interactions in distribution grid

C1.23	Transmission investment decision points and trees
C1/C4.36	Review of Large City & Metropolitan Area power system development trends taking into account new generation, grid and information technologies
C1.39	Optimal power system planning under growing uncertainty

C1.22	New investment decision processes and regulatory practices required to deal with changing economic drivers
C1.37	Optimal transmission and distribution investment decisions under growing uncertainty
C1.41	Closing the gap in understanding between stakeholders and electrical energy specialists

C1.34	ISO Series 55000 Standards: General Process Assessment Steps and Information Requirements for Utilities
C1.38	Valuation as a comprehensive approach to asset management in view of emerging developments
C1.43	Requirements for Asset Analytics data platforms and tools in electric power systems

Table 2 Needs and opportunities: changes within the electricity sector

High-level challenges and needs	More detailed challenges and needs	Near-future state of the art	Longer term needed evolution
System dominated by renewables	Adequate dynamic models available to planners	Models of existing plant and new plant made conveniently available to TSO planners	TSO has ability to see “inside the box” of equipment and their controls and can specify control requirements
	Reliability impacts fully understood and quantified	Integrated and complementary modeling of energy, capacity, and diverse new ancillary services markets for generation investment decisions	Detailed (appliance-specific) VOLL modeling
		New paradigms developed for the assessment of system resilience and associated investment needs	Resilience integrated in multi-criteria stochastic planning
Flexibility from storage	Optimal use of storage from various sources	Full and agreed assessment of storage services from different sources	Business models and regulation of storage services
Ubiquitous use of power electronics	Adequate models of controls with low/no mechanical inertia available to planner	New control paradigms specified and modelled, e.g., “grid forming converters,” synthetic inertia	Inertia reduction managed by new ancillary services, accounted for in planning studies (e.g., inertia market)
	Accurate load model	Frequency and voltage responsiveness and harmonic injections from loads adequately modelled	System harmonics understood and managed

(continued)

Table 2 (continued)

High-level challenges and needs	More detailed challenges and needs	Near-future state of the art	Longer term needed evolution
Dynamic behaviors of the system fully considered	Synchronous sources replaced by non-synchronous	Dynamic modelling of new devices, especially non-linear	Stability assessment of multiple future operational scenarios made practical
New ancillary/system services	Identify and model need for ramping, fast response; ancillary services from RES + DER, quantify and organize market provision of flexibility services	Modeling + evaluation of need + supply for each service for long-term planning before the operational need may have come and the product defined—need to see need and value in planning studies before it becomes realistic to adjust the market design	All interdependent product + services markets modelled in stochastic master/subproblem structure; multi-services provided by different flexibility means

Table 3 Needs and opportunities: considerations beyond today's electricity sector

High-level challenges and needs	More detailed challenges and needs	Near-future state of the art	Longer term needed evolution
Remove barriers to a global grid	Enable joint investments despite differences in market design/central planning	Define minimum common trading rules and some global governance structure	Global connection, planning, operations, and market grid codes which allow for significant flexibility in each country while codifying rules necessary for secure operations
Climate change/environment fully considered	Address economics, reliability and environment in explicit tradeoffs	CO_2 and direct effects fully considered in CBA, partly quantified or monetized, partly as multi-criteria tradeoffs; for G, T, D	Climate change limit 1.5° drives all planning studies for energy incl. electricity G, T, D; wholly consider all externalities to attain global optimization
	Climate change adaptation and contingency planning	Systematically consider risks to the power system from climate change, and its resilience	Include resilience against climate change risks in stochastic, multi-criteria planning
	Identify and represent options beyond a single utility's boundaries of influence	Move from national to (sub)continental scale of electricity system planning, especially transmission, to enable efficient handling of regional surpluses/deficits of RES at high penetrations	Multi-energy sector, multi-system models used as standard
Whole energy system planning/sector coupling	Develop and test models for quantitative planning and analysis of electricity, gas, heat, and transport together	Consistent forecasting and scenarios of production and demand in electricity, gas, heat and transport sectors, taking account of government policy effects	Make tax + subsidy differences explicit in cross-sector planning studies; perform studies with consistent taxes + subsidies even before those are real; pursue harmonized taxes and subsidies in each country and globally

Table 4 Decision making

High-level challenges and needs	More detailed challenges and needs	Near-future state of the art	Longer term needed evolution
Customer + stakeholder engagement	Without societal and customer support, the difficult energy transition toward climate protection might fail	Transparency of planning process to the public, especially on assumptions and impact, what-if-not analysis; consultation management	Because energy in a decarbonized system, and the electric grids at its center, are a well-recognized foundation for all citizens in a sustainable society, energy system planning is a consensus and effectiveness-driven public process
		Utilities, regulators, and all levels of government engage customers and stakeholder in several planning and authorization process steps, especially early steps, but speed of planning and authorization is improved	Many customers actively use their market options to jointly determine the direction the energy system takes, based on transparent info from experts and consistent price signals
New challenges require more explicit management of risk	New reliability standards are developed and used in system operation, suited for system dominated by fluctuating renewables	Planning models take account of new reliability standards through complementary modeling of energy, capacity and ancillary services markets for G, T, D investment decisions	Customers price elasticity of demand, appliance-specific, influences both market functioning and system planning
Balance of centrally planned and decentral market decision making	With markets: Optimal system evolution despite unbundled market-based decision making	Decisions of SOs modeled in generation investment optimization and vice versa	New business models for grid operators

(continued)

Table 4 (continued)

High-level challenges and needs	More detailed challenges and needs	Near-future state of the art	Longer term needed evolution
	Consistent price signals within electricity and across all energy sectors	High-resolution price signals (time + location) drive markets, are published, and are modeled for planning,	All pricing + investment decisions based on locational time of use and scarcity pricing; even on Blockchain-based peer-to-peer trading
	With central plans: optimal multi-sector development within budgetary constraints	Costs are known to system operators and important participants in the energy system, drive operational and planning decisions	All participants/customers understand fluctuating costs and react to system needs based on system signals

System Development/Planning

There are no current working groups that specifically consider generation planning. Rather, WGs examine the impacts on transmission and distribution planning of the growing uncertainty regarding generation locations, fuel use, and levels of competitive market implementation. This is particularly true where significant investment in solar and wind generation is occurring as this may be quite dispersed, and at both transmission and distribution levels.

WG C1.23, “Transmission Investment Decision Points and Trees” is examining the use of target networks and decision trees for a range of scenarios related to transmission expansion. With the growing uncertainties associated with transmission planning, it is essential to consider a range of scenarios prior to committing to a particular investment pathway. This WG is reviewing the use of the decision tree concept for this, which can be crucial for systematic treatment of decisions under uncertainty and for the evolution of firming up decisions over the years of the planning horizon toward a long-term target network. Thus, this WG is an important step toward the possible future approach of stochastic optimization of investment plans. Pursues key theme 6, stochastic optimization.

WG C1/C4.36 is reviewing large city & metropolitan area power system development trends taking into account new generation, grid and information technologies. It thus addresses a crucial part of current and even more future power systems worldwide, i.e., the growing number and size of metropolises. The work considers the impact on planning of development trends over the last ten years in relation to major cities and associated metropolitan areas. Among other things, it is intended to identify special planning requirements and key economic drivers. It is also looking at existing and potential technologies that will deliver improved sustainability and controllability while ensuring appropriate power system security is delivered. Pursues key theme 1, joint data and processes.

WG C1.39, “Optimal Power System Planning Under Growing Uncertainty” is taking a more general perspective on the impact of growing uncertainty on planning investment decisions. Uncertainties considered include generation, demand side, transmission, and distribution. Mechanisms, methods, and criteria of power system planning are being examined for different market schemes with the aim of developing guidelines for the design of future projects. Pursues key theme 6, stochastic optimization.

Interconnectivity—Horizontal and Vertical

This section considers the current working groups that cover some aspects of the subject headings of planning integration, horizontal and vertical interconnections, active distribution and big data, and modeling of DC, storage, new operations and control tools. These aspects are of growing importance to the operation and planning of power systems, driven by the rapid growth of wind turbines, solar generation and associated smart technologies, and the need to share and trade electricity resources across utility and country boundaries in order to make the highest value use of renewable energy surpluses and deficits.

WG C1.33, “Interface and Allocation Issues in Multi-Party and/or Cross-Jurisdiction Power Infrastructures Projects, ” is considering all the aspects that should be examined for cross-jurisdictional projects. This includes allocation of costs, benefits, and risks across borders and between operators, together with levels of regulation, business models and tariff impacts. Where possible, general principles, and guidelines will be proposed. Pursues key theme 1, joint data and processes.

WG C1.35, “Global Electricity Network Feasibility Study” is carrying out a high-level feasibility study on the potential benefits, challenges, and economic viability of a global electricity network. This is a first-stage investigation and necessarily will make a number of assumptions regarding consumption and supply volumes as well as the key technologies to be used for the infrastructure.

WG C1.44, “Global Sustainable Electricity System: Effects of Storage, Demand Response and Trading Rules’ updates C1.35” results with improved modeling of the named aspects. Both pursue key themes 1, joint data and processes, and 8, multi-criteria cost-benefit analyses.

WG C1.40, “Planning Coordination between System Operators, Transmitters and Distributors: Frameworks, Methods, and Allocation of Costs and Benefits” is examining the planning coordination between different network owners including cost allocation, data exchange, and growth forecasts in generation and load. Pursues key theme 1, joint data and processes.

Working Group C1/C6.42, “Planning Tools and Methods for Systems Facing High Levels of Distributed Energy Resources (DER),” is focusing on the growing impact of DER at the distribution level and its broader effect on the power system as a whole. It is considering methods and benefits of aggregating DER and the use of tools to examine the impact on reliability and resilience and its associated economic aspects. Pursues key themes1, joint data and processes, 2, high-resolution price signals in time, location and system services, and 3, price elasticity.

WG C6/C1.33, Multi-Energy System Interactions in the Distribution Grid, is exploring the opportunities and impacts of multi-energy systems in the future electric power systems. This is looking at the interactions between the various mechanisms for providing energy including a range of storage options and various forms of heating and cooling. Various technical and economic challenges to the adoption of the multi-energy systems are being considered. Pursues key themes 4, consistency across energy sectors and 8, multi-criteria cost-benefit analysis.

Economics and Investment (including Stakeholder Interaction)

This section considers the current working groups that cover some aspects of the subject headings of investment decisions; climate protection, environmental constraints and multi-criteria tradeoffs; stakeholder and citizen engagement; and planning, regulation and economics in energy markets with shifting roles of environmental and reliability constraints. There is no doubt that the higher risks being imposed by the rapid changes in electricity provision are impacting investment decisions, and communicating the impact of the changes in a simple effective way is equally challenging.

Working Group C1.22, "New Investment Decision Processes and Regulatory Practices Required to deal with Changing Economic Drivers," is reviewing the impact of the changing energy environment on decision processes. Issues that are being considered include the changing nature of generation, network and load usage, and the increasing cost of ancillary services due to the demands from intermittent generation. Pursues key theme 8, multi-criteria cost-benefit analysis.

Working Group C1.37, "Optimal Transmission and Distribution Investment Decisions Under Growing Uncertainty" is investigating how transmission and distribution scenarios are used to ensure appropriate investment decisions are made by both TSOs and DSOs. This is being considered in an environment of growing uncertainty due to the growth of DER, transport electrification, greater interconnection and changes to consumer heating methods, all under the umbrella of global emissions targets. Pursues key theme 6, stochastic optimization.

Working Group C1.41, "Closing the Gap in Understanding between Stakeholders and Electrical Energy Specialists," is examining the gap in understanding among stakeholders and technical specialists in relation to the changing nature of the power system. Recommendations on how to improve understanding of both all stakeholders will be drawn from a number of case studies. Pursues key theme 7, engagement and understanding.

Asset Management

While a number of Study Committees consider various aspects of asset management that are particular to their area of study, SC C1 examines the high-level asset management aspects that are generally common to all areas. This includes new standards such as the ISO 55000 as well as a general overview of asset management methods.

WG C1.34, "ISO Series 55000 Standards: General Process Assessment Steps and Information Requirements for Utilities," is considering a number of aspects related to asset management and associated systems. A particular focus is relating to the changes brought on by the move from the PAS 55 standard to the ISO 55000 standard and the level of readiness of utilities to move to this new level of certification. Pursues key themes 1, joint data and processes, and 7, Big Data.

WG C1.38, "Valuation as a Comprehensive Approach to Asset Management in view of Emerging Developments," is reviewing international practice for justification of asset sustainment investments and the management of risk. Issues such as the influence of regulatory regimes and the degree of integration with new capital expenditure are considered. Pursues key themes 1. joint data and processes, 2. high-resolution price signals in time, location and system services, 3. price elasticity, and 4. multi-criteria cost-benefit analysis.

WG C1.43 is titled, "Defining a Typical Set of Requirements for Asset Analytics Data Platforms and Tools aimed at Supporting Asset Management Decision-Making Processes." In considering asset analytics tools, recommendations will be made in relation to requirements for data management, methods to assess tool vendors, and outputs that will facilitate benchmarking within and between utilities. Pursues key theme 7, Big Data.

4.3 Suggested RD&I Priorities

From the tables in Sect. 4.1 the following eight key themes for needed evolutions of the state of the art can be summarized. They will need to be continuously reviewed as technological solutions evolve and our understanding of the changing nature of the power system improves:

1. **Joint data and processes** across transmission and distribution, across asset management and planning, and increasingly across all energy sectors: This will need to be pushed forward within SC C1 by the system development/planning topic for increasing exchange and consistency of data as well as increasing compatibility of planning methods between transmission and distribution, by the asset management topic for the integration of asset management and system planning data, criteria and processes, and by the interconnections topic for the integration across energy sectors. Within CIGRE, SCs C5 and C6 will also contribute strongly to the evolution of this key theme.
2. **High-resolution price signals in time, location, and system services** drive customer and market/system participant choices, are modeled and drive system planning, in both market and centrally planned energy systems (as mix of cost and price signals): This will need to be pushed forward within SC C1 by the system development/planning topic for planning approaches which anticipate future evolutions toward more precision in price and cost signals in time and location, and the important growing differentiation in the required system services (inertia, ramp rates, etc.). These evolutions also affect the asset management topic and have begun to affect its WG priorities. Within CIGRE, SCs C4, C5 and C6 will also contribute strongly to the evolution of this key theme.
3. Scarcity pricing and eventually appliance-specific **price elasticity** become the basis of highly reliable systems in renewables-dominated systems characterized by frequent very low energy prices and occasional price spikes, and planning must anticipate that in its modeling before it becomes reality: This will need to be pushed forward within SC C1 by the system development/planning topic for planning approaches which build on our TB 715 to incorporate price elasticity and new approaches to system adequacy and reliability into system planning. These evolutions will also affect the economics and investment as well as asset management topics' priorities. Within CIGRE, SCs C5 and C6 will contribute strongly to the evolution of this key theme.
4. Price and cost signals must become **consistent across energy sectors**: This will need to be pushed forward within SC C1 by the interconnectivity topic but within CIGRE, also especially by SC C6.
5. **Engagement and understanding** of customers, market/system participants, and stakeholders: The work now starting in WG C1.41 within SC C1's economics and investment topic will need to be continued and be broadened toward customers and market/system participants' understanding and engagement with price signals, sector coupling, etc. Within CIGRE, SC C3 will contribute strongly to this key theme.

6. Moving from target networks in transmission and distribution via consideration of multiple time steps toward decision tree concepts and **stochastic optimization:** This will need to be pushed forward within SC C1 by the system development/planning topic for supporting utilities' growing sophistication in scenario approaches, target networks, steps toward them, and eventually decision tree and stochastic optimization. As planning and asset management become integrated, SC C1's asset management topic will also push this forward, including from the risk perspective.
7. **Big data** improving computational and algorithmic capabilities, and data hubs, with data privacy-controlled access to data for market actors, improves asset management, forecasting and planning: Data, computational, and algorithmic capabilities affect all four topics in SC C1 but will be especially pushed forward by the system development/planning and the asset management topic. It also affects many other CIGRE SCs and especially SCs C5 and D2.
8. And perhaps most importantly, the global goal of limiting climate change to 1.5° but also other economic, social, environmental, and reliability criteria are fully incorporated into system planning and asset management through **multi-criteria cost-benefit analysis** approaches: This also affects and will be pursued by all four topics in SC C1, and especially by the economics & investment topic as the cost-benefit analyses mostly affect new investments. Within CIGRE, SC C3 will contribute strongly to it.

The influences on planning are of a global nature and it is, therefore, important to be aware of the work being done by organizations outside of CIGRE such as the IEA, IEEE, NERC, ENTSO-E, IRENA, ETIP SNET, Mission Innovation, Clean Energy Ministerial, and other research organizations in various countries.

5 Conclusions

The SC C1 chapter addresses the electricity supply system of a future several decades ahead from the perspective of system development and economics. It shows what the main technical aspects of the system of the future mean for system planning, economics, and asset management: the Paris Agreement on climate protection which will likely lead to renewable energy sources dominating electricity systems, decarbonization of the entire energy system with sector coupling and electrification of heating and transport, the strong effect of the energy transition on citizens and stakeholder relationships, continental-scale interconnections and microgrids, and the balance between the goals of reliability, economics and the environment.

The evolution of generation, transmission, distribution, and integrated planning is illustrated with generic optimization model formulations, emphasizing the handling of uncertainties, the rise of the prosumer reacting to high-resolution price signals not only for energy but also for reliability and multiple new system services needed for stability, and planning in an unbundled market environment. Special emphasis is given to state-of-the-art multi-criteria cost-benefit analyses, vertical and horizontal interconnectivity, with global grid feasibility studies and strong focus on ever improving cooperation between transmission and distribution system planners, business management including stakeholder relations, and asset management which in evolving beyond risk-based into value-based methods which also require high-resolution price signals and likely lead to more integrated system planning and asset management processes.

Innovation needs for challenges not fully addressed in the state-of-the-art focus on active distribution and Big Data, Modeling of DC, storage, new operations and control tools, climate protection, environmental constraints and multi-criteria trade-offs, sector coupling, stakeholder and citizen engagement, regulation and economics in energy markets with shifting roles of environmental and reliability constraints. This led to a table representation of research needs toward the network of the future, structured along processes, changes, considerations beyond today's electricity sector, and decision making. From these tables, the following **eight key themes** are identified as enablers of the evolutions needed:

1. **Joint data and processes** across transmission and distribution, across asset management and planning, and increasingly across all energy sectors
2. **High-resolution price signals in time, location and system services** do not yet drive customer and market/system participant choices, but power system evolution, planning and management could become more holistic if they do. If so, they need to be modeled and drive system planning, in both market and centrally planned energy systems (as mix of cost and price signals)
3. Scarcity pricing and eventually appliance-specific **price elasticity** become the basis of highly reliable systems in renewables-dominated systems characterized by frequent very low energy prices and occasional price spikes, and planning must anticipate that in its modeling before it becomes reality
4. Improved consistency of price and cost signals **across energy sectors** can help to achieve 2050 climate neutrality with less controversy and economic inefficiency
5. **Engagement and understanding** of customers, market/system participants and stakeholders
6. Moving from target networks in transmission and distribution via consideration of multiple time steps toward decision tree concepts and **stochastic optimization**
7. **Big data**, improving computational and algorithmic capabilities, and data hubs, with data privacy-controlled access to data for market actors, improves asset management, forecasting, and planning
8. And perhaps most importantly, the global goal of limiting climate change to 1.5° but also other economic, social, environmental, and reliability criteria are fully incorporated into system planning and asset management through **multi-criteria cost-benefit analysis** approaches.

New technologies like low-cost solar and wind generation, batteries, computational and algorithmic advances incl. Big Data, artificial intelligence, platforms or block chain can disrupt or support progress everywhere in the world equally. They even have strong potential to enable developing countries to leapfrog developed countries, if building new, much larger electric systems makes it easier to adopt the most modern solutions than in well-established systems where every large change creates winners and losers and thus opposition to change.

References

1. Poncela-Blanco, M., Spisto, A., Hrelja,N., Fulli, G.: Generation Adequacy Methodologies Review. JRC Science Hub (2016)
2. ENTSO-E.: ENTSO-E Target Methodology for Adequacy Assessment-Updated Version after Consultation. ENTSO-E: Brussels, Belgium (2014)
3. ENTSO-E.: Mid-term Adequancy Forecast-2019 Edition. ENTSO-E: Brussels, Belgium (2019)
4. Mastropietro, P., Rodilla, P., Batlle, C.: National capacity mechanisms in the European internal energy market: opening the doors to neighbours. Energy Policy **82**, 38–47 (2015)
5. Hasani, M., Hosseini, S.H.: Dynamic assessment of capacity investment in electricity market considering complementary capacity mechanisms. Energy **36**(1), 277–293 (2011)
6. CEPA: Study on the Estimation of The Value of Lost Load of Electricity Supply in Europe, in ACER/OP/DIR/08/2013/LOT 2/RFS 10 (2018)
7. Munoz, F.D., Hobbs, B.F., Ho, J.L.: Kasina S (2013) An engineering-economic approach to transmission planning under market and regulatory uncertainties: WECC case study. IEEE Trans. Power Syst. **29**(1), 307–317 (2013)
8. ENTSO-E: Ten Year Network Development Plan 2012. ENTSO-E Brussels (2012)
9. Monticelli, A., Pereira, M.V.F., Granville, S.: Security-constrained optimal power flow with post-contingency corrective rescheduling. IEEE Trans. Power Syst. **2**(1), 175–180 (1987)
10. Capitanescu, F., Ramos, J.L.M., Panciatici, P., Kirschen, D., Marcolini, A.M., Platbrood, L., Wehenkel, L.: State-of-the-art, challenges, and future trends in security constrained optimal power flow. Electr. Power Syst. Res. **81**(8), 1731–1741 (2011)
11. Capitanescu, F., Glavic, M., Ernst, D., Wehenkel, L.: Contingency filtering techniques for preventive security-constrained optimal power flow. IEEE Trans. Power Syst. **22**(4), 1690–1697 (2007)
12. Jabr, R.A., Coonick, A.H., Cory, B.J.: A homogeneous linear programming algorithm for the security constrained economic dispatch problem. IEEE Trans. Power Syst. **15**(3), 930–936 (2000)
13. Cheng, Y., Zhang, N., Kang, C.: Low-carbon economic dispatch for integrated heat and power systems considering network constraints. J. Eng. **2017**(14), 2628–2633 (2017)
14. ENTSO-E: Mid-term Adequancy Forecast-2018 Edition, Methodology and Detailed Results. Brussels, Belgium (2018)
15. Theresa, S., Antina, S.: European Grid Report, Beyond Public opposition-Lessons Learned from Across Europe. Renewables Grid Initiative, Berlin, Germany (2013)
16. Künneke, R.W.: Electricity networks: how ‘natural’ is the monopoly? Util. Policy **8**(2), 99–108 (1999)
17. Huang, W., Zhang, N., Dong, R.: Coordinated planning of multiple energy networks and energy hubs. Proc. CSEE **5**(1), 1–11 (2018)
18. Cheng, H., et al.: Challenges and prospects for AC/DC transmission expansion planning considering high proportion of renewable energy. Autom. Electr. Power Syst. **41**(9), 19–27 (2017)
19. Zhang, N., Chongqing, K.: Low carbon transmission expansion planning considering demand-side management. Autom. Electr. Power Syst. **40**(23), 61–69 (2016)
20. Zhuo, Z., et al.: Incorporating massive scenarios in transmission expansion planning with high renewable energy penetration. IEEE Trans. Power Syst. (2019)
21. ENTSO-E: European Network Codes. Available from https://www.entsoe.eu/network_codes/ , 26 Nov 2019

22. Huang, W., et al.: Construction of regional energy internet: concept and practice. J. Glob. Energy Interconnection **1**(2), 103–111 (2018)
23. Liu, Z., et al.: A concept discussion on northeast Asia power grid interconnection. CSEE J. Power Energy Syst. **2**(4), 87–93 (2016)
24. Liu, Z.: Global Energy Interconnection. Academic Press (2015)
25. Wu, D., et al.: Techno-economic analysis of contingency reserve allocation scheme for combined UHV DC and AC receiving-end power system. CSEE J. Power Energy Syst. **2**(2), 62–70 (2016)
26. Zhuo, Z., et al.: Optimal Operation of Hybrid AC/DC Distribution Network with High Penetrated Renewable Energy. In: 2018 IEEE Power and Energy Society General Meeting (PESGM). IEEE (2018)
27. Dragan Jovcic, et al.: Task 6.1 develop system level model for hybrid DC CB. 2016. In: PROMOTioN-Progress on Meshed HVDC Offshore Transmission Networks
28. Marjan, P., et al.: D6.2 develop system level model for mechanical DCCB. 2016. In: PROMOTioN—Progress on Meshed HVDC Offshore Transmission Networks
29. Western Electricity Coordinating Coucil: 10-Year Regional Transmission Plan, 2020 Study Report. WECC (2011)
30. Bacher, Rainer, Peirano, Eric, de Nigris, Michele: VISION 2050, Integrating Smart Networks for the Energy Transition: Serving Society and Protecting the Environment. ETIP SNET, Brussels (2018)
31. ETIP SNET: White Paper Sector Coupling: Concepts, State-of-the-Art, Perspectives, Jan 2020

Konstantin Staschus is from Berlin, Germany, and holds a Ph.D. in Operations Research from Virginia Tech, USA. After 9 years at PG&E, USA, where he developed and led teams for methodology and software development for long- and medium-term electric utility planning, he held management positions in German utility associations, including 6 years as Managing Director of the association of grid operators, VDN. In 2009, he became the first Secretary-General of ENTSO-E in Brussels, with legal mandates for the EU's biennial network development plans, for drafting network codes which become binding EU Regulations, for operational coordination rules, and for RD&I plans. Since 2017, he is Director in the Berlin office of Navigant Energy Germany, A Guidehouse Company, and additionally consults part-time for ENTSO-E and the European Technology and Innovation Platform "Smart Networks for Energy Transition". He participated in CIGRE WGs since the 1990s and was member and later expert in SC C1 "System Development & Economics" since 2004, before becoming its Chair 2014–2020. He published over 60 papers in scientific and engineering magazines.

Chongqing Kang is Professor and Dean of Department of Electrical Engineering, Tsinghua University, China. He is fellow of IEEE and IET. He was awarded the National Science Fund for Distinguished Young Scholars. He was a visiting scholar at University of Cambridge, UK, from 2007 to 2008. His research interests include power system planning and operation, renewable energy, and electric market. He currently serves as Member of CIGRE SC C1 Strategic Advisory Group, Editor-in-Chief of International Transactions on Electrical Energy Systems(Wiley), Long-Range Planning Committee Member of IEEE PES, and Fellows Nomination Resource Committee Member of IEEE PES.

Antonio Iliceto served as technical officer in Italian Army, in the National broadcasting corporation and in the National Utility ENEL after receiving M.Sc in Electrical Engineering from Rome University, Italy, with highest degrees and prize-winning Master Thesis, he; he spent one year in Africa as Junior Professional Officer at United Nations technical cooperation. He then joined for a decade the Oil and Gas major ENI (Italian Oil Major), working in Strategies, Investments Planning, Merging and Acquisitions, International Business Activities. Since 2001, he is with Terna, Italian TSO, covering several positions in: Power Exchange Pool initial set-up, Market Settlement, Business Development, Technology Engineering, Grid planning, Realization of several Interconnection projects. Since 2013, he focuses on R&D and Innovation, cooperation, and coordination among TSOs, in EU funded project Best Paths (Chairman of Consortium), in **ENTSO-E** (Convenor of Working Group “Future Energy Systems” and past Convenor of WG “RDI Planning” in the Committee Research, Development and Innovation), in **ETIP SNET** (EU Platform for energy cross–sector coordination of R&D and Innovation): vice-chair of the Governing Board and Chairman of WG Grids and System View. He is also active in Association of Mediterranean TSOs (**MedTSO**), Advisory Committee on T&D (**IEC** ACTAD), **ISGAN Annex6** (alternate national member), **Dii—Desert Energy** (member of Advisory Board and several WGs on interconnection studies), **AEIT**–LEE (Italian Electricity Journal as Editorial Board member and reviewer). In **CIGRE**, Antonio Iliceto is incoming Chairman of Study Committee C1 (System Development & Economics); since 2010, he actively contributes as convenor/co-convenor of 6 WGs on planning drivers, global grids, TSO-DSO relation, vertical and horizontal interconnections, African electrification; special reporter, postre session, member of Strategic Advisory Group to the Chair.

Ronald Marais has over the last 28 year contributed to the development of African power grid within South Africa and Southern African power grid. He graduated from the Witwatersrand Technikon and continued his studies at the Tshwane University of Technology. He has a B.Tech degree in electrical power engineering and is registered as a Professional Technologist at the Engineering Council of South Africa. He currently heads the South Africa electricity power utility, Eskom, Transmission Strategy Grid Planning section. The key focus areas include strategic grid planning of the South African transmission power grid, Southern African energy strategic planning, and long-term transmission power system design and stakeholder relationship management. He participated in the South African Department of Energy renewable energy bid process and chaired the Southern African Power Pool Planning Sub-Committee. Ronald Marais contributed to CIGRE C1 System Development and Economics as the Southern African Study Committee member (2008–2016), Strategic Advisory Group member (2016–) and Special Reporter Paris (2018).

Keith Bell joined the University of Strathclyde in 2005 after a number of years working in the UK electricity supply industry and, before that, a Ph.D. at the University of Bath and spells as a post-doctoral researcher in Manchester and Napoli. In 2013, he was appointed to the Scottish Power Chair in Smart Grids. He is a co-Director of the UK Energy Research Center (UKERC), and in April 2019, became a member of the UK's Committee on Climate Change. He is a Chartered Engineer and has led many research projects in collaboration with academic and industrial partners. He is involved with The IET Power Academy and is an invited member of CIGRE Study Committee C1. In recent years, he has given advice on electricity system issues to the Scottish Government, Ofgem, the UK government's Department of Business, Energy and Industrial Strategy (BEIS), and the Government of Ireland.

Phil Southwell has had over forty years experience in the power industry. This has included a number of technical and managerial roles, culminating in senior executive positions with oversight of system planning, economic regulation, strategic planning, and smart grid development. Phil's leadership roles in CIGRE have included Study Committee Chair of C1 and Convenor of several Working Groups. He has been on the Board of CIGRE Australia for the past four years and has received a number of CIGRE awards including Honorary Membership in 2014 and a Fellow Award in 2016. He was also on the Board of the Australian Power Institute for a number of years as well as a number of Industry Boards. He has degrees in Electrical Engineering and Management and is a Fellow of the Institute of Engineers Australia.

Yury Tsimberg is a Director of Asset Management with Kinectrics Inc. where, for the last several years, he has been leading corporate consulting services in Asset Management area. In this capacity, he successfully completed a number of Asset Management projects across North America, taught Asset Management courses all over the world, and was a presenter at many industry conferences and forums. Yury was designated by a regulatory organization in Ontario, Canada, as an expert witness in Asset Management and has participated as such in rate hearings. Prior to joining Kinectrics, Yury spent 30 years with Ontario Hydro and Hydro One working in various areas of the electrical utility transmission and distribution business, including Asset Management, system planning, power system operations, M&A, regulatory, lines maintenance, and customer service. Yury Tsimberg was Canadian member of the international panel revising PAS 55 specification; Canadian representative on North American Electrical Reliability Corporation (NERC) committees developing North American transmission planning standards and is currently Canadian representative and management team member as the Asset Management Convener for International Council on Large Electric Systems (CIGRE) Study Committee SC1 “System Development and Economics.” In 2018, he was awarded a prestigious CIGRE Technical Council Award in recognition of his outstanding contribution to CIGRE’s work. Yury holds Bachelor of Applied Science and Master of Engineering degrees in Electrical Engineering from the University of Toronto and is a Registered Professional Engineer in the Province of Ontario, Canada.

Power System Operation and Control

Susana Almeida de Graaff and Vinay Sewdien

System operators face significant evolving conditions in power systems with the increasing penetration of RES, the growing competitiveness of the free electricity market, the integration of new technologies and the need to increase flexibility and control capabilities into the operational framework. Operational processes in today's power system are still primarily based on the availability of sufficient conventional synchronous generation. Operation of the future power system, however, will be characterised by time instances with few to no conventional synchronous generation in operation, urging operators to adapt their knowledge and skills, methods, tools and processes accordingly. This chapter describes the current practices and provides insight into the expected operational challenges inherent to the future power system. To cope with these challenges, ongoing developments of innovative technological- and market-based solutions are presented. Finally, the need for more integration and coordination, and the role of sector coupling in the future power system are highlighted.

1 Introduction

System operations are evolving continuously due to a variety of external drivers from political, regulatory, environmental and technological background. For instance, the constant debates worldwide on climate change, carbon dioxide (CO_2) emissions and environmental sustainability give a very strong political direction to electrification and sector coupling, which will influence the manner how the system will be operated in the future.

On behalf of CIGRE Study Committee C2.

S. A. de Graaff (✉) · V. Sewdien
TenneT TSO B.V., Arnhem, The Netherlands
e-mail: susana.de.graaff@tennet.eu

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_11

One can simply say that ‘system operators need to keep the lights on’ today, as well as in the future. However, behind this simple statement, there is an increasing level of complexity that needs to handle more volatile operational conditions. This increased volatility is due to the increasing penetration of renewable energy sources (RES) and the growing competitiveness of the free electricity market, which consequently requires the integration of new technologies, more coordination and the need to increase observability, flexibility and control capabilities.

The high-level *operational* objective of a power system can be defined as meeting at all times the requested demand/load in a secure and cost-effective manner, where predefined reliability and power quality criteria are respected. When the system does deviate from this operating point, several measures exist to ensure that the system returns to an acceptable operating condition as fast as possible. This chapter will highlight some of the relevant processes, actions and timeframes that have a crucial role in meeting the objective defined above.

First, the state of the art of system operations will be presented, including the definition of power system states. Next, the timeframes that are relevant for system operations will be explained. Important processes such as capacity calculation, security analysis and load-frequency control are highlighted. In the following section, aspects of power system restoration are presented, after which some aspects of control room operators’ training will be presented.

In the second part of this chapter, the focus is shifted towards the future operational challenges resulting from the energy transition, and ongoing developments and requirements that enable the path for a secure operation of the power system today and in the future.

2 State of the Art

System operation is an essential and complex task that has the goal to meet the energy demand continuously and adequately. Control room operators are often called upon to take decisions and prompt actions, which require a trade-off analysis between system security and economic efficiency. Although operational complexity and system conditions will evolve, the ultimate goal of system operation remains.

2.1 Power System States

The operation of the power system is governed by three sets of generic equations. First, there is a set of differential equations that describes the physical laws and dynamic behaviour of system elements. Second, there is a set of algebraic equations describing the load-generation balance (i.e. the equality constraint, EC). And lastly, another set of inequality constraints describing the operating limits of elements, such as maximum permissible currents and voltages (i.e. inequality constraints, IC).

This same set of inequality constraints, termed security constraints (SC), is used to judge the security of the power system state in case of contingencies [1, 2]. If security constraints are violated, the operating state is considered insecure. In a way, security is representing the level of available reserves and system robustness in case of contingencies.

Depending on its operating condition, the power system can find itself in one of the following five operating states: normal, alert, emergency, *in extremis* or restorative state [3]. In Table 1, an overview is given of the definition of these states for the North American and European jurisdictions.

Figure 1 illustrates the possible transition between these different states, whereas Table 2 shows for each operating state whether equality and all inequality constraints are satisfied or violated.

Following small disturbances, the security margin of the power system could reduce to below the desired level, which would cause a transition of the operating state from normal to alert. In this operating state, the equality and inequality constraints are still satisfied, whereas the security constraint is violated. From the alert state, the preferred security level can be achieved using preventive control actions (e.g. generation redispatch).

However, when no preventive control is applied and some disturbance occurs, the system condition could deteriorate and degrade to the emergency state. In this state, inequality constraints are breached. As a result, generators could be disconnected from the grid. Emergency control actions (e.g. fault clearing) could be taken to restore the system to the alert state. When these control actions are ineffective and the system is still overstressed, the power system disintegrates and finds itself in the *in extremis* case. In this case, equality as well as inequality constraints are violated. The system is no longer intact and large amounts of system load would be disconnected. In this state, the main goal of emergency control (e.g. load shedding or controlled system separation) is directed to keeping as much as possible of the power system intact. Once system collapse has been halted, the operators start to restore the system, where control actions aim to pick up all lost load and resynchronise the system. The power system finds itself in the restorative state. From the restorative state, the system can evolve to either the alert or the normal state.

Continuous changes in the state of the power system are inherent to the operation of the transmission system. These changes are the result of disturbances, planned or unplanned outages, change in loading conditions and of generation patterns (which are nowadays driven by market and RES conditions). It is crucial to be prepared for emergencies in order to limit their consequences and to be able to quickly restore the system to its normal state. Several processes are in place to manage the secure operation of the power system. These processes take place across different operational timeframes, which are discussed next.

Table 1 Definitions of operating states in NA and EU

Operating state	NA definition [3]	ENTSO-E definition [4]
Normal	All constraints are satisfied, indicating that the generation is adequate to supply the existing total load demand and that no equipment is being overloaded. Furthermore, sufficient reserve margins are available to provide an adequate level of security	A situation in which the system is within operational security limits in the N-situation and after the occurrence of any contingency from the contingency list, taking into account the effect of the available remedial actions
Alert	Equality and inequality constraints are still satisfied, but the existing reserve margins would be such that some disturbance could result in a violation of some inequality constraints. In the alert state, the security constraint is violated	State in which the power system is within operational security limits, but a contingency from the contingency list has been detected and in case of its occurrence the available remedial actions are not sufficient to keep the normal state
Emergency	Inequality constraints are violated and system security is breached. The system is still intact	The system state in which one or more operational security limits are violated
In extremis (NA)/blackout state (EU)	Equality as well as inequality constraints have been violated. The system would no longer be intact, and major portions of the system load would be lost	The system state in which the operation of part or all of the transmission system is terminated
Restorative	System state where control actions are being taken to pick up all lost load and reconnect the system. From this state, the system could transit to either the alert or the normal state	The system state in which the objective of all activities in the transmission system is to re-establish the system operation and maintain operational security after the blackout state or the emergency state

2.2 System Operation Timeframes

Throughout time, the design and operation of the power system have changed in such a manner that the time scale on which various decisions need to be made has been expanded in both directions: grid and generation planning decisions are now influenced by environmental goals, which increase the required time for completion of projects. The project cycle time for new grid and generation project can easily

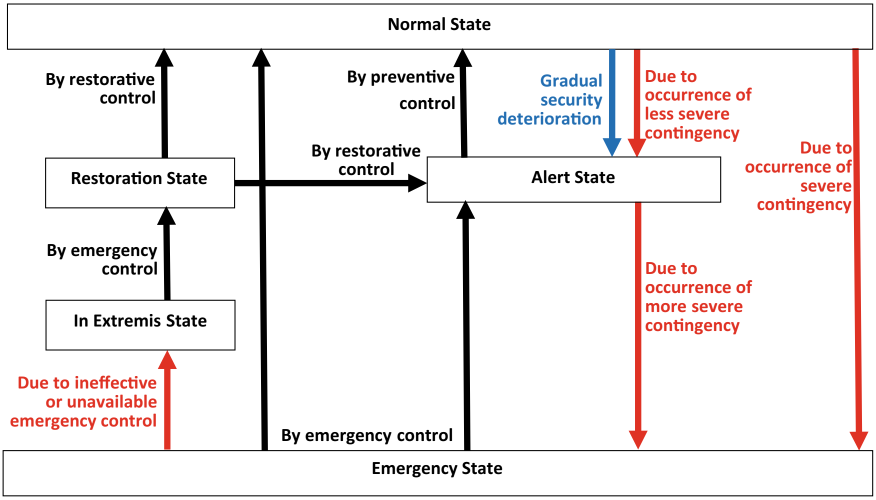


Fig. 1 Power system operating states

Table 2 Constraints satisfaction for operating states

Operating State	EC satisfied?	IC satisfied?	SC satisfied?
Normal	✓	✓	✓
Alert	✓	✓	✗
Emergency	✓	✗	✗
In extremis	✗	✗	✗
Restorative	✗	✓	✗

reach up to tens of years until final delivery. On the other hand, system operators are operating the system increasingly at its edge, which results in new and frequently observed dynamic phenomena. Some of these occur within a fraction of an AC cycle, requiring monitoring and control of the system in much shorter timeframes. The range of relevant timeframes in power system planning and operation is graphically illustrated in Fig. 2 [5].

In the very long term (5 up to 25 years), the main activities in power systems cover the design and construction of new generation and transmission facilities and the expansion and/or retirement of existing facilities. This timeframe can be defined as the *expansion planning* phase.

System *planning* and *operational* timeframes encompass the following:

- Long term (2 up to 5 years), where the main activities evolve around the establishment of long-term contracts and strategic management of generation (e.g. nuclear fuel management and management of multi-year reservoirs for hydro power plants);

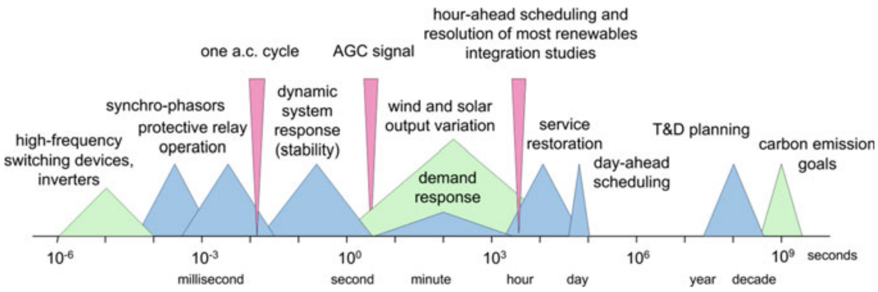


Fig. 2 Timeframes in power system planning and operation [5]

- Medium term (1 month up to 2 years), where the important activities relate to maintenance scheduling (outage planning) and seasonal adequacy forecast (e.g. seasonal load and generation forecast and annual management of water reservoirs);
- Short term (1 up to 4 weeks), where the main activities include short-term adequacy forecast, purchase of operational reserves, scheduling of weekly shutdown and start-up of thermal generation. In this timeframe, outage plans are reassessed and, in interconnected power systems, coordinated. This allows to account for unforeseen changes (such as dry periods or important forced outages) to the initial maintenance plans;
- Very short term (1 h up to 1 week), where the main activities include coordinated capacity calculation for the day-ahead and intraday, (coordinated) security analysis, with remedial action preparation and activation (e.g. topological adjustments and redispatch) and detailed decisions of starting up and shutting down of generation facilities.

In the close to and *real-time* operation (up to 1 h), the main activities evolve around load-frequency and voltage control for quasi-steady-state operating conditions, emergency control (e.g. protection activation, load shedding, controlled islanding, etc.) for when the system is in the emergency or *in extremis* operating state and after a disturbance, analysis and power system restoration. Figure 3 [6] gives an overall

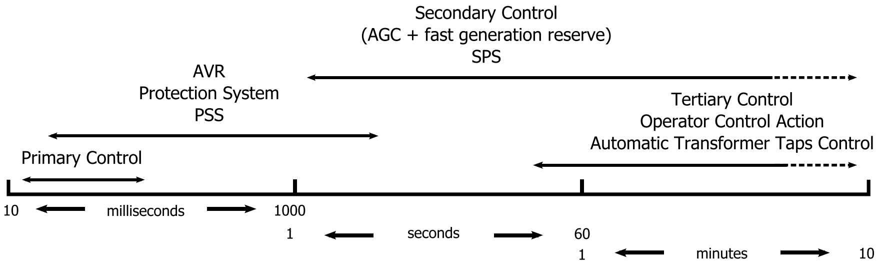


Fig. 3 Timescales for types of control [6]

overview of the type of controls (automatic and manual) present during real-time operation and their time scales.

Load-Frequency Control[1]

One of the requirements of a stable operating point is maintaining power equilibrium. This essentially means that the power generation must equal the power consumption at all times. Disturbances in this equilibrium will result in a deviation of the system frequency from its setpoint (i.e. 50 or 60 Hz). With constant generation, an increase in the demand leads to a decrease in the system frequency, whereas a decrease in the demand results in an increase of the system frequency. This imbalance will initially be offset by the kinetic energy of the synchronous generators and motors. However, this regulating energy is not sufficient to account for both, changes in demand and outages in generation and transmission facilities. Therefore, generators must have sufficient flexibility in changing their generation level.

The overall process for maintaining the power equilibrium involves primary, secondary and tertiary control actions. After the occurrence of an imbalance, primary control will react with the aim of limiting the frequency deviation. After a predefined time interval for its operation, secondary control kicks in. The aim of the secondary control is to restore the frequency back to its nominal value and to restore the primary control reserves. Then, the tertiary control takes over, with the aim of restoring the secondary control reserves or the primary control reserves in case of outages. This process is graphically depicted in Fig. 4 [7].

A deviation of the actual frequency from its setpoint will activate the controllers of generators involved in primary control, in the timeframe of a few seconds. The controllers will alter their generators' output power until a balance is re-established,

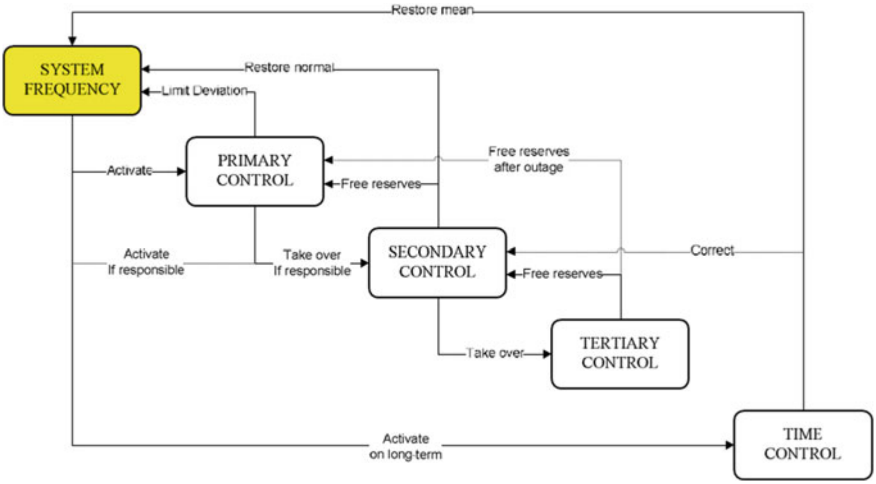
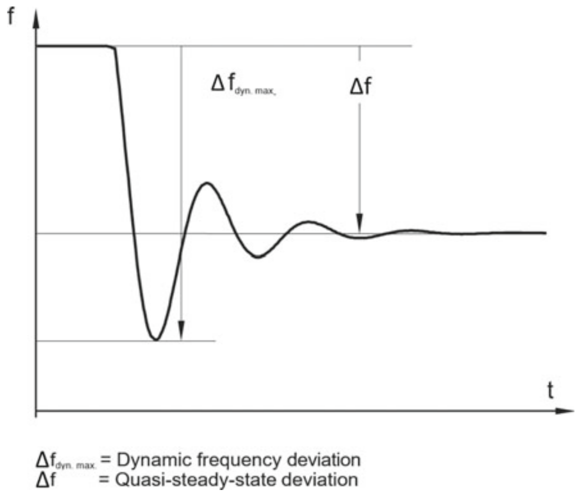


Fig. 4 Frequency control [7]

---

[1] This section is based on [7].

Fig. 5 Frequency response primary control [7]



after which the frequency stabilises around a new quasi-steady-state value. This value is different from the system frequency setpoint, as illustrated in Fig. 5. In this figure, the dynamic frequency deviation ($\Delta f_{\text{dyn.max}}$) is among others dependent on the size of the disturbance and the amount of primary control reserve. The quasi-steady-state frequency deviation (Δf) is among others related to the governor droop settings of turbine generators participating in the primary control.

The contribution of a generator to the correction of frequency after a disturbance depends mainly on the droop of the generator and the primary control reserve (or frequency containment reserve). The droop essentially determines the change in operating setpoint of the generator, following a frequency excursion. In Fig. 6, the droop of two generators (generator a and generator b) are given, where both generators have the same amount of primary control reserve. When a relatively small frequency excursion happens (f_a), the contribution from the generator with the smallest droop (generator a) will have the largest absolute contribution. In the case of major disturbances (frequency offset $\geq f_b$), the primary control reserve of both generators is exhausted.

The target efficiency of the primary control depends on the defined reference incident (e.g. the reference incident for Continental Europe is the loss of 3000 MW generation or load). The frequency performance of a system following the occurrence of the reference incident can qualitatively be given as shown by curve A in Fig. 7. The curves B1 and B2 represent the frequency response after an incident smaller than the reference incident, where curve B1 is the response of a system with more self-regulating loads.

The function of the secondary control or load-frequency control or power control is to keep or to restore the power balance and consequently to keep or restore the system frequency to its predefined setpoint value. The secondary control operates

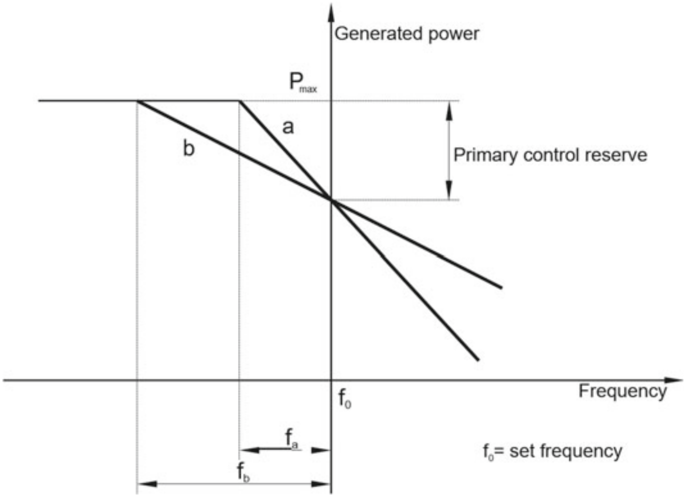


Fig. 6 Primary control of two generators [7]

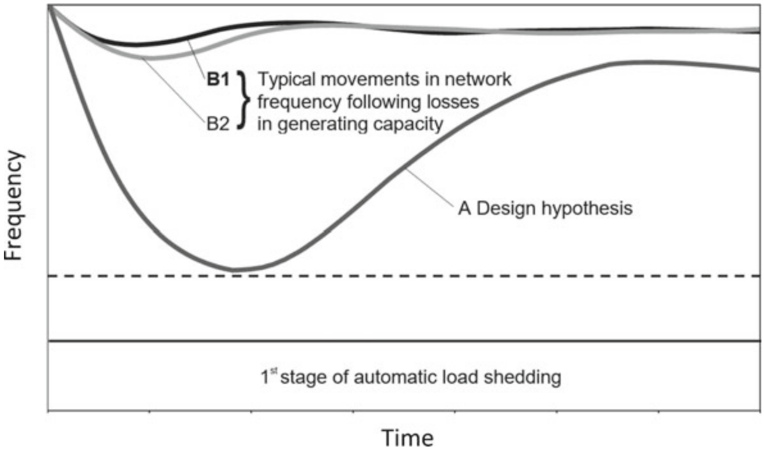


Fig. 7 Frequency response in relation to reference incident [7]

for periods of several minutes (and is therefore timely decoupled from the primary control).

The secondary control is ensured in many countries through the automatic generation control (AGC), which acts in the timeframe of seconds up to e.g. 15 min after a system imbalance. AGC is a centralised and continuous control system that automatically adjusts the selected generation set that is associated with it, in order to maintain the cross-border exchange schedule between control areas and to perform its share of frequency regulation, which is represented by ‘K’ in Fig. 8 [6].

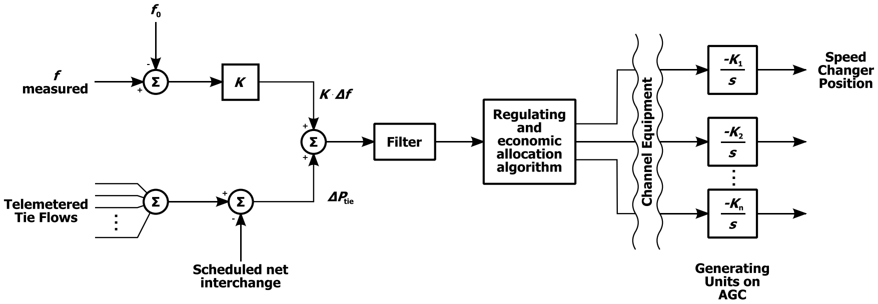


Fig. 8 Automatic generation control scheme [6]

AGC must divide the load variations by the included generating units, which requires suitable monitoring, telemetering, processing and controlling functions to coordinate directly the speed governors of the generating units, in order to impose the necessary power output.

Tertiary control is any automatic or manual change in the working points of generators or loads in order to:

- Guarantee the provision of an adequate secondary control reserve at the right time
- Distribute the secondary control power to the various generators in the best possible economical way.

These changes can be achieved by connecting, disconnecting or increasing/decreasing of generation, by changing the output of generators that are participating in the secondary control, and by means of load control. Typically, the operation of tertiary control is bound to the timeframe of scheduling, but has the same impact on operation as the secondary control.

It should be mentioned that the reserves associated with the primary, secondary and tertiary control are currently predominantly provided by conventional synchronous generation.

Coordinated Capacity Calculation

With the aim of improving the economic efficiency of interconnected power systems, cheaper generation from one control area can be used to cover part of the demand in another control area, which contains more expensive generation. This generation-load combination leads to cross-zonal exchanges, which can use the available cross-border transmission capacity facilitated by HVAC and HVDC connections. However, the available transmission capacity to facilitate cross-border flows is limited by its technical capability and imposed security and reliability criteria. The calculation of this capacity needs to be coordinated to ensure that it is reliable and that optimal capacity is made available to the market. There are two main approaches when calculating cross-zonal capacities: *flow-based* or based on *coordinated net transmission capacity*.

The flow-based approach is a capacity calculation method in which energy exchanges between zones are limited by power transfer distribution factors and available margins on critical network elements. This approach is preferred for short-term capacity calculation in highly meshed and highly interdependent grids. The flow-based approach is, for example, implemented in the Central Western Europe capacity calculation region (CCR), and to be implemented in the future in the Core CCR (including western and eastern Europe), where the methodology is explained in [8].

On the other hand, the coordinated net transmission capacity approach is based on the principle of assessing and defining *ex ante* a maximum energy exchange between bordering zones and can be applied in regions where cross-zonal capacity is less interdependent. The coordinated net transmission capacity approach is, for example, implemented in some regions of Europe and the USA, where in the USA the methodology is defined by the NERC and detailed in [9].

Operational Security Analysis

The aim of the security analysis, consisting of two steps, is to identify possible security restrictions and associated remedial actions after the market closure. For interconnected power systems, the security analysis is mostly a coordinated process, where security assessment and identification of multi-lateral solutions are performed at the regional level.

In the first step, the security is analysed based on the so-called (N-1) security principle. The (N-1) criterion defines that, in a given situation, the transmission grid remains secure when one[2] of the available transmission network elements is lost. In other words, after entering the (N-1) situation, the electrical parameters of voltages, currents and system stability criteria should remain within the defined limits, i.e. equality and inequality constraints are respected (normal or alert state, see Fig. 1). For interconnected power systems, the (N-1) criterion should also take into account that after entering the (N-1) situation the consequences of the disturbance is as much as possible contained within the system operator's control area.

If any violations are detected, remedial actions are identified, coordinated and validated in the second step. Such remedial actions include, but are not limited to:

- Topology changes
- Adjusting settings of power flow control devices such as phase-shifting transformers (PST)
- Changing reactive power compensation
- Reduction of interconnection capacities
- Generation redispatch.

The coordinated security analysis and decision-making process in Europe are coordinated among system operators together with a Regional Security Coordinator (RSC) and encompass the following two timeframes:

---

[2] Under special circumstances, double tripping of transmission lines or loss of busbars are also simulated.

- Day-ahead Congestion Forecast (DACF), which begins in the afternoon after day-ahead market and ends late in the evening (before midnight).
- Intraday Congestion Forecast (IDCF), which begins before midnight and includes an hourly rolling forecast of all remaining hours of a calendar day.

Coordination Among System Operators

In interconnected power systems, coordination is necessary for the capacity calculation, security analysis, emergency situations, restoration and reserves procurement processes due to the interactions and impact among the different system operators. Coordination improves awareness and efficiency when operating the interconnected system.

The need for cooperation and coordination in the operation of power systems started at the same time as the first interconnections of power systems were established. Before the liberalisation and deregulation of the electricity market, utilities in many countries were vertically integrated and were responsible for generation, transmission and distribution. In those days, the interconnection of the power system was mainly aimed at mutual support in case of disturbances. After the unbundling, there was the establishment of system operator (SO) and market operator (MO) organisations, which became important organisations for the cooperation and coordination in the industry. The SO function can, in short, be defined as the responsibility for balancing and operational security of the power system. The MO function can be defined as the responsibility for matching sale/generation and purchase/demand and by this establishing a market price for electricity for physical delivery. The functions performed, the responsibilities and the way they were organised vary, mainly because of history and tradition in the country, regulatory framework or political goals for the electricity sector.

Due to these changes, the interconnected system no longer serves just for mutual support; nowadays, it has become the base platform for trading electricity, allowing the shifting of increasing volumes of power across the system, and it facilitates the increasing integration of RES and it requires the efficient use the network. Therefore, the daily routine of transmission system operators has become more complex and control room operators are frequently faced with complex situations caused by the stressed system operating conditions, and consequently, an increasing need for coordination and cooperation.

Following the 4 November 2006 emergency situation in Europe [10], the European Commission, together with TSOs, starts looking into ways to improve coordination between TSOs to guarantee a secure operation of the interconnected system, maintaining the security of supply. European legislation demands of the TSOs to cooperate more closely, to develop methods and take actions to improve system security of the European transmission grid. Especially, the continuous development of the international trade and the increase of the low predictable wind power generation lead to unexpected and rapid changes of load flows in the interconnected grids of the concerned TSOs. In 2008, two service provider entities, CORESO [11] and TSC [12], were created to fulfil this challenging task. In recent years, also in Europe, there are developments for cooperation in the field of balancing: creation of coordinated balancing areas, which means a cooperation with respect to the exchange of balancing services, sharing of reserves or operating the imbalance netting process between two or more TSOs [13].

Independent System Operators (ISOs), e.g. USA and South America, are entities that do not own transmission assets, unlike TSOs, e.g. in Europe, and among others, are responsible for operating the network reliably and economically and for the coordination with neighbouring control areas, including cross-border trade.

The abovementioned is the so-called horizontal coordination. However, the operational practices become more integrated not only horizontally, but also vertically, increasing the coordination and the information exchange between different players, such as TSO-TSO, TSO-RSC, RSC-RSC and TSO-DSO.

Power System Restoration

Restoration of the power system is an important aspect of a SO's role in managing the bulk power system. Electric power grids in developed economies generally exhibit a very high degree of reliability thanks to the well-established standards and criteria for the design, planning, construction and operations of the integrated network and the close interconnection in certain continents or regions. Despite prudent planning and operations, major interruptions to the electric power grid (complete or partial blackout) do occur from time to time due to events (disturbances) that either exceed the basic design criteria or due to various causes such as multiple equipment failure, protection relay miscoordination or malfunctioning, human errors and natural disasters.

When such disturbances occur, the power system may experience wide-area, regional or local area blackout with or without damages or prolonged outages to major facilities. Restoring the integrity of the electrical grid and supply to end-use customers is of paramount importance to reduce and minimise undue hazard to social welfare, public safety, infrastructure security and business activities.

To help restoring the power system after major disturbances, control centre's operating personnel are trained and provided with a set of guidelines and procedures, defining the strategy, to placing top priority on restoring stable operation of the power system with sufficient skeleton so that resources and power supply to end-use customers can be restored as expeditiously as possible to minimise interruptions to social life and businesses. The key to successful and expeditious restoration thus depends to a great extent on the SO's preparedness, which includes operator training, availability of guideline and procedure documents, effective communication protocols, provision and assurance of blackstart capability, verification of cranking path's sustainability, etc.

Therefore, the objectives of power system restoration (PSR) are summarised as enabling the power system to return to normal conditions securely and rapidly, minimising restoration time and associated losses, and diminishing adverse impacts on society [14].

Despite having the same objectives, a review conducted by the CIGRE C2.23 working group concluded that system restoration preparedness may vary from one

SO to another, or may differ between interconnected systems due to differences in system characteristics and/or market design/rules [15]. In addition, the lessons learnt from actual events suggest that there are challenges which would warrant the exploration of modified or innovative ways to improve the effectiveness and efficiency in system restoration [16]. An overview of the past major incidents is given in Table 3.

System operators regularly conduct restoration exercises, either in a simulation environment or in the real system. In general, there are two basic strategies for power system restoration, namely the *bottom-up* strategy and the *top-down* strategy.

The **bottom-up restoration strategy** is based on the use of blackstart generators (these are able to re-energise the system without external support) and applies in

Table 3 Overview of past major incidents [14]

Date	Location	Lessons learned
14 August 2003	Northeast USA/Canada	Lack of testing and verification of: • Blackstart capability • Cranking path procedure[a]
4 November 2006	Europe	Lack of tools to assist operators to effectively restore the system
10 November 2009	Mid-West and South of Brazil	Lack of testing and verification of: • Blackstart capability • Cranking path procedure
4 February 2011	Northeast Brazil	Lack of testing and verification of: • Blackstart capability • Cranking path procedure
8 September 2011	San Diego, USA	Lack of tools (such as wide-area observability) to assist operators to effectively restore the system
30 July 2012	Northern India	Lack of: • Dedicated communication infrastructure for the power system • Availability and preparedness of personnel at generation stations and substations, leading to high start-up time of the restoration • Tools (such as wide-area observability) to assist operators to effectively restore the system
28 September 2016	South Australia	• Changes in system dynamics with increased amounts of generation from non-synchronous and inverter-connected plants • Unknown critical settings of several generating systems

[a] Cranking paths are transmission corridors that extend from blackstart generation units to the targeted facilities needing offsite power

case of total system blackout and non-existent interconnection assistance. Normally, blackstart units and selected ultra-high voltage transmission facilities are connected to form balanced electrical islands that can be further on synchronised with similar islands to restore the grid and gradually restore load.

Due to many requirements like size, number and location of the blackstart units, points of interconnection, number of necessary control teams (if islands are restored in parallel) and control systems, substation and telecommunication equipment, communication protocols and procedures, it is a regular practice to prepare restoration plans in advance and to update it regularly. These plans must comply with the requirements imposed by regulators or similar authorities.

An example of a restoration exercise using the bottom-up approach is presented. Following the disturbance in the Northern Region of India on 30 July 2012, restoration exercises on the real system are now performed annually. Such exercises have three main components:

1. Creation of an island with the blackstart unit and testing the running of the unit in an islanded environment;
2. Black out in the island and revival of the island according to the bottom-up approach;
3. Resynchronisation of the island with the main grid.

The steps of such an exercise are illustrated in Fig. 9 [17].

On the contrary, the **top-down restoration strategy** is based on neighbouring interconnection, and it applies when such assistance is available. Typically, start-up power is coming through interconnections and is used to establish the bulk power transmission system (backbone) first, using interconnection assistance or

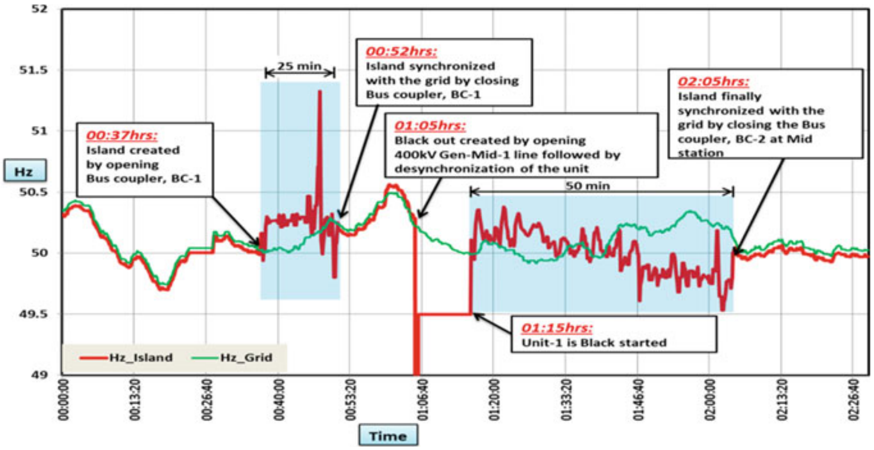


Fig. 9 Restoration exercise by Indian TSO [17]

hydro plants (if available) with large reactive absorbing capability. Then, operators energise loads, start-up generation, balance load and resynchronise such areas to the backbone and finally reconnect remaining loads.

An example of a top-down restoration test was performed in 2013 by Terna (Italian TSO) and Swissgrid (Switzerland's TSO). In this test, the path of 1000 km was energised in 13 min with 4 switching actions performed by Terna. It took another 4 min to synchronise the unit of Presenzano with a ramp of 140 MW. This was possible due to a pre-configured/compensated transmission path divided into 4–5 main sections. Each section consists of several substations and related transmission lines which are energised once after the other. The voltages measured at the Musignano substation in Italy are shown in Fig. 10 [17] for the full restoration exercise.

Both approaches have their advantages and disadvantages, thus many system operators choose a **hybrid approach** to restoration (i.e. combination of bottom-up and top-down strategies), as the best fit for their conditions. In this approach hydro and gas turbine generators are used as blackstart units to facilitate the bottom-up strategy, whereas AC and VSC HVDC interconnections are used as blackstart units to facilitate the top-down strategy. Table 4 gives an overview of blackstart strategies implemented throughout the world.

Operators' Training

Control room operators play a decisive role in the good performance of the power system and to achieve all the essential tasks for which it was designed. The operator's ability to manage a large amount of data, to adequately understand, decide and execute on time suitable remedial actions, is extremely important. Analysis of the recent

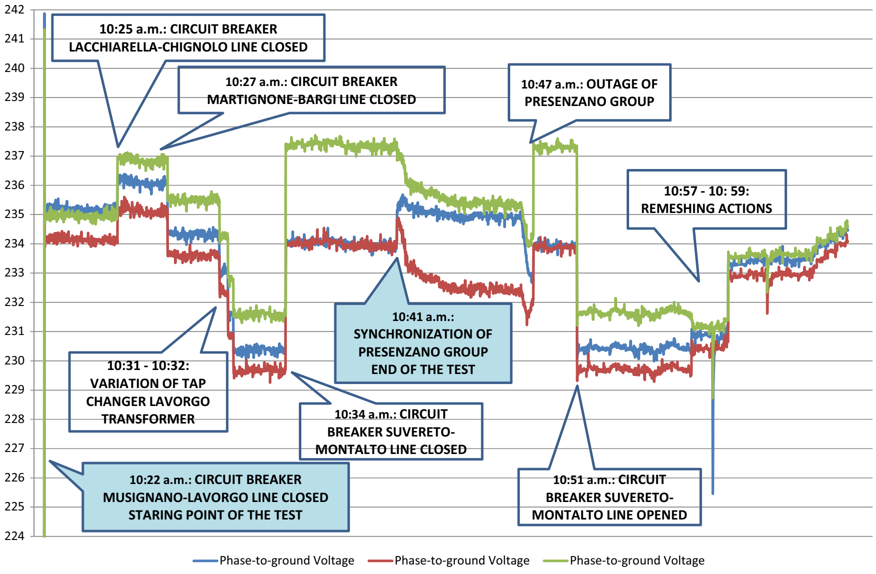


Fig. 10 Musignano phase voltages during execution of restoration test [17]

Table 4 Worldwide strategies for blackstart

Country	Approach	Blackstart: top-down	Blackstart: bottom-up
Australia	Hybrid	AC interconnections from bordering states	Hydro + pumped storage + gas turbines
Brazil	Hybrid	LCC HVDC + AC interconnections	Hydro
India	Hybrid	AC interconnections from bordering states	Hydro + gas turbines
Ireland	Hybrid	VSC HVDC + AC interconnection	Hydro + pumped storage + gas turbines
Italy	Top-down	AC interconnections from bordering national power system	
USA	Top-down	AC interconnections from bordering states	

emergencies and blackout incidents suggests that mistakes by system operators are a significant contributor, being just the second main cause of these events (with natural disasters being the first) [16].

The consequences of system operator errors, i.e. their extent and severity, depend not just on the current power system state and available system resources (including reserves), but also on operator actions and the available and activated defence measures (from predefined defence plans).

Generally, operational mistakes can be attributed to several reasons, such as

- Insufficient situational awareness;
- Mistakes in control decisions due to incomplete mental model of the process or incomplete analysis;
- Incorrect interpretation of constraints;
- Incorrect interpretation of conditions under which protection acts;
- Misjudgement of the effects from the initiated control actions;
- Misunderstanding in communication.

Based on the above-listed reasons, available and related defence measures can be identified. These are divided into measures aimed to reduce the likelihood and measures aimed to reduce the impact of such events.

Emergency-related defence measures associated with the operator errors, although not simple to design, maybe developed, procured and implemented. However, insufficient operator training can increase the likelihood of operator errors and thus reduce the effectiveness of other preventive measures. Training must be aimed at the development of operator knowledge, skills and decision-making abilities, especially for handling complex fast-developing emergencies and different type of disturbances. This can be done through systematic and permanent education and training processes that include on-the-job training and learning from previous large disturbances, especially those with operator error involvement, along with the root cause and/or contributing factors analysis.

Within this process, the operator/dispatcher training simulator (OTS/DTS) plays a very important role, since OTS-supported processes can increase human operator capabilities to analyse complex, fast-evolving situations to aid decision-making and taking prompt and proper actions.

Several other aspects can also positively contribute to the reduction of number and consequences of operator errors:

- Better ergonomics or improved coordination/interaction in the control room;
- New and improved application support software, relevant to emergency states, that can speed up detection and classification of the power system state;
- Integration and better presentation/visualisation of the existing data and information;
- Timely development of training requirements for operators involved in inter-TSO coordination.

Training Goals, KPIs and Training Methods

Operator training goals are normally not part of higher, corporate level goals. Training is performed in all companies that were surveyed in [18], but in different forms and using different KPIs, where the organisation and coordination of the training are done internally.

Figure 11 [18] illustrates the frequently used training goals. The training of the operators covers several operating conditions, including blackstart and restoration procedures.

Likewise, KPIs used across different utilities to evaluate operator training is given in Fig. 12.

The results show that there is wide variation in KPIs used to measure training performance. The KPI based on a qualitative rating is used by most companies to define training success.

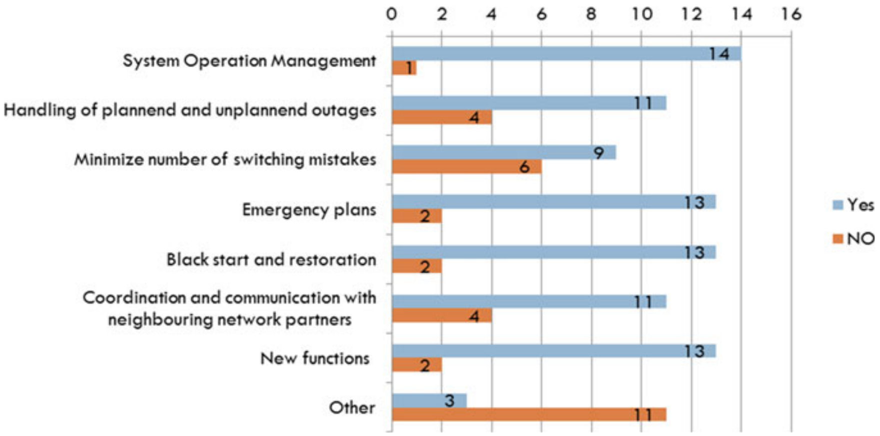


Fig. 11 Training goals frequently used, $N = 15$ [18]

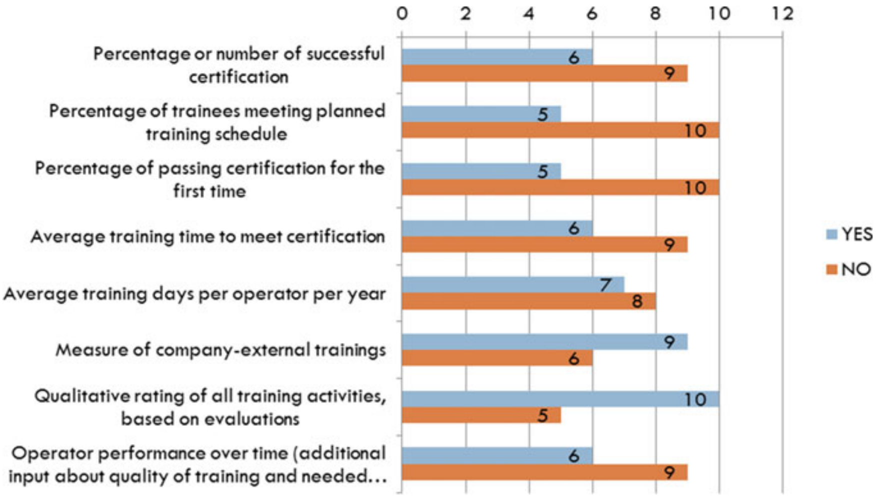


Fig. 12 Frequently used training KPIs [18]

The training itself can be done in different ways, from lectures over OTS to innovative e-learnings. Lectures, site visits and on-the-job training are done by almost all companies surveyed in [19], while OTS training is performed with slightly lower frequency as shown in Fig. 13 [18].

E-Learning is an upcoming training method, owing this to its flexibility with respect to time and place. All these training methods have advantages and disadvantages, and therefore, a mixture of different methods can provide a good balance.

Training Content

For effectively handling the emergency and restoration power system operation states,

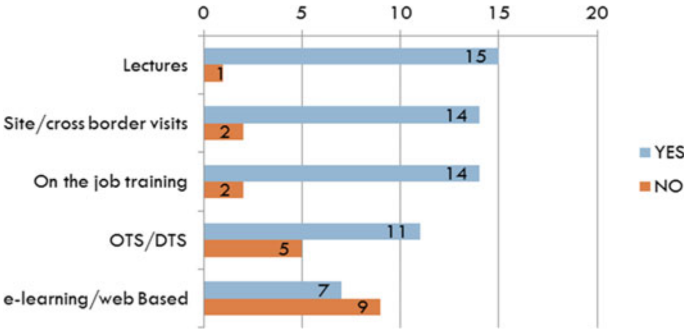


Fig. 13 Training methods used, $N = 16$ [18]

an advanced set of training modules is needed to raise the operator's knowledge and skills. Such a training module would contain, for example:

- Principles of power system dynamics
- Principles of power system stability controls
- Identification of possible emergency states
- Operation of the power system in the emergency state
- Handling power shortage situations (i.e. generation adequacy)
- Principles of load shedding
- Power system restoration principles and procedures.

Operator Training Tools

The main tool for restoration training today is an OTS, also known as dispatcher training simulator (DTS). The survey conducted in [19] identified that 80, 90 and 90% of those with an OTS use it for training of conditions with normal power system state, for emergency handling and system restoration, respectively. After the major incidents that occurred worldwide in the last 10–15 years, we can expect that almost all companies that do use an OTS/DTS for operators' training, use it extensively for emergency handling and restoration training.

An example of an OTS/DTS architecture, including subsystems power system model (PSM), control centre model (CCM) and instructional subsystem (ISS), is illustrated in Fig. 14 [19].

The PSM is responsible for the realistic representation of all basic power system elements (generation, network and consumers, together with their main control and protection devices). Apart from modelling, this subsystem also includes algorithms that simulate all relevant dynamic behaviour of the power system.

The CCM is responsible for the exact representation of the power system control centre equipment (typically SCADA/EMS system) that operators use in their daily

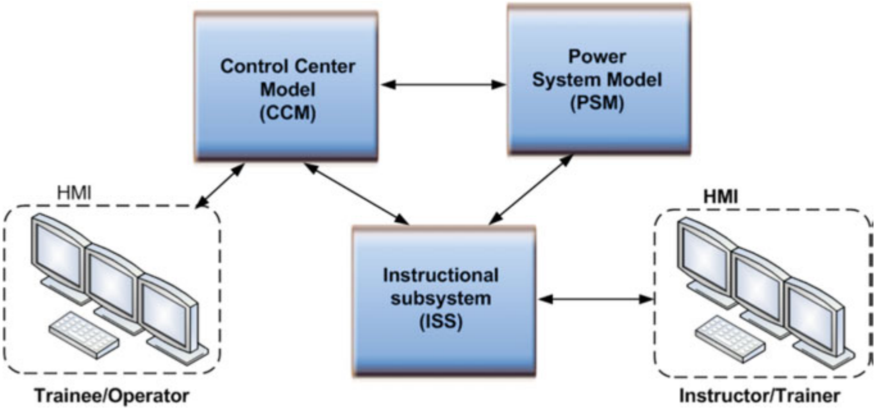


Fig. 14 Traditional OTS/DTS generic architecture [19]

work to monitor, analyse, support decision-making and finally control the system. The operator training on a replica of their SCADA/EMS system yields the highest possible training effect, though use of generic CCM is possible too (mainly for improving understanding of the power system reaction on the operator's actions).

Finally, the ISS should enable the instructor to monitor and control (start, stop, pause) a training session, introduce events, emulate other non-modelled parties and support creation, validation and maintenance of training scenarios.

In the simulator training environment, the operators can train under task-relevant stress conditions, i.e. conditions that characterise real-life incidents/restorations should also be recreated during the training session. Stress conditions can, for example, be emulated with additional (numerous) phone calls, by shortening of some time constraints or resources, and/or by the introduction of unknown events.

3 Stepping into the Future of System Operations

The worldwide energy landscape is undergoing a transition, of which the pace is different in different parts of the world. From a system operation's perspective, the main contributing factors identified with regard to this ongoing energy transition are: large penetration of power electronics interfaced devices (PEID) and the transition to variable renewable energy sources; new regulatory framework; and the increasing difficulty of building new transmission lines. This impacts the operation of the electric power system, from the operational planning until real-time operation, for which system operators have to be prepared to ensure the security of supply to all customers with current reliability levels.

A rapid technological change is taking place from traditional rotating machines to power electronics interfaced generation (PEIG) and load and from pure AC systems to hybrid AC/DC systems.

The transmission system-connected conventional synchronous generator is increasingly being replaced by transmission- and distribution-connected variable renewable energy sources (RES) such as wind and solar generation, which are intermittent and uncertain in nature, introducing a volatile production pattern in the generation mix. System operators need to cope with operational conditions where almost no conventional synchronous generator is available due to high RES production, but also with operational conditions where wind and sun are not present. In addition, the location of the generation dispatch becomes more volatile and, depending on weather conditions and market behaviour, the production may be located regionally, also at the distribution level or even offshore. Markets with large penetration of RES tend to have more volatile prices and fewer periods in which conventional power plants can compete and, consequently, fewer running hours for many conventional plants, which decrease their competitiveness in the day-ahead and intraday market.

Second, the regulatory framework influences the design, planning and operation of the power system. Network codes and requirements have to be able to keep the development pace providing the adequate framework to cope with the upcoming needs. Harmonised regulatory framework is imperative not only on transmission, but also on distribution level. Unfortunately, this evolves at medium speed.

Lastly, increasing opposition for new overhead lines combined with high costs for and lack of expertise in design of long underground cables, result in a slow pace of realisation of new transmission facilities. The very long times to build additional transmission capacity increases the likelihood of operating the system with congestion management schemes and also closer to the security limits.

Taking these observations into account, the energy transition poses an important operational challenge for system operators: ***how should the future, non-traditional, low inertia power system be operated, while guaranteeing at least the same level of operational reliability of today, at affordable cost?***

More PEIG creates several challenges for the electricity system: voltage, frequency and transient stability phenomena might occur more frequently. Section 3.1 first gives a brief overview of major operational challenges that operators could expect in the future as a result of the ongoing energy transition. Then, some key developments required for confidently stepping into the future are discussed in Sect. 3.2. These focus on new services, flexibility, cooperation and coordination, and sector coupling. In Sect. 3.3, the evolution of the control centre as well as new requirements with regard to operator training are presented.

3.1 Foreseen Operational Challenges

Throughout the world, the introduction of PEIG comes with different flavours: energy policies with different support schemes for RES and tariffs for connections to the grid can be found. In some regions, there is a strong boost of offshore wind power connections, while others focus on the integration of onshore wind power and PV. Independent of the primary energy source, the integration of these RES is happening at an enormous pace. As a result, there are differences in the generation mix throughout the world, which is then reflected in the type of operational challenge that emerges. Depending on the grid structure and type, location and amount of load and generation, there will be an increasing challenge to guarantee the same level of operational security and power quality in the future.

System Stability Issues

Figure 15 [20] gives an overview of eleven power system stability challenges resulting from the energy transition as identified by TSOs in Europe. These issues were divided into four categories: rotor angle stability (two issues), frequency stability (two issues), voltage stability (five issues) and a category others (two issues). The decrease of synchronised inertia (frequency stability, issue 3) was perceived as the most crucial issue by these TSOs [21]. It is also already of major concern in, e.g. Australia [22], Ireland [23] and Texas, USA [24].

The inertia within today's power systems is largely provided by synchronous generators and the mechanically coupled turbines of conventional power plants.

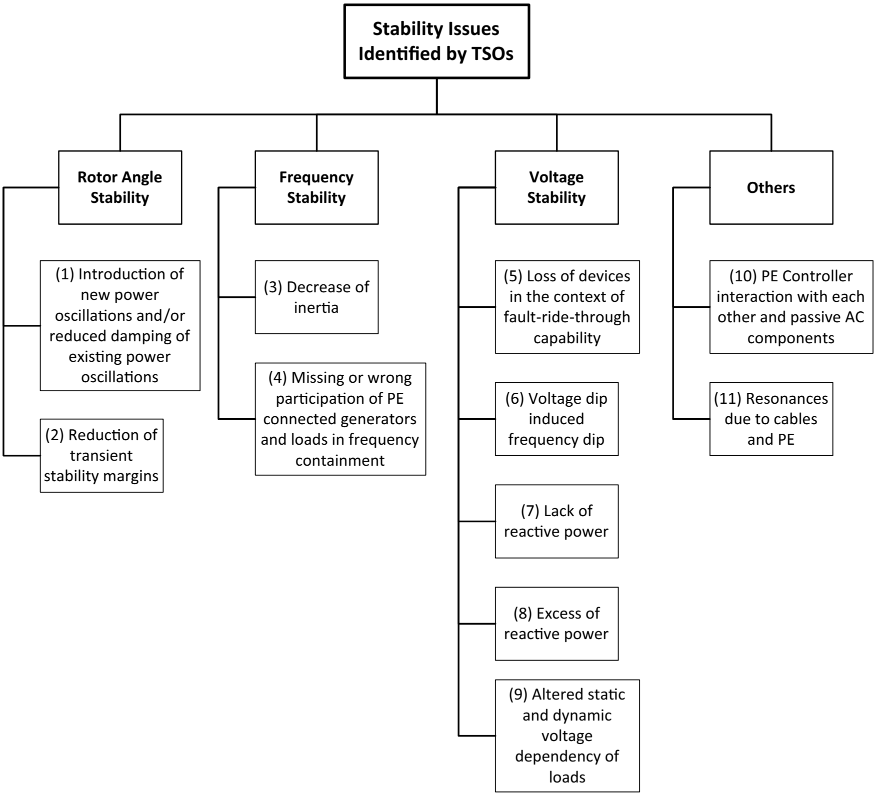


Fig. 15 Stability issues from MIGRATE [20]

Less and less conventional synchronous generators remain connected to the grid, leading to a decrease of inertia. That is why, in certain synchronous areas, inertia development is already being monitored and minimum inertia requirements are being implemented in operational timeframes. Furthermore, large hourly volume changes of cross-border trade introduce high power ramping rates, resulting in increased and larger frequency deviations, which have to be solved in a coordinated way by TSOs.

As long as there is no supplementary control, the PEIG decouples the electrical and the mechanical (or in case of PV the photoelectric) part of the generating device, which results in a lack of inertial response to variations in the grid frequency. Additionally, the directly grid-connected motor load is also increasingly being interfaced with converters. Both aspects lead to a significantly reduced remaining inertia of the power system [25–27]. While the power system's inertia decreases, the reference incident, which is the other main factor influencing the rate of change of frequency (ROCOF) and the frequency nadir, remains constant or even increases. Both effects combined lead to higher ROCOFs and dynamic frequency nadirs or peaks. As an example, Fig. 16 [26] shows the frequency versus time for the same incident with

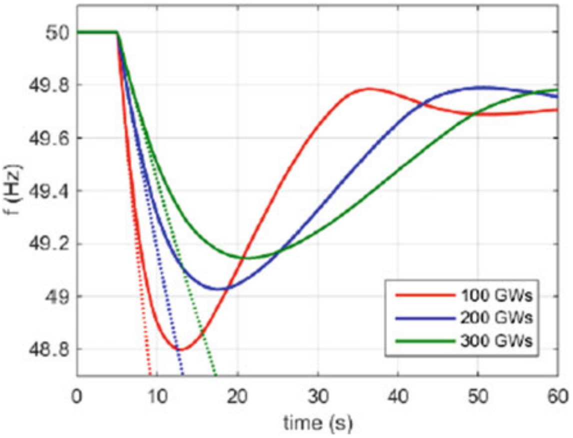


Fig. 16 Effect of the amount of inertia on the behaviour of frequency after the loss of generation with (solid) and without (dotted) FCR [26]

three different amounts of inertia expressed as the energy stored in the rotating masses in GWs. The dotted lines exclude frequency containment reserves (FCR), i.e. primary control reserves, and load reaction and therefore show a frequency decrease with the initial ROCOF. The solid lines include FCR.

Another impact of the displacement of conventional synchronous generation is the reduction in system strength [28]. System strength is usually described in terms of available fault current (or fault level in MVA). It is an inherent characteristic of any power system and is a means to describe the network's ability to withstand variations in active and reactive power flows as well as its resilience to network disturbances. It is a useful measure for quantifying system robustness following a disturbance. Typically, higher fault levels are associated with stronger power systems, i.e. meshed networks with multiple transmission lines and generation sources contributing fault current. Such networks typically have a better ability to stabilise voltages following disturbances (small or large). In comparison, weak power systems are typified by lower network fault levels and more volatile voltage deviations. Other consequences of reduced system strength are the reduced sensitivity of certain protection devices due to reduced fault currents (see Fig. 17) [29], increased probability of HVDC LCC commutation failure [30] and instability of the phase-locked loop of power electronic converters [31].

Congestion Management Issues

The characteristics of RES concerning variability and uncertainty impact generation dispatch, system balancing and the power flow pattern in the network. Mainly wind generation is often installed in the transmission system far away from consumption centres. This will create more volatile, and longer distances, even cross-zonal, power flows across interconnected systems, resulting in a more utilised power system being operated closer to its security limits. Another factor is that physical flows do not coincide with realised schedules due to, e.g. portfolio management of market players. As a consequence, the dependency from available remedial actions is

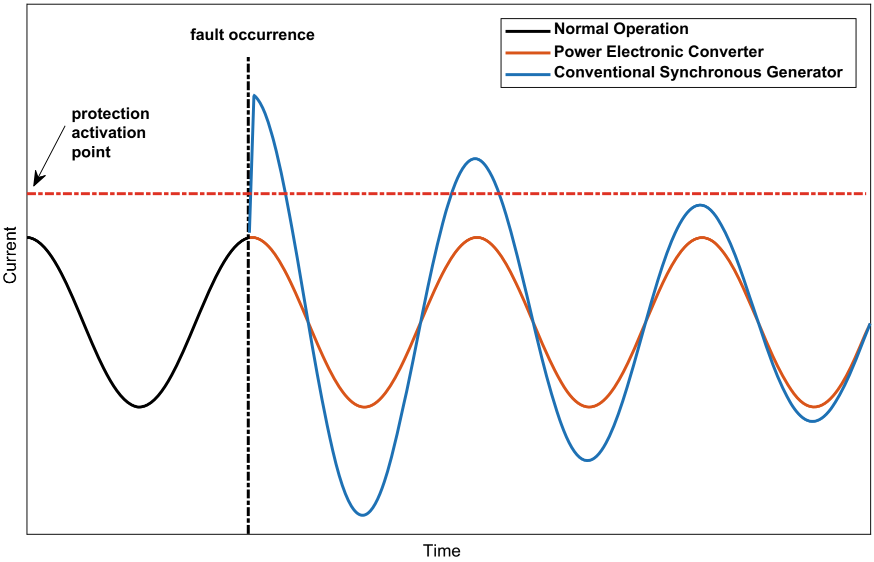


Fig. 17 Protection activation versus fault level: synchronous generation versus PEIG [29]

increasing. In addition, increasing penetration of RES limits the availability of both active and reactive power reserves, including costly redispatch possibilities, which are essential for network security, as the increasing competition causes an increase in decommissioning and mothballing of power plants.

The need to find operational strategies to cope with this becomes increasingly important.

3.2 *Finding Solutions*

To maintain acceptable levels of operational security, enhancement of observability, controllability and flexibility is required. For instance, ancillary services can be delivered by efficiently utilising the capabilities of power electronics interfaced technology. In addition to RES, battery energy storage systems (BESS) and electrical vehicles are expected to play an important role in ensuring secure operation of the future power system.

The operational practices will become more integrated vertically and horizontally, increasing the coordination and the information exchange between TSO-TSO, TSO-RSC and TSO-DSO. Additionally, the development of new methodologies, tools and criteria is also essential to operate the power system in a more complete, integrated and coordinated way.

Requirement for New Services

While facilitating increasing levels of RES, new services will be required. These services are power system-specific and their need could be different across different systems. Some examples of such new services, designed for Irish power system, are [32]:

- **Synchronous inertial response**: Incentivises synchronous plant with higher inertia and lower minimum generation levels, including synchronous condensers. This product is required to help keep more inertia on the system at times of high wind output and help arrest high rates of change of frequency after faults or generator trips.
- **Fast frequency response**: This is a reserve product which aims to provide an active power response in advance of primary operating reserve, supplementing any inherent synchronous inertial response. FFR is defined as the additional increase in MW output from a generator or reduction in demand following a frequency event that is available within a predefined and system-dependent time interval. This product will increase the time to reach the frequency nadir and mitigate the ROCOF in the same period, thus lessening the extent of the frequency excursions during power imbalances. There are multiple ways of providing FFR. One of the methods currently being investigated is the synthetic inertia concept.
- **Dynamic reactive response**: This is an inherent response from synchronous generators which helps maintain the integrity of the transient angular stability of the power system. At high levels of instantaneous penetration of non-synchronous generation, there are relatively few conventional (synchronous) units left on the system and the electrical distance between these units is increased. The synchronous torque holding these units together as a single system is therefore weakened. This can be mitigated by an increase in the dynamic reactive response of PEIG during disturbances. It should, however, be kept in mind that the fault current contribution of PEIG is significantly lower compared to conventional synchronous machines.
- **Ramping margins (1/3/8 h)**: The management of variability and uncertainty is critical to a power system with high levels of wind penetration. The ramping margin (RM) products will incentivise the portfolio to provide the necessary margins to securely operate the power system. Ramping margin is defined as the guaranteed margin that a unit provides to the system operator at a point in time for a specific horizon and duration. Horizons of one (RM1), three (RM3) and eight (RM8) hours with associated durations of two, five and eight hours, respectively, are proposed.
- **Fast post-fault active power recovery**: Fast active power recovery can assist in mitigating high ROCOF values following transmission faults. If a large number of generators do not recover their MW output following a transmission fault, a

significant power imbalance can occur, giving rise to a severe frequency transient. This product is designed to address the voltage-dip-induced-frequency-dip phenomena.

Following the South Australian blackout system event in September 2016, updated generator licencing conditions for all types of generating systems in South Australia were determined by Essential Services Commission of South Australia (ESCOSA) in August 2017 [33]. New requirements include (but are not limited to) enhanced frequency control capabilities, mandatory provision of ramp rate controls, enhanced voltage and frequency disturbance ride-through capabilities (including a requirement to ride-through a certain number of faults in quick succession), maximum active power recovery rates following FRT and minimum levels of reactive power injection during voltage depressions, minimum system strength withstand capability and the ability to assist in system restoration following a blackout event. This was then used as a basis for developing generator technical performance standards for all five regions in the national electricity market. These new requirements were determined by the Australian Energy Market Commission in October 2018, where some of the key differences with the ESCOSA licensing conditions includes the exclusion of requirements on system restoration support and system strength withstand capability [34].

It is also crucial to consider the opportunities delivered from new technologies. In South Australia, there currently is a 100 MW (129 MWh) BESS installation at Hornsdale, and a 30 MW (8 MWh) BESS installation at Dalrymple. One of the aims of these batteries is to provide frequency control ancillary services. Successful operation was demonstrated on 14 December 2017. The battery in Hornsdale provided fast frequency response and discharged with millisecond response (see Fig. 18, [17]) to quickly arrest the frequency excursion following a trip of a 560 MW coal-fired power plant. On a smaller scale, two government launched schemes in South Australia could see 90,000 new batteries with up to 400 MW of controllable storage connected to the network at the distribution level.

Provision of ancillary services from renewable generation is another ongoing development in several parts of the world, whereas in certain systems it is even mandatory. In Spain, RES generation is already providing voltage control and balancing reserves (secondary reserve, tertiary reserve and replacement reserve), including congestion management [35].

In 2016, a pilot project was initiated in the Netherlands with six parties (TenneT, NewMotion, Senfal, Engie, Peeeks and KPN) providing FCR (primary control) by aggregating the responses from a pool of assets (e.g. electrical vehicles, heat-pumps, Bio-CHPs, battery installations, wind turbines and residential energy storage). The goals of the project were:

- to prepare for a future with less large-scale generation by investigating the technical feasibility and barriers for entering the ancillary services market with a pool of aggregated assets and/or new technologies such as renewable energy sources and demand response;

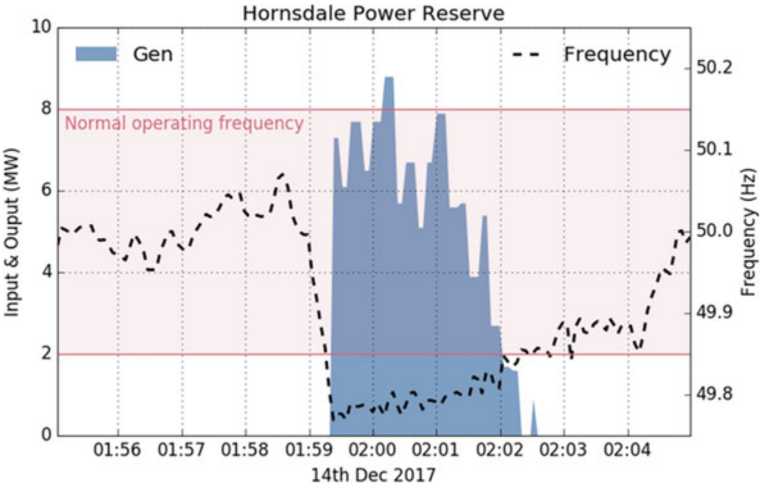
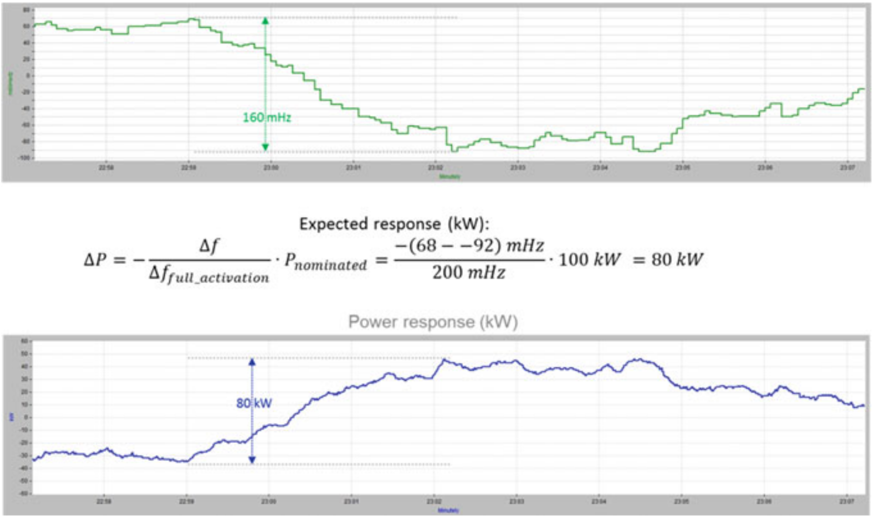


Fig. 18 Hornsdale power reserve response to disturbance of 14 December 2017 [17]



Expected response (kW):

$$\Delta P = -\frac{\Delta f}{\Delta f_{full\_activation}} \cdot P_{nominated} = \frac{-(68 - -92)\ mHz}{200\ mHz} \cdot 100\ kW \ = 80\ kW$$

Fig. 19 Response of FCR pilot assets to frequency deviation [36]

- to provide a level playing field for different technologies and where possible reduce the existing barriers for market parties aiming to join the ancillary service market;
- to facilitate an efficient ancillary service market with a wide range of market parties and sufficient competition.

Figure 19 [36] shows the power response to a frequency deviation. Based on monitoring results, it was concluded that most of the time delivery of FCR was sufficient. The main barriers to participate in the FCR market appeared to be the real-time data communication with a leased line to TenneT and the measurement requirements for a pool.

At the end, all these new services aim to increase the power system's flexibility, which is needed to facilitate increasing RES generation, as will be illustrated in the next section.

Increased Flexibility

The variable production of RES combined with fluctuations from demand-side results in a net-load profile of high volatility. Flexibility can be defined as the power system's ability to manage expected and unexpected changes in the system's operating condition. It is needed to manage equipment failure, load fluctuations and, to cope with the variability in RES generation [37].

In the future, more players and technologies are expected to play a role in the provision of system flexibility. Together with technology integration and utilisation, more flexible market products, with an increasing number of players, maybe one of the solutions to enhance flexibility, both for upwards and downwards direction.

Within power systems, flexibility is preferred across the following segments [38]:

- Generation: generation facilities that have high ramping capabilities and/or deep turndowns[3] are preferred;
- Transmission: grid interconnections and smart network technologies that better optimise transmission usage and increases controllability of flows (e.g. PST and HVDC);
- Demand: demand-side management, enabling customers to respond to market signals. Battery energy storage systems, electrical vehicles and flywheels also provide flexibility that fit in this segment. Digitalisation and the Internet of things concepts will enable large numbers of customers to participate in the electricity sector and to provide flexibility services for the electricity system such as balancing, congestion management and voltage support. Intelligent or smart services will be provided as well by smart controls of buildings and individual households being part of smart cities, local energy communities or microgrids;
- Operations: practices that help extract flexibility out of the existing physical system, such as shorter market time units and increased accuracy of forecasts.

Generation and demand flexibility can be characterised by three indices: ramping limit, power capacity and energy capacity. The ramping limit is defined as the maximum change a flexibility source can accomplish on its operating point in a certain time. Ramps can be steep when large fluctuations in wind speed or irradiation coincide with rapid demand changes. The power capacity refers to the minimum and

---

[3] Operation of dispatchable generations at low levels. High wind speeds and irradiation during low load, creates the need for generators to turn down their output to low levels, but remain available to ramp up again.

maximum power outputs of any generation source. The energy capacity concerns the fuel or energy supply of a power source.

Without sufficient flexibility, system operators may need to frequently curtail wind and solar generation, and may not have enough resources to solve network congestions. Although low levels of curtailment may be a cost-effective source of flexibility, significant amounts of curtailment can increase the return on investment, impact investor confidence in renewable energy revenues and slow down the energy transition. Therefore, flexibility is regarded as a basic prerequisite for allowing higher RES penetration in an economical way as is shown in Figs. 20 and 21 [39]. Figure 20 shows for a specific study by ERCOT the fraction of curtailed wind generation as a function of the wind generation penetration level and amount of flexibility. Flexibility, in this case, is provided by the conventional generators. The general conclusion from this figure is that for the same amount of curtailed wind generation, increasing levels of flexibility enables higher penetration of renewable energy sources.

The same conclusions can be drawn from Fig. 21, where the flexibility is provided by storage. Having massive RES connected to the electricity system means an even bigger dependency of generation related to weather conditions. Consequently, one might expect that solutions to that should also be found in ways to create a flexible demand side. TSOs need to be able to deal with relatively long periods (2–3 weeks) without sufficient wind and sunshine at the same time. This scenario is a very real one as the example of Germany in winter 2016/2017 has shown with the so-called Dunkelflaute [40]. In such cases, large storage facilities could be an ideal technical (but not yet an economic) solution.

In principle, such services should be defined in a way that they are technology-neutral. It is obvious that TSO and DSO roles and responsibilities as system operators

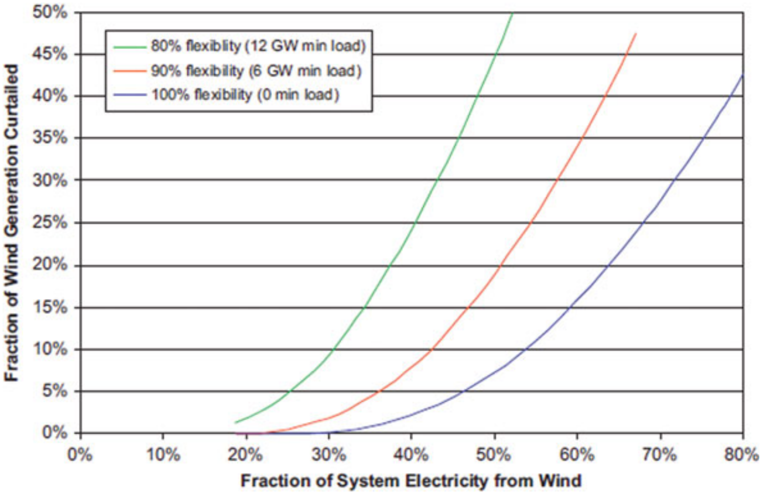


Fig. 20 Total curtailment as a function of usable wind energy penetration for different system flexibilities [39]

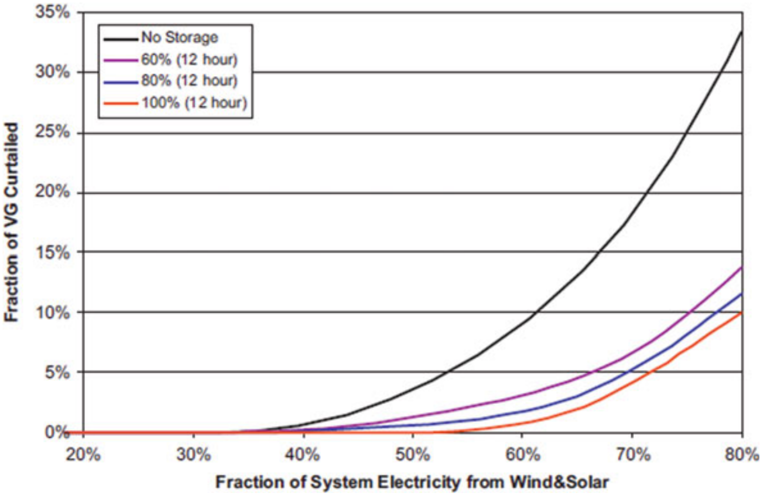


Fig. 21 Total curtailment as a function of variable RES penetration for different amounts of storage efficiencies [39]

and as neutral market facilitators need to be well recognised and respected. Creating an efficient level playing field and incorporating a non-discriminatory and market-based approach to market parties providing new flexibility services is part of these responsibilities.

Increased Controllability

PEID have a higher level of control possibilities that can be developed to enhance system operations and network stability, such as synthetic inertia, grid forming controls, supported system restoration, active and reactive power control, power oscillation damping, among others.

Grid forming control concepts implemented to RES and storage devices could enhance the stability of the system. The new grid forming schemes could ensure a natural voltage-source behaviour of PE and not a current control behaviour as it is the case for the current PE applications that utilise the grid following control concept. Grid forming control could remove the PE dependency on the short-circuit power levels in the network and could provide local frequency smoothing capability. Although the EU connection codes provide the framework to demand synthetic inertia, the implementation of this capability is still under development. Grid forming controls is a more novel concept, not required yet in the connection codes. The implementation of both control concepts needs further development and harmonisation. A classical solution to improve system stability is the use of synchronous condensers, which are often the selected alternative to power electronics interfaced devices, providing inertia, short-circuit current and voltage control.

In the transmission network, grid interconnections and smart network technologies are required to better optimise transmission network utilisation and to increase controllability of flows (e.g. PST and HVDC). The increasing need for power transmission capacity, both internal and cross-border, has made HVDC technology an important element towards the cost-effective and efficient integration of RES. The inherent controllability of HVDC links could be used to solve part of the system operation challenges, such as the possibility to set and control active power flows within the network. In the meshed AC/DC system, embedded HVDC links could be part of the optimised remedial actions to mitigate congestions and minimise costs, to minimise AC system losses and to keep adequate voltage profiles. In addition, FACTs systems integrated with storage not only increase system controllability, but can be used to optimise system operation, controlling active and reactive power flows. The primary active power source could be battery storage or other fast active power sources such as flywheels or supercapacitors, depending on the time constants that are needed for the specific system application.

Finally, the development of adaptive protection systems and wide-area control systems, capable to operate in different operational conditions, may require further investigation in a power system with high PE penetration and more volatile short-circuit power levels. In Iceland, a control system based on WAMS is currently operational for controlled islanding of the system, following a disturbance [41].

System's observability improvement is another crucial point to take into account in the future in order to be able to cope with the energy transition. The enhancement of observability will be tackled in the control centre evolution chapter, because it is strictly connected with the operational planning and real-time activities.

Enhanced Cooperation and Coordination

For highly meshed grids, an improved regional cooperation and coordination in all operational processes and timeframes is of key importance to resolve operational challenges. Enhancement of regional cooperation and coordination among countries need to be supported by further harmonisation of the regulatory foundation coming along with the implementation of new legislation.

Cooperation and coordination among Member States in Europe is being prescribed in the risk preparedness regulation [42], where scenarios on how to deal with crisis events from a regional perspective are developed. In Europe, the regional security coordinators will give support to TSOs for the regional operational planning covering more Member States. An example where coordination is key is for the optimal use of the multiple phase-shifting transformer across Continental Europe.

In North America, coordination among the Reliability Coordinators is prescribed in Standard IRO-014-3 [43] and aims at ensuring that each reliability coordinator's operations are coordinated such that they will not adversely impact other reliability coordinator areas and at preserving the reliability benefits that come from interconnected operations.

Besides inter-TSO coordination, cooperation and coordination of TSOs and DSOs is essential to activate all possible flexibility resources. Increased data exchange between TSOs and DSOs should enable increased observability and controllability of the available flexibility resources at both the transmission and distribution level. For that reason, the so-called observability is of TSOs need to be further developed in a vertical direction in order to see relevant grid elements on DSO level and vice versa. In this sense, cybersecurity is a crucial precondition and if a high impacting event takes place, appropriate measures should automatically take care that the criteria for resilience are met. Resilience is defined as the ability to limit the extent, severity and duration of system degradation following an extreme event. To further increase the resilience of the electricity system, regional risk preparedness plans are developed that enable mutual support in case of crisis situations. Such plans are then also trained on a regular basis among the stakeholders.

The impact of activating flexibility resources on one or the other voltage levels can then be taken into account, while sharing of metering data also enables adequate settlement. Data quality of exchanged large volumes of data should go hand in hand with improved decision support tools that make use of sophisticated algorithms (artificial intelligence). More data has to be processed in shorter time cycles to be of added value to the operator. This will also mean that new concepts for a combination of congestion management and balance management can be applied and optimised to increase even further the efficiency of the whole electricity system. In other words, this will enable a single system approach for the benefit of all customers, where a continuous trade-off between sustainability (decarbonisation), security of supply and costs is considered. It becomes increasingly important that all types of network users (generation, demand, distribution networks) play an active role in providing the capabilities and ancillary services, without negatively affecting neither distribution nor the transmission systems.

With the emerging integration of HVDC interconnections combined with the high pace of RES connections and low pace of development of new/upgraded transmission facilities, attention should also be given to the coordinated security analysis. As mentioned previously, the security analysis is based on the (N-1) principle. There are already ongoing discussions to deviate from this fundamental (N-1) principle, with the aim of speeding up RES integration even further. A critical part of the discussions covers the issue whether or not to apply a probabilistic approach for grid planning, i.e. should the grid be designed for a 100% RES peak or do we accept a system that is designed to accommodate less than 100% RES peak. Further investigation is then needed to assess the impact of this on the dimensioning of the required load frequency and balancing reserves.

Independent of the case, it is evident that increased vertical and horizontal cooperation and coordination is essential to securely operate the future power system. Table 5 summarises some major benefits of this coordination.

Sector Coupling

Whereas the previous section elaborated on the need for increased cooperation and coordination *within* the electricity sector, this section will elaborate on the possibilities of cross-sector cooperation, also known as *sector coupling*.

Sector coupling is the integrated approach by all sectors and will create possibilities of energy conversions between electricity, heat and gas. Expectations are that more electrification will take place, thus increasing the load in the system on the one hand and further pointing out the necessity of having storage services at hand.

Table 5 Overview of benefits from TSO-DSO and TSO-TSO cooperation and coordination

TSO-DSO cooperation and coordination	TSO-TSO cooperation and coordination
Management of bidirectional flows	Efficient calculation of interconnection capacity
Increased observability and controllability of DER by increased data exchange between TSO and DSO	Enhanced operational security (e.g. coordinated security analysis, management of critical grid situations)
Provision of ancillary services by DSO-connected devices: • Blackstart services • Frequency control • Voltage control	Guaranteeing transmission adequacy (e.g. coordinated outage planning) and generation adequacy
	Frequency management (primary reserve distribution between TSOs)
Congestion management at DSO and TSO level	Congestion management at TSO level
Restoration support (top-down approach)	Restoration support (top-down approach)

In order to make an efficient transition to a sustainable energy system, it is necessary to use all the available technologies in a smart way. As a first step, it seems to make sense to convert excess energy in one sector to energy in another sector where there either might be a shortage, or more storage capacity or flexibility. However, such coupling also brings along interdependency and more exchange of information. One should not forget that interdependency between sectors and more digitalisation could lead to a number of risks (e.g. more vulnerability for all systems together and cybersecurity), but also opportunities (e.g. additional redundancies).

The electricity system, on the one hand, allows the production of large quantities of renewable energy, but it cannot provide long-term storage, except for the already available large hydro reservoirs (including pump storage) in some countries. To be able to use such storages also in a wider region often means the necessity to create stronger interconnections. On the other hand, the gas system's ability to incorporate large quantities of renewable energy is limited, but its storage capability is high. The electricity system is a fast-reacting system which is mostly based on real-time operation, and as such it is featured with limited flexibility, whereas the gas system is a slow responding but very flexible system and can, therefore, provide the flexibility to the electricity system. From a system perspective, a potential coupling of the electricity and gas sector might result in a creation of a more efficient system as a whole.

The electricity system already links to all other energy sectors and further expansion is possible, as is shown in Fig. 22 [44]. Therefore, SOs see the electricity system in the centre of expanded sector coupling. Having a good overview of the entire electricity system will enable them to provide an optimised solution for the whole system that includes all sectors of energy. To play this central role, TSOs will need to liaise with all stakeholders to understand the entire field of energy and coordinate the interaction between different sectors.

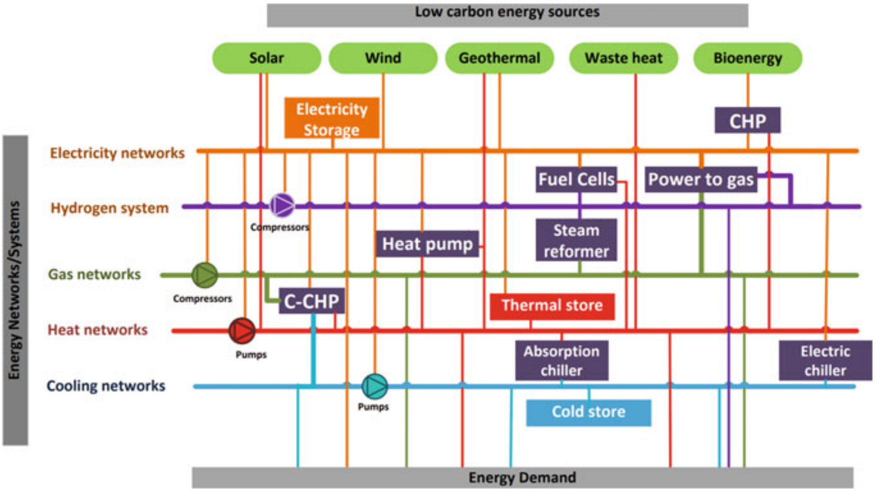


Fig. 22 Possible interactions between different energy carrier systems [44]

Political choices can drive sector coupling forward quicker than currently expected. Some countries do already have further research on the use of sector coupling to prepare for future efficiency and increase the percentage of renewable energy in the entire system by using existing infrastructure. Looking at the political agenda and statements already given from political institutes it is expected that sector coupling will gain more importance in the future.

3.3 Control Centre Evolution

Control centres are an essential structure of power systems since they provide the coordination between all the major participants of the electricity chain. During the last decades, remarkable developments on the functions and architectures of control centres have been made. Starting with the use of big analogue computers, poor monitoring, non-reliable communications systems and weak grids, the control centres have evolved to flexible and strong infrastructures that support the operator to coordinate the delivery of electric power (Fig. 23, illustrating a first-generation control centre, versus Fig. 24, a modern control centre, utilising well-defined information exchange standards).

For many years, the information to the operators has been given through the supervisory control and data acquisition (SCADA), which is updated every two to six seconds. This has been proven adequate for quasi-steady-state operations, while it is insufficient to detect the details of transient phenomena that occur on a time scale of milliseconds.

Fig. 23 First generation control centre, 1980 (Courtesy of XM Colombia)

Fig. 24 Modern control centre, 2019 (Courtesy of XM Colombia)

The ongoing energy transition incites the evolution of control centres. The dispersion and poorly manageable variability of RES requires increased attention and readiness of control centre operators to act (in order to secure the supply). In order to cope with challenges in an efficient manner, control centres must be equipped with tools that automate processes in order to aid operators. Challenges for operators include [45]:

- Assessment of the impact of inaccurate forecasting of demand and RES generation;
- Guaranteeing the appropriate response from manageable resources, once demanded;
- Dispatch, observability and control of a large number of small intermittent generators across distribution and transmission networks;
- New transmission operations criteria to cater for intermittent and DER;
- Managing risks to system security and stress situations due to the uncertainties of intermittent energy resources;
- Operating the system with changing flow patterns due to significant amounts of distributed connected RES;
- Fault or disturbance management (short-circuit level, stability, etc.).

Developments towards enhanced real-time security assessment tools in the control centre are emerging. Examples are, but are not limited to, online inertia and short-circuit level monitoring tools, tools for actively managing the dispatch of RES (e.g. GEMAS in Spain), enhanced dynamic security assessment (DSA) tools (including voltage stability, e.g. WSAT in Ireland), tools to estimate in real time the system damping for existing modes and decision support tools.

Increased System Observability

With increasing distributed energy resources and reducing conventional generation, special attention should be given to power system restoration in low inertia systems. A list of enhancements worth considering to further improve the restoration effectiveness and efficiency is presented in [15]. One of them is adopting advanced SCADA and EMS functionalities, such as wide-area security assessment or a fully integrated control landscape including SCADA/EMS and phasor measurement units (PMUs) within wide-area monitoring systems (WAMS) to enhance awareness and analytical capability to improve the restoration process.

Wide-area monitoring systems based on PMUs are increasingly being used by system operators worldwide in the operational environment, giving the control room information about the dynamic behaviour of the network and consequently increasing awareness for system dynamics [46]. Next to the improved situational awareness and decision support, the synchrophasor technology in the control room can contribute to power system restoration. When compared to traditional SCADA measurements, synchrophasors have an added value of synchronised voltage phase angle information between areas that have to be re-energised and/or reconnected, which can significantly benefit the restoration process. In the preparation phase of the restoration process, state estimation data and synchrophasors provide precise information of the remaining system, its division in islands and available components in the system. This information helps to construct the restoration strategy. From a restoration viewpoint, the restoration stage can be enhanced with critical data such as synchrophasor measurements from generating units and critical load. In the restorative control module (as part of the SCADA), the algorithm constituting of synchrophasor and state estimation data can help in the automated process of re-energisation of the shed load, resynchronisation of multiple islands and automated building up of power generation. The automated algorithm assists the operator in rebuilding the system again with reduced time [46].

In addition, SCADA/EMS solutions need to be developed to face future challenges. New generation of EMS/SCADA systems need more capabilities of handling complex analysis (e.g. dynamic security assessments and short-circuit power level calculations) and provide decision support to control room operators (e.g. remedial actions optimisation).

Distributed Energy Resource Management Systems

In order to integrate the maximum amount of generation from renewable energy sources into the electricity system, whilst ensuring quality levels and security of supply, in mid-2006 *Red Eléctrica de España* (REE) designed, put in place and started the operation of the Control Centre of Renewable Energies (Cecre) [47]. The Cecre is an operating unit integrated in the main control centre of Spain and monitors and controls production from renewable generation facilities, or groups of facilities, with a power capacity greater than 5 MW,[4] creating observability of 99% of wind generation facilities and 70% of photovoltaic plants. For these units, every 12 s real-time information on the connection status, active and reactive power production, and voltage at the connection point is provided to REE's control centre. This information is continuously shared with the Cecre operators, allowing for real-time security analysis. In this way, increased integration of renewable energy into the system is being made possible (it also guarantees the coordination between balancing processes and congestion management), while maintaining the same level of operational security. In other countries, other monitoring and control systems of DER can be adopted.

Possible Future Solutions and Trends OTS/DTS

Looking into the future in the electricity system also requires the right training of TSO and DSO operators to be able to deal with the above described possible new phenomena. Development of simulation tools and methods for assessing the risk of breakdowns during reconnection and to detect weaknesses in the electricity system with respect to reconnecting DER and storage system is of key importance. There is also the need for interactive system restoration simulation tools.

The next generation of the OTS/DTS should support simulation in the ambience of the multiple control centres, which requires a PSM that represent the entire interconnected power system interconnection (i.e. IPSM in Fig. 24) and multiple CCMs, one for each of the control areas/control centres. This opens a complex problem of heterogeneous control systems integration. Depending on the position (i.e. local or remote control centre), generic or customised (replica) CCM (with appropriate HMI) can be used. The global architecture of such a perspective OTS/DTS is shown in Fig. 25 [19].

Power system planning and operational complexity will increase significantly. This has influenced many regulatory authorities to require, not just the certification

---

[4] For units larger than 5 MW: observability and controllability. For units between 1 and 5 MW: observability.

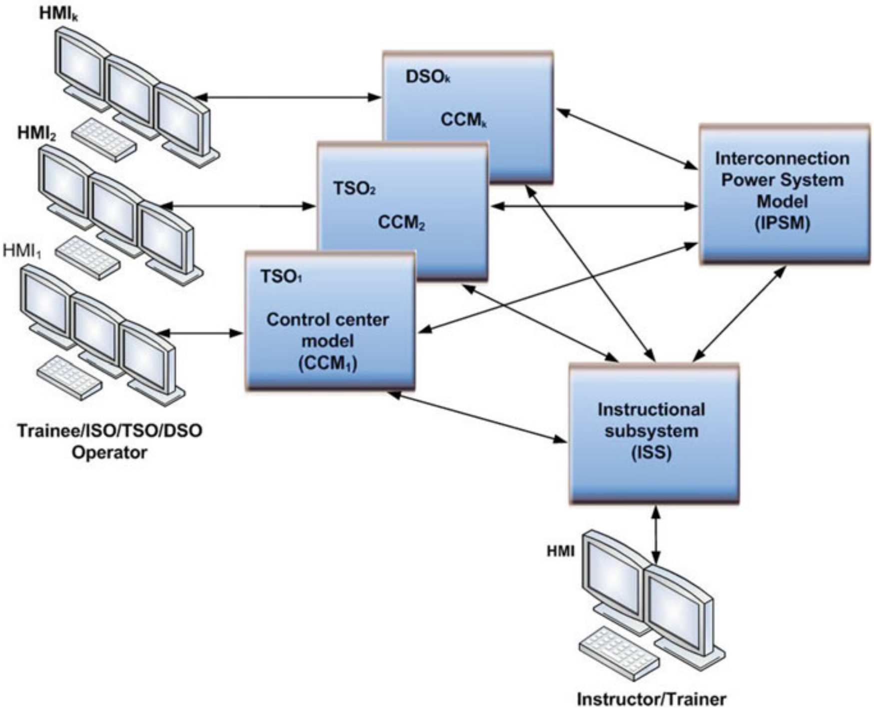


Fig. 25 Global architecture of the future centralised multi-control centre OTS/DTS [19]

of control centre operator competences to attest to their ability to operate the system, but also accreditation of their training programs. Hence, training programmes and training tools (OTS/DTS at the first place) have to be changed accordingly to include, not just knowledge of new topics but also the formation of new skills. This relates especially to the restoration simulation capabilities of many of the existing simulators.

The future environment is characterised by increased penetration of RES/DER sources, ever-changing market rules and relations between the actors, complemented with different ICT support monitoring, diagnostic and control systems. All this should be accommodated within the new generation of OTS/DTS systems.

The new OTS/DTS power system modelling capabilities must be such that they realistically model:

- Renewable generation, including its intermittent nature
- Different RES network connection (converter) arrangements
- HVDC lines and equipment
- Flexible alternating current transmission system (FACTS) devices of different types
- Protection devices
- System integrity protection scheme (SIPSs) devices

- Modelling of different storage options, including electrical vehicles
- Customer load modelling and their demand-side management.

Analogously, new application functionalities that appear in the TSO/ISO control centre, integrated or not with SCADA/EMS, should also be included in the CCM with the goal to increase the fidelity of training in part of the applications that operators use in their daily work. Examples of such new applications are WAMS, DSA, dynamic line rating systems and weather forecasts (incl. lightning and geo-magnetic storm detection).

Finally, regarding possible future development, there is a need for an additional layer of software (system), above SCADA/EMS that can defend the control system from operator mistakes. This system (of the decision support/business intelligence type) might be based on faster than real-time dynamic simulators, which include different power system dynamic phenomena and check operator control actions before they are applied.

The Way Forward

System operators are now and in the future responsible for operating the system within frequency and voltage limits, for performing congestion management, for guaranteeing availability of power reserves and for facilitating the electricity market.

In order to cope with the challenges that are inherent to non-traditional, low inertia power systems, research and innovation in the electrical energy sector are crucial. Concerning the successful integration of large-scale power electronic interfaced devices in the system, TSOs should emphasise the focus on increasing system observability, controllability and flexibility, with power system stability as boundary conditions. A higher level of control possibilities and utilisation of novel control concepts to effectively benefit from the opportunities that come with new technologies should be further investigated. It is essential to capture all these requirements adequately in training programs for control room operators.

Furthermore, international and multi-lateral developments are essential to achieve a secure and sound socio-economic system operation. Cooperation and coordinated decisions among several (cross-sector) stakeholders should lead to enhanced network security and cost efficiency. The common understanding of roles, common analysis tools and procedures are key factors for successful realisation of future networks and sound system operation.

Acknowledgements Main contributors: Carlos Vanegas (CO),[5] Jens Jacobs (DE),[6] Susana Almeida de Graaff (NL),[7] Danny Klaar (NL)[3], Vinay Sewdien (NL)[3], Ole Gjerde (NO)[8] and Ninel Cukalevski (RS).[9]

---

[5] Carlos Vanegas is with XM Colombia, the Colombian TSO.

[6] Jens Jacobs is with Amprion GmbH, one of the German TSOs.

[7] Susana Almeida de Graaff, Danny Klaar and Vinay Sewdien are with TenneT TSO BV, the Dutch TSO.

[8] Ole Gjerde is with Statnett, the Norwegian TSO.

[9] Ninel Cukalevski is with Institute Mihailo Pupin, Serbia.

Study Committee C2 is grateful to Anjan Bose, Babak Badrzadeh, Michael Power, Walter Sattinger and Jan van Putten for their invaluable contribution in reviewing this chapter.

References

1. Liacco, T.E.D.: Real-time computer control of power systems. Proc. IEEE **62**(7), 884–891 (1974)
2. Alsac, O., Stott, B.: Optimal load flow with steady-state security. IEEE Trans. Power Appar. Syst. **PAS-93**(3), 745–751 (1974)
3. Fink, L.H., Carlsen, K.: Operating under stress and strain. IEEE Spectr. **15**(3), 48–53 (1978)
4. Official Journal of the European Union., "COMMISSION REGULATION (EU) 2017/ 1485—of 2 August 2017—establishing a guideline on electricity transmission system operation," no. 2 (2017)
5. Von Meier, A.: Integration of renewable generation in California: coordination challenges in time and space. In: Proceedings of the International Conference on Electrical Power Quality and Utilization (EPQU), no. October 2011, pp. 768–773 (2011)
6. de Almeida, S.: Portugese Transmission Grid Incidents Risk Assessment. FEUP (2010)
7. UCTE, Appendix 1 : Load-Frequency Control and Performance (2004)
8. ENTSO-E, Core CCR TSOs' proposal for the regional design of the day-ahead common capacity calculation methodology in accordance with Article 20 ff. of Commission Regulation (EU) 2015/1222 of 24 July 2015 (2017)
9. NERC, Available Transmission System Capability (MOD-001-1a) (2016)
10. UCTE, Final report—system disturbance on 4 November 2006 (2007)
11. CORESO, CORESO. [Online]. Available https://www.coreso.eu/
12. TSCNET, "TSCNET." [Online]. Available: https://www.tscnet.eu/
13. European Commission, Electricity Balancing Guideline. Brussels (2017)
14. Liu, Y., Fan, R., Terzija, V.: Power system restoration: a literature review from 2006 to 2016. J. Mod. Power Syst. Clean Energy **4**(3), 332–341 (2016)
15. CIGRE WG C2.23, Technical Brocure 712: System Restoration Procedure and Practices. CIGRE, Paris (2017)
16. CIGRE WG C2.21, Technical Brochure 608: Lessons Learnt from Recent Emergencies and Blackout Incidents. CIGRE, Paris (2015)
17. Crisci, F., et al.: Power system restoration—world practices & future trends. CIGRE Sci. Eng. J. **14**, 6–22 (2019)
18. CIGRE WG C2.35, Technical Brochure 677: Power system operator performance: corporate, operations and training goals and KPI's used. Paris (2017)
19. CIGRE WG C2.33, Technical Brochure 524: Control Centre Operator Requirements, Selection, Training and Certification. Paris (2013)
20. Sewdien, V.N., et al.: Effects of increasing power electronics on system stability: results from MIGRATE questionnaire. In: 2018 IEEE PES International Conference on Green Energy for Sustainable Development, pp. 1–9 (2018)
21. Breithaupt, T., et al. Deliverable D1.1 Report on Systemic Issues (2016)
22. AEMO, Inertia Requirements Methodology: Inertia Requirements & Shortfalls. Melbourne (2018)
23. Bomer, J., Burges, K., Nabe, C., Poller, M.: All island TSO facilitation of renewables studies (June 2010)
24. Sharma, S., et al.: ERCOT tools used to handle wind generation. In: IEEE Power and Energy Society General Meeting, pp. 1–7 (2012)
25. Dudurych, I., Burke, M., Fisher, L., Eager, M., Kelly, K.: Operational security challenges and tools for a synchronous power system with high penetration of non-conventional sources. In: CIGRE Sess. 2016, February, pp. 1–11 (2016)

26. Ørum, E., Laasonen, M., et al.: Future system inertia, pp. 1–58 (2015)
27. ENTSO-E, Frequency Stability Evaluation Criteria for the Synchronous Zone of Continental Europe, p. 25 (2016)
28. Sewdien, V.N., et al.: Effects of increasing power electronics based technology on power system stability: performance and operations. CIGRE Sci. Eng. J. **11**, 5–17 (2018)
29. AEMO, System Strength Requirements Methodology: System Strength Requirements & Fault Level Shortfalls, Melbourne (2018)
30. CIGRE WG 14.05, Commutation failures: causes and consequences (1995)
31. CIGRE WG B4.62, Connection of wind farms to weak AC networks, Paris (2016)
32. Commission for Energy Regulation, DS3 System Services Technical Definitions: Decision Paper (2013)
33. Essential Services Commission of South Australia, Application form for the issue of an Electricity Generation Licence, Adelaide (2017)
34. Australian Energy Market Commission, National Electricity Amendment (Generator Technical Performance Standards) Rule 2018, Sydney (2018)
35. Llorente, M.S., López, R.F.-A., de la Rodríguez, M.T., Merino, J.B.: Ancillary services provision with wind power plants in Spain and its coordination with congestion management. In: 16th Wind Integration Workshop, vol. 8, no. 2, pp. 175–184 (2017)
36. Klaar, D.: Pilot projects for ancillary services. In: Proceedings of the 2018 CIGRE Session (2018)
37. Mohandes, B., El Moursi, M.S., Hatziargyriou, N.D., El Khatib, S.: A review of power system flexibility with high penetration of renewables. IEEE Trans. Power Syst. (2019)
38. Cochran, J., et al.: Flexibility in 21st Century Power Systems, Denver (2014)
39. Denholm, P., Hand, M.: Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. Energy Policy **39**(3), 1817–1830 (2011)
40. van der Meijden, M.A.M.M.: Future North Sea wind power hub, enabling the change. In: 2018 CIGRE Session Opening Panel (2018)
41. Wilson, D.: Icelandic operational experience of synchrophasor-based fast frequency response and islanding defence. In: Proceedings of the 2018 CIGRE Session (2018)
42. European Commission, Proposal for a Regulation of the European Parliament and of the Council on Risk-preparedness in the Electricity Sector and Repealing Directive 2005/89/EC., Brussels (2016)
43. NERC, Standard IRO-014-3 Coordination Among Reliability Coordinators (2008)
44. Abeysekera, M.: Combined Analysis of Coupled Energy Networks. Cardiff School of Engineering (2016)
45. CIGRE WG C2.16, Challenge in the Control Centre (EMS) Due To Distributed Generation and Renewables, September. CIGRE, Paris (2017)
46. CIGRE WG C2.17, Technical Brochure 750: Wide Area Monitoring Systems—Support for Control Room Applications, Paris (2018)
47. De La Torre, M., Juberias, G., Dominguez, T., Rivas, R.: The CECRE: supervision and control of wind and solar photovoltaic generation in Spain. In: IEEE Power and Energy Society General Meeting (2012)

Susana Almeida de Graaff has dedicated her professional life to power system operations. She received her Licenciatura (5 years degree), M.Sc. and Ph.D. degrees in Electrical Engineering from Porto University, Portugal, respectively in 2000, 2006 and 2010. Her Ph.D. work 'Portuguese Transmission Grid Incidents-Risk Assessment' was approved with distinction. In 2005, she was awarded with REN prize for her M.Sc. thesis in electrical power systems. She was with REN, the Portuguese TSO, since the beginning of 2001, with System Operations in the development of activities such as network security analysis, online risk assessment and disturbance/blackout analysis. Since November 2010, she is with TenneT TSO B.V. in the Netherlands, in International Development within System Operations, focusing in innovation, research and development, cooperation and coordination among TSOs, developing methodologies for capacity calculation, network security on a European level, including R&D projects. In 2018, she received the Hidde Nijland Prize in the Netherlands, in recognition for contributions to the development of the electrical power system. Dr. Susana Almeida de Graaff is the chair of CIGRE Study Committee C2 on System Operation and Control since August 2016, and contributing actively to CIGRE SC C2 activities since 2006, as working group member, special reporter and national member. In 2013, she was awarded with CIGRE Technical Committee Award.

Vinay Sewdien received his Masters of Science in Electrical Engineering (cum laude) from KU Leuven and TU Delft in 2013. After his graduation, Vinay started at TenneT TSO, the Dutch electricity transmission system operator, and worked on topics such as transparency policies for the electricity industry, wide-area measurement systems, and power system stability. He is currently part of the System Operations–International Development team, where he is investigating the technical implications of the energy transition on the operation of the power system. In parallel, Vinay started to pursue his Ph.D. degree from the Delft University of Technology since January 2016. Vinay is the Technical Secretary of CIGRE Study Committee C2 on System Operation and Control. Furthermore, he is a member of several CIGRE working groups and of IEEE PES.

Power System Environmental Performance

Henk Sanders, César Batista, Flavia Serran, Mercedes Miranda Vázquez, and Hector Pearson

Abstract The energy world is rapidly changing. This chapter examines the implications of this change for environmental and social aspects. It describes the three main changes foreseen in 2030 and beyond: scale dynamics, increased stakeholder engagement and impacts of climate change.

Keywords Sustainability · Environment · Sustainable development goals · Scale dynamics · Stakeholder engagement · Climate change

1 Introduction

According to World Economic Forum, "no matter which country you're in, the energy transition is underway". This transition is a challenge for the world and, in contrast with other historical changes in the energy industry; this change is being driven as a response to environmental and climate concerns. A new decarbonised energy model is needed, and the world is running out of time.

The energy world is going through a historic change. It is moving away from the traditional model of large-scale, carbon-intensive generation and subsequent

---

On behalf of Study Committee C3.

H. Sanders (✉)
TenneT, Arnhem, The Netherlands
e-mail: henk.sanders@tennet.eu

C. Batista
Vale, Rio de Janeiro, Brazil

F. Serran
Rio de Janeiro Federal University (IPPUR/UFRJ), Rio de Janeiro, Brazil

M. M. Vázquez
Red Eléctrica de España, Madrid, Spain

H. Pearson
MRTPI, London, UK

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_12

transmission and distribution towards a much more complex system of low carbon and decentralised generation connecting to more localised energy networks. This energy gap is expected to be filled by renewable power sources, by DC subsea interconnection with other countries, by storage and by energy demand flexibility.

Besides these changes, there are still parts of the world that lack energy supply, sometimes in quantity, sometimes in quality. Therefore, this energy transition could also lead, along to technological improvements, to reduce still existing inequality.

Other chapters consider the technical, engineering and market aspects of these changes. The purpose of this chapter is to examine what the implications of these changes are not only for the environment and, in particular, people. It will consider the implications on people and social dynamics in both urban and rural societies across the globe.

Sustainable development as a concept is of overriding importance and this is considered in Sect. 4. In the context of this chapter, the authors believe that there are three major changes which will occur by 2030. These are:

- Scale dynamics of electricity generation;
- Increased stakeholder engagement and input; and,
- Impacts of climate change.

We are considering below what is going to happen or what we consider that is best for the people and the environment.

Scale dynamics of electricity generation. Much has been written about the need to change from centralised fossil-fuelled power stations to much more renewable sources of generation in order to slow adverse climate change, for the benefit of species, (including humans) and their habitats. A further consequential change is that renewables often mean much more localised and smaller sources of generation. This creates its own “micro-grids” and some communities may benefit, while others may be left behind. Some communities may feel ownership for micro-grids and localised sources of generation; other communities, particularly poorer communities or remote communities, may feel disadvantaged.

On the other hand, large-scale renewable generation may also take place, for example, large-scale offshore wind farms and solar farms in desert areas.

Increased stakeholder engagement and input. Society is becoming increasingly more aware of environmental issues and of their ability to exercise their own rights or have their say. Increasingly, citizens are holding politicians, corporations and other organisations to account. Corporations and governments are trusted less than they were, and electricity companies are not excluded from this, with citizens being more prepared to confront organisations about the decisions they take and where they site equipment and apparatus. The authors believe that these trends will continue into the future. There may, however, be consequences in terms of social inequality: wealthy and articulate communities will seek to exercise their powers, perhaps at the expense of poorer communities. Power companies must ensure equal access to affordable energy supply.

Impacts of climate change. With minor exceptions, there is wide consensus amongst the international community that climate change is one of the mayor problems that the world must face:

- The Intergovernmental Panel on Climate Change's 2018 special report called for increased urgency of action and reiterated the need to attain zero GHG emissions, in order to avert significant climate-related consequences for ecosystems, human communities and economies.
- The last reports of the World economic Forum (in Davos) have identified climate change as one of the major risks for the planet.
- The Paris Agreement has been broadly supported by governments. In accordance with this, countries have set reduction targets (NDCs) with the intention to limit global warming to 2 °C. According to the last reports, more ambition is needed and warming should be reduced to 1.5 °C.
- Companies, cities and other actors are increasing their commitment and are also setting reduction targets. A lot of initiatives (SBTi, We mean business, CDP, United Nations Global compact business ambition) are being supported by the private sector, investors and society.

The power sector has a central role to achieve emissions reduction targets. The network of the future will make possible the transition to a decarbonised economy but, at the same time, the network of the future must be developed with the least impact on the environment and people

2 What Is the Future?

What future are we talking about? Is it 10 years, 20 years or 30 years ahead? This Green Book considers the future to 2030. However, in terms of environment, we must think and plan further ahead. Many actors (policy makers, companies, NGOs, research organisations, etc.) are already doing this. A number of organisations are already doing this. For example, the EU and many national governments have set clear environmental objectives until 2030 and, as a vision beyond that, have already established where to be by 2050; ETIP SNET,[1] in its Vision 2050, supports the long-term decarbonisation strategy of the European Union. Energy companies as well as countries vary in their look-aheads. Environmental campaign organisations also look beyond 2030.

According to the experts, electricity has a crucial role in the decarbonisation path; for this reason; electricity demand in countries is expected to grow significantly by say, 2050, driven by increased better access to energy, electrification of transport and heating. For example, in the UK, it is predicted that there could be as many

---

[1] European Technology and Innovation Platform of Smart Networks for Energy Transition (ETIP SNET).

as 11 m electric vehicles (EVs) by 2030 and 36 m by 2040.[2] Although it is hard to predict peak demand in these scenarios because it depends on how much "smart charging" takes place (such as charging at off-peak times and using vehicle-to-grid technologies.

In terms of heat, in colder countries, a mix of low carbon heating solutions and better thermal efficiency of buildings is likely to take place. Rising electricity prices, or government legislation, would drive this change.

Are All Our Futures the Same?

Of course not. The only thing that is the same for every country and every company is that the energy transition is going fast. Whether you call it *climate change* or use other names, it is for sure that we all have to take the changes into account. But every country, every company, has its own history, its own culture, its own legislation and so on.

Also, there is not only a difference between countries, but even within countries. It is on every *scale*. Renewables and new technologies have their influence in different scales; we see large windfarms and at the same time small smart metre developments.

Public participation is also affecting the way countries and companies will deal with the future. Social media can no longer be ignored and it will have influence on how countries and companies will make their future plans. This also will differ from place to place.

Therefore, for all the three main trends (climate change, scale dynamics and public participation), we can conclude that there is no common, same future to predict.

What Do We Want the Future to Be? How Will We Get There?

CIGRE has made a strategic plan for the (near) future. It is a general plan, not focussed on the different isolated study committees. It gives an overview in general how CIGRE will and can contribute to the coming years.

CIGRE wants to act in order to:

- Give access to electricity for all;
- Reduce the social and environmental impacts; and,
- Improve participation.

CIGRE has currently four strategic directions. Amongst these are environment and sustainability and unbiased information for all stakeholders. Two of the challenges CIGRE focusses on are renewable energy sources and growing environmental requirements.

---

[2] National Grid, Future Energy Scenarios, July 2018.

3 Sustainable Development

In 2015, the United Nations (UN) adopted the 17 sustainable development goals (SDGs) of the 2030 Agenda for sustainable development to ensure greater environmental sustainability.

CIGRE, as the "global expert community for electric power systems", has resolved to support the SDGs and considered them in reference paper[3] in 2018. To quote from the paper:

> Just looking at these titles it becomes clear that power systems – and thus the expertise CIGRE contributes worldwide to well developed and managed power systems – are of direct relevance to several of these. In analyzing our contributions to the SDGs, CIGRE's Technical Council identified nine SDGs for which CIGRE's contributions are especially relevant, and these can be grouped into the four dimensions of climate protection, efficiency, global cooperation, and development.

The nine SDGs which are particularly relevant are set out below. In the context of this chapter, and in dealing with the external world and environment (rather than in CIGRE's own organisation), some comments are made against them.

- **SDG 5, "gender equality"**: ensure that both genders have equal access to energy sources. For instance, to ensure that women and young children are not disadvantaged in a domestic situation to other users and groups, such as commercial interests.
- **SDG 7, "affordable and clean energy"**: increase the focus on ensuring universal access to affordable, reliable and modern energy services; on energy efficiency; on facilitating access to clean energy research and technology, including renewable

---

[3] CIGRE Reference paper: *Sustainability—At the heart of CIGRE's Work*, September 2018.

energy, energy efficiency, and advanced and cleaner fossil-fuel technology (also with more focus on pollutants and particulates from generation and networks); on investment cases for energy infrastructure and clean energy technology; and on expanding infrastructure and upgrading technology for supplying modern and sustainable energy services for all in developing countries.

- **SDG 9: "industry, innovation and infrastructure"**: enhance technological and technical support to lesser-developed countries.
- **SDG 11: "sustainable cities and communities"**: increase attention on sustainable and resilient buildings utilising local raw materials; to protecting and safeguarding the world's cultural and natural heritage; and to reducing the adverse per capita environmental impact of cities, including by paying special attention to air quality, and municipal and other waste management.
- **SDG 12: "responsible consumption and production"**: promote public procurement practices that are sustainable, in accordance with national policies and priorities, and encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle. Improve CIGRE's publication practices to contribute to people everywhere having the relevant information and awareness for sustainable development and lifestyles in harmony with nature, and to support developing countries to strengthen their scientific and technological development to move towards more sustainable patterns of consumption and production. Address inefficient fossil-fuel subsidies that encourage wasteful consumption.
- **SDG 13: "climate action"**: Address resilience and adaptive capacity to climate-related hazards and natural disasters on all continents, and the integration of climate change measures into national policies, strategies and planning. CIGRE's work should systematically bear in mind the need to improve education, human awareness and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning signs.
- **SDG 14: "life below water"**: especially for connecting offshore windfarms, wave and subsea turbines.
- **SDG 15: "life on land"**: although this topic is most frequently covered CIGRE needs to ensure that this topic remains a priority.
- **SDG 17: "partnerships for the goals"**: Multi-stakeholder partnerships that mobilise and share knowledge, expertise, technology and financial resources can also be used to support the achievements of the sustainable development goals in all countries while encouraging and promoting effective public, public-private and civil society partnerships, building on the experience and resourcing strategies of partnerships.

4 Scale Dynamics of Electricity Generation

As mentioned before, the environmental aspects of the future are hard to predict. One of the reasons for this is the scale dynamics of our sector.

To balance our grids and combined with more market-driven business operations, we see the need for grid expansion. Also interconnections will grow, even as sea cables. So the scale of our work will be bigger and more international. On the other hand, the introduction of renewables, especially on smaller scale, will force our business to invent local solutions for balancing the grid.

Both sides, scale enlargement and scale reduction, are taking place at the same time. This is a quite recent development. New techniques are being developed, TSOs and DSOs have to work more closely together, the need for storage is increasing, consumers will become producers, local communities will have state of-grid solutions. All of these developments have just started.

There is an increasing tendency that generation of energy will take place within urban areas—this is micro and distributed generation. Urban aspects will probably be much more related to the generation and transmission/distribution of energy than has been seen in the past. So, in the future maybe we will have to discuss energy and urban aspects more closely than today, such as access to energy, urban mobility, housing. The generation of energy and aspects related to it will be part of the "urban landscape and culture".

The main task of SC C3 is to study the environmental effects of the above-mentioned developments, but because these developments are very recent, we have not an overview of the environmental and sustainable effects of them.

What we can predict is that the work of SC C3 will increase, to find out what the environmental effects of all these developments are. SC C3 is already preparing for this yet unknown future, by releasing its new strategic plan and more specifically by the new preferential subject for the Paris 2020 session (how to deal with the negative impacts of energy transition).

5 Increased Stakeholder Engagement and Input

Recent years have witnessed a growing voice within communities to be heard and to seek to influence decisions and practices of large organisations. This growing voice fits within the concept of sustainable development. The responsibilities of sustainable development strengthen the need for organisations to engage with stakeholders to deliver specific objectives, as well as to meet more extensive social, environmental and economic challenges. Stakeholder engagement is therefore fundamental to an organisation's performance, and to its understanding of what sustainability means. Without stakeholder engagement, it is very unlikely that an organisation or company will succeed in today's or tomorrow's world.

Although there is universal acceptance of the benefits of electricity, by its very nature (with its sites of generation, means of transmission and distribution, the development of new points of generation, whether they be large nuclear, gas-fired or hydropower stations, and their associated networks), electricity can have an impact on individuals, communities, the natural environment, landscape and cultural heritage. This will occur during construction and operation.

Consultation generally means finding ways to involve stakeholders in some of what the electricity organisation does. This process is as much about understanding opportunities as it is about preventing conflict and mitigating risk.

TB 548 summarises a survey of electricity organisations worldwide on their attitudes to and experiences of stakeholder engagement, particularly in relation to the development of electricity construction projects, within the context of sustainable development. The report analyses the results of the survey and draws conclusions based also on the experiences and knowledge of the individual members of the working group. A number of case studies are also presented in the report.

The conclusions from TB 548 were as follows:

- The relationship between organisation and stakeholder is primarily driven by legal and regulatory obligations; however, the results of the survey show that the level of voluntary stakeholder engagement is increasing. More and more companies recognise that good stakeholder engagement is a prerequisite for good risk management.
- The survey found that stakeholder engagement policies are less common than environmental policies in electricity organisations. Legal obligations, reputation, values and ethical issues are the main drivers for stakeholder consultation. While formal environmental statements, major projects and legal requirements are key prompts for stakeholder consultation, policy development is not.
- Electricity organisations report that stakeholders are most concerned about nature conservation, visual impact and EMF/health issues.
- Although many companies choose to carry out consultation significantly beyond the minimum level required, there is no global common practice evident in identifying stakeholders. There was no single existing standard strategy amongst electricity organisations relating to stakeholder engagement.
- While a flexible approach to stakeholder engagement is beneficial, there is a global need for a standard set of principles for communication, consultation and engagement.

The working group produced a set of eight key principles for stakeholder engagement in the electricity sector. It is recommended that these be taken forward for CIGRE members.

These eight key principles apply equally to a world of more decentralised generation and more local energy networks. The authors believe that citizens' rights and powers will only increase, making these principles just as important for small localised projects as large ones. The eight key principles are as follows.

Key Principles for Stakeholder Engagement[4]

1. **Approach to stakeholder engagement**

The approach to stakeholder engagement should be fundamentally consistent for all of a company's construction projects. This approach could be flexible, varying according to the scale and type of the project, but should still be consistent. Consistency should occur across stakeholder groups and localities. The aim must be to establish trust amongst stakeholders.

2. **Project Scoping (proportional approach)**

The value from engagement should be optimised by scoping the requirements for the project. Be clear about the real constraints of the project—what engagement and communication can assist with, and what is out of scope. Be aware of what project phases are to be the subject of engagement. A lot of effort and resource on engagement at the margins of a project may realise limited additional benefit. It may also be beneficial to engage key stakeholders (particularly those representing different community interests) at the start of a project to establish their views on what they would consider to be a "proportionate approach".

3. **Stakeholder Identification (identify and understand your stakeholders)**

Establish a consistent approach to mapping stakeholders and understanding their likely viewpoints, needs and expectations from engagement, and the potential value that could be realised from engaging them. There should be a clear commitment to community engagement at a local level. It is also important to define the "voiceless" or "hard to reach" stakeholders such as those with mobility difficulties, sight or hearing loss, literacy difficulties, alternative language requirements, etc.; or people too busy to engage with traditional consultation methods. Identify and target these groups specifically.

4. **Start engagement early**

Early engagement in a scoped manner will help to build project awareness and understanding, so helping to reduce the risk of "surprise" later. Engage key stakeholders early in the scoping phase to enable them to contribute to the development of effective solutions. They may have information and views that will be of benefit to the proposal, and securing their endorsement for an approach to stakeholder engagement, and for securing data will be of considerable value. Stakeholders must have the opportunity to comment and influence at the formative stage. Be clear about the stage of the project when engaging: stakeholders should not expect all project details to be available at the early stages, and should appreciate that they are being involved in formative stages.

---

[4] CIGRE TB 548, pp. 67–68.

5. Targeted mix of consultation/engagement methods

A combination of methods for stakeholder engagement should be considered and chosen depending on the stage of the project, the stakeholder groups involved and their individual concerns, needs and priorities. Methods should be tailored to the required output, such as awareness building, gaining understanding, inviting comments, or enabling constructive debate. Methods could include provision of information through news media; published information sheets or leaflets; exhibitions; websites; online questionnaires; discussion events; workshops, perhaps independently facilitated; community panels, etc. Dedicated community liaison and engagement staff could be utilised. Regular engagement with key stakeholders will enable relationships to be developed and maintained.

6. Create an open and transparent process

It is important to manage the expectations of stakeholders by clearly stating the objectives and scope of the engagement from the outset. Some aspects of a project will be "out of scope" for consultation, such as legislative or regulatory obligations; however, it should be recognised that there may be different ways of satisfying these obligations. Similarly, timescales should be clearly defined at the outset. The engagement or project process should be openly publicised, and be clear, so that as many obstacles to engagement are removed as possible. Project information should be tailored for audiences in format and style, for example, non-technical material or specialist, detailed material.

7. Provide feedback to stakeholders (monitor and evaluate)

It is important that stakeholders can see how their comments have been taken into consideration. Feedback mechanisms should be developed to demonstrate how views have been considered and addressed. This is not necessarily a simple task for complex or controversial projects where large numbers of comments may be received. It is important to demonstrate not only that engagement has taken place, but that it has been an effective part of the process. It is important to be clear about how views are reflected in, or used to influence, subsequent decisions, processes and plans. When comments have been considered but the proposals have not changed, it is good practice to explain why not.

8. Engagement should be proactive and meaningful

Stakeholder engagement should be appropriate for the purpose and the target audience and should be proactive and meaningful. Stakeholders should generally be involved at project stages where they are able to influence an outcome or decision. The approach to the engagement of citizen communities should be proactive, accessible and inclusive.

6 Impacts of Climate Change

As already said, fighting against climate change have become one of the most important drivers to define energy strategies. Moving towards a decarbonised economy is a goal for the international community.

The energy sector has a decisive role in **climate change mitigation**: a transition from carbon-intensive energy to renewable energy is essential to achieve emission reduction goals.

In this context, we must be aware that, despite new developments (renewable, submarine cable, distribute generation, storage) are needed to reach this transition, they can also involve some environmental effects that must be addressed.

A lot of work must be done regarding environmental impacts. Examples of some of these impacts are:

- What are the effects on biodiversity from solar parks?
- How many bird collisions will occur in onshore and offshore windfarms and will these affect viability of species?
- What developments will occur in the coming years concerning electricity storage and what will be the environmental effects of it? (i.e. impact of batteries)
- What will be the impact of sector coupling on environment, landscape and nature?
- What about the use of hydrogen in the coming years?

On the other hand, there are several studies from the scientific community regarding the potential effects from the increase of temperature: severe weather incidents, flood risk, coastal change, increased arid areas, water supply, biodiversity changes and landscape changes, increase of diseases….

The environmental and social impacts will be different depending on the resilience of each country and people to receive these impacts.

For this reason, it is also necessary to work on **adaptation to climate change**. We must be prepared for the impacts that cannot be avoided. Working to adapt electricity industry to the new conditions and to reduce the climate change effects on society (people) is a big challenge and we must start working now to be able to face the future problems.

7 Conclusions

The energy world is going through a historic change, mainly led by the need to reduce emissions and fight against climate change. It is moving away from the traditional model of large-scale, carbon-intensive generation and subsequent transmission and distribution towards a much more complex system of low carbon and decentralised generation connecting to more localised energy networks.

Society is becoming increasingly more aware of environmental issues and of exercising their own rights. Increasingly citizens are holding politicians, corporations and other organisations to account. Corporations and governments are trusted less than they were, and electricity companies are not excluded from this, with citizens being more prepared to confront organisations about the decisions they take and where they site equipment and apparatus. At the same time, it is important that governments and electricity companies ensure that disadvantaged and minority communities have full access to electricity. The authors believe that these trends will continue into the future.

8 Glossary

European Network of Transmission System Operators-Electricity (ENTSO-E) An association of European electricity TSOs established by the EU which aims at further liberalising electricity markets in the EU

European Technology and Innovation Platform for Smart Networks for the Energy Transition (ETIP) Set up under the EU Horizon 2020 programme

EU European Union

Electric Vehicle (EV) Vehicle driven by electric motor

TSO Transmission System Operators

Bibliography

1. CIGRE, TB 548: Stakeholder Engagement Strategies in Sustainable Development—Electricity Industry Overview. CIGRE (2013)
2. ETIP SNET: Vision 2050, Integrating Smart Networks for the Energy Transition: Serving Society and Protecting the Environment. EU (undated but post 2015)
3. National Grid: Future Energy Scenarios. UK, July 2018
4. RSPB: The RSPB's 2050 Energy Vision: Meeting the UK's Climate Targets in Harmony with Nature (2016)
5. Staschus, K., Vazquez, M., Sanders, H.: CIGRE Reference paper: Sustainability—At the heart of CIGRE's Work. CIGRE, September 2018

Henk Sanders is advisor at TenneT, the Dutch TSO. Studied social and economic geography at Nijmegen University (now Radboud University) and business and public administration at WUR (Wageningen University and Research). Always working in public infrastructure: 11 years with Dutch Railways and over 20 years in electricity with TenneT. Involved in topics like licensing, environment (EIA, SEA), policy making (SF6, EMF, bird protection, landscape and nature) and last years involved in department of CSR (corporate social responsibility). Involved in CIGRE since 2002 in several working groups, later member of SC C3 and since 2015 chairman of SC C3. Most recent publication was reference paper: “sustainability, at the heart of CIGRE’s work”.

César Batista is a social scientist and political scientist. A 13 years track record in environmental, social and economic issues in energy sector and further infrastructural projects, with experiences ranging from planning through field execution. Experiences including planning, strategic environmental assessment, hydroelectric inventory of hydrographic basins, social and environmental impact assessment and land studies, basic environmental projects for hydroelectric power plants; participation in energy auctions, permitting process, client management amongst other steps from energy chain production; actions in social responsibility projects and corporate report on sustainability. Currently, César Batista acts in a worldwide Brazilian Mining company dealing with social management in a corporative position. Since 2018, César Batista is a Cigre member, contributing for C3 Study Committee and for Working Group C3.15 (“Best environmental and socio-economic practices for improving public acceptance of high voltage substations”).

Flavia Serran is a biologist with graduate training in energetic and environmental planning. Over 29 years of Brazilian and international experience in environmental diagnosis, identification of environmental and social impacts, and development of mitigation measures, mainly for infrastructure power sector projects (planning, construction and operation), including all steps of the permitting process. Experience in negotiation with environmental institutions and local and indigenous population. Participation in hundreds of Phase I environmental assessments and health and safety audits (petrochemical, pharmaceutical and manufacturing industries) and regulatory support for multilateral-funded infrastructure projects, comprising power sector, refineries and linear projects, for IDB and NDB. Experience on environmental management systems development and monitoring. Currently, Flavia Serran is a consultant for Environmental Resources Management (ERM) in Brazil and a researcher at the Regional and Urban Planning Institute at the Rio de Janeiro Federal University (IPPUR/UFRJ). Since 2014, Flavia Serran is a member of the C3 Strategic Advisory Committee.

Mercedes Miranda Vázquez is agricultural engineer. Expert in environment, sustainability and climate change. (19 years' experience). Since 2003 working for Red Eléctrica de España (Spanish TSO). Main activities: environmental management system (ISO 14.001), environmental management (maintenance and construction of facilities), environmental impact assessment and strategic environmental assessment of the electricity planning, environmental due diligence, communication and training activities, environmental reporting and risks management. Currently: working at Sustainability department in REE. Responsible for: implementation of climate change strategy (including policy, GHG Inventory, reduction targets and action plans, suppliers engagement, risk and opportunities assessment, SF6 management). Sustainability report and stakeholders report for environmental issues. (Sustainability report, investors and other stakeholders reports.) Member of CIGRE since 2007, participating in several working groups, member of the SAG. Secretary of SC3 since 2012.

Hector Pearson MRTPI is independent consultant. Hector was planning policy manager at National Grid plc until December 2017. There he was responsible for leading planning policy and stakeholder engagement strategy for the transmission business of National Grid. It included the approach to developing new major infrastructure projects. His role covered the whole of the 400 and 275 kV electricity network across England and Wales. Hector was heavily involved in the major infrastructure provisions of Acts of Parliament and in national policy, in both seeking to influence the Bills and emerging government guidance, and in helping to design the company's own internal policy and processes to meet the needs of the new Acts for major infrastructure. He led a national £500 M project to reduce the visual impact of power lines in national parks and AONBs across England and Wales (the VIP Project (Visual Impact Provision Project)). This would replace sections of 400 kV overhead line in the most important landscapes with underground networks. Before joining National Grid, he was a planning consultant with Atkins and also with Arup and began his career in municipal government in the UK. He was chair of Energy UK's Planning Group, the trade body for the energy sector. Hector is a chartered urban planner and has degrees in urban planning and environmental management. Hector has been involved in CIGRE since 2006, chairing two working groups and as a member of others. He was the UK regular member of Study Committee C3 from 2012 to 2018 and is currently a member of the C3 Strategic Advisory Group and two C3 working groups. He received the CIGRE Technical Committee award for C3 in 2014.

Power System Technical Performance

Genevieve Lietz and Zia Emin

Abbreviations

5G	Fifth generation (cellular frequency band)
AEMO	Australian Energy Market Operator
CFL	Compact fluorescent lamps
CG	Cloud-to-ground discharges
DE	Flash/stroke detection efficiency
DER	Distributed energy resources
DSO	Distribution system operator
EGM	Electro-geometric model
EHV	Extra high voltage
EM	Electromagnetic
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
EMT	Electromagnetic transient
EUE	Equivalent unserved energy
EV	Electric vehicle
FACTS	Flexible AC transmission systems
FFR	Fast frequency reserves
HVAC	High-voltage alternating current
HVDC	High-voltage direct current
GIL	Gas-insulated line

On behalf of CIGRE Study Committee C4.

G. Lietz
DIgSILENT GmbH, Gomaringen, Germany

Z. Emin (✉)
Power Systems Consultants UK Ltd, Warwick, United Kingdom
e-mail: zia.emin@cigre.org

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_13

GIS	Gas-insulated substation
GMD	Geomagnetic disturbance
IC	Intracloud discharges
IGE	Induction generator effect
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of things
LA	Location accuracy
LED	Light-emitting diode
LISN	Line impedance stabilisation networks
LLS	Lightning locating systems
LOLE	Loss of load expectation
LSA	Line surge arrester
LTE	Long-term evolution
LV	Low voltage
MOA	Metallic oxide arrester
MV	Medium voltage
NEM	National Electricity Market
NSG	Ground strike point density
OHL	Overhead line
PE	Power electronics
PLC	Power line carrier
PLL	Phase-locked loop
PMU	Phasor measurement unit
PQ	Power quality
PSS	Power system stabiliser
PV	Photovoltaic
RES	Renewable energy sources
ROCOF	Rate of change of frequency
RC-VD	Resistive capacitive voltage divider
RTS	Real-time simulator
RVC	Rapid voltage changes
STATCOM	Static compensator
SVC	Static VAR compensator
SSCI	Sub-synchronous control interaction
SSO	Sub-synchronous oscillations
SSR	Sub-synchronous resonance
SSTI	Sub-synchronous torsional interaction
TOV	Temporary overvoltage
TRV	Transient recovery voltage
TSO	Transmission system operator
UFLS	Under-frequency load shedding
UPS	Uninterruptable power supply

VFTO	Very fast transient overvoltages
VSC	Voltage source converter
VT	Voltage transformer

1 Introduction

Power system technical performance issues involve the development and review of methods and tools for analysis with specific reference to dynamic and transient conditions and to the interaction between the power system and its apparatus/subsystems, between the power system and external causes of stress and between the power system and other installations.

The time frame of phenomena that fall within power system technical performance range from nanoseconds to hours, which includes everything from lightning, switching, power quality (PQ), electromagnetic compatibility and electromagnetic interference (EMC/EMI) and insulation co-ordination to power system stability, modelling and long-term system dynamics. Figure 1 shows the range of phenomena along with their time frame that fall within the remit of power system technical performance.

To better investigate these activities, the following five broad topics of interest are defined:

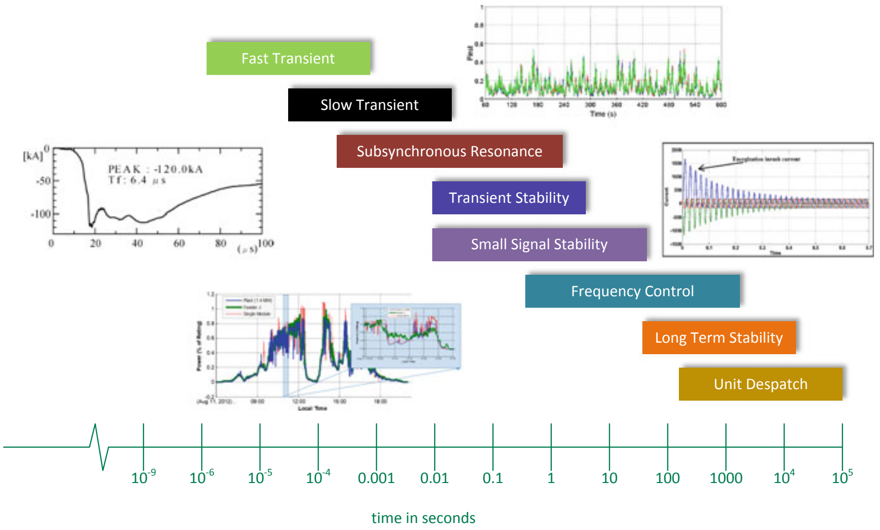


Fig. 1 Time frame of various system phenomena of interest in power system studies

- Electromagnetic compatibility and interference (EMC/EMI)
- Power quality (PQ)
- Insulation co-ordination
- Lightning
- Power system dynamics.

The common theme among the above broad topics is the investigation and development of new tools, models, analysis methods and techniques for the assessment of such phenomena. The need for models ranges from the equipment level to the system level, with the focus being on modelling for analysing the system and equipment interaction. Measurement set-ups, techniques and their use in terms of validating the complex simulation models all form parts of the modelling effort. The broad list provided above also relates to the emerging smart grid, micro-grid and distributed and renewable energy resource technologies (such as wind and solar), with emphasis concerning PQ and advanced tools for the analysis of electromagnetic and electromechanical transients and dynamic performance.

2 EMC/EMI

2.1 EMC/EMI and Their Importance in Electricity Supply Systems of the Future

EMC refers to whether equipment, when exposed to external disturbances in its environment, can still perform its function to an acceptable degree. Equally, EMC is where equipment does not generate disturbances in its environment that can prevent adjacent equipment from performing its function to an acceptable degree.

For external disturbances that are continuous, such as low levels of supply voltage distortion, these disturbances must have a minimal effect on the functional performance of the equipment. For external disturbances that are of very short duration and rare (surges), a temporary effect on the equipment functional performance is acceptable provided the equipment after the disturbance continues with normal operation. For external disturbances that are temporary, severe and rare (voltage dips and interruptions) shutdown by the equipment or external intervention to continue with normal operation is acceptable.

EMC can be achieved by totally blocking the emissions from sources of disturbances or by designing equipment to be totally immune to all disturbances. However, these approaches are not practical, so a compromise is reached—emissions are limited to a reasonably low degree for sources of disturbances and equipment exposed to these disturbances is designed with a reasonably high degree of immunity.

The following subsections focus on high-frequency conducted voltage disturbances and high-frequency radiated electromagnetic disturbances. Low-frequency conducted disturbances are covered under PQ in the next section.

2.2 State of the Art

Product and generic standards are compiled specifying emission limits and immunity requirements for different types of equipment operating in different environments. The IEC 61000-6-5 [1] generic standard has successfully addressed the EMC immunity requirements for the equipment used in the power station and substation environments.

2.3 Aspects Influencing EMC/EMI

The two aspects influencing EMC/EMI are the levels of emission in an environment (of both high-frequency conducted voltage disturbances and high-frequency radiated electromagnetic disturbances) and the level of immunity of the equipment operating in that environment (to both high-frequency conducted voltage disturbances and high-frequency radiated electromagnetic disturbances).

The levels of high-frequency disturbances in an environment can be reduced by filtering (conducted voltage disturbances) or by screening (radiated electromagnetic disturbances). The level of immunity of equipment can be increased using the same techniques—filtering and screening.

Equipment can also be made more immune to high-frequency conducted voltage disturbances by operating the equipment off its own supply. Increased separation from the sources of high-frequency radiated electromagnetic disturbances can also be used to increase the immunity of equipment to these high-frequency radiated electromagnetic disturbances.

2.4 Potential Future Impacts

A major source of high-frequency disturbances in the future grid will be converters consisting of circuits that use power semiconductor devices to convert power in some form (e.g. DC voltages and DC currents from solar panels) to another form (e.g. AC currents flowing against AC grid voltages for exporting power back into the AC grid).

In order to achieve low carbon emission levels, electric vehicles (EVs) will replace fossil-fuelled road vehicles in the near future. These EVs will require charging and the battery chargers will be grid-connected converters conducting high-frequency voltage disturbances back into the AC grid and radiating high-frequency electromagnetic disturbances near the converter. The EVs themselves will contain variable speed drives which will be a source of high-frequency radiated electromagnetic disturbances. Photovoltaic (PV) panels as renewable energy sources export power through grid-connected converters that conduct high-frequency voltage disturbances back into the AC grid and radiate high-frequency electromagnetic disturbances near the converter. The same can be said for renewable energy sources (RES) consisting of variable speed wind turbines. In the case of PV, there is an extensive network of DC cables connecting the PV panels to the grid-connected converters, and these are a new source of high-frequency conducted voltage disturbances and high-frequency radiated electromagnetic disturbances.

On the load side, many motors will be controlled by grid-connected converters to achieve increased energy efficiency. Similarly, the next-generation lighting (compact fluorescent lamps (CFLs) and light-emitting diodes (LEDs)) are being fed off grid-connected converters. At the utility level, there are very large (up to thousands of MW) grid-connected converters to improve the operation of the power system such as high-voltage direct current (HVDC) schemes and static compensators (STATCOMs).

In future, with the introduction of the smart grid requiring communication between devices, there will be greater use of power line carrier (PLC) and the Internet of Things (IoT). IoT sources are beginning to transmit in the fifth generation (5G) cellular frequency band which extends to 86 GHz—equipment in the vicinity will have to have the appropriate immunity.

Additional developments include the trend to switch converters at higher frequencies to reduce the size of the filter components and to switch the power semiconductor devices faster (shorter turn-on and turn-off times) to reduce the power semiconductor device switching losses. Both raise the frequencies of the conducted voltage disturbances and the radiated electromagnetic disturbances. A modern converter hall of an HVDC scheme is shown in Fig. 2.

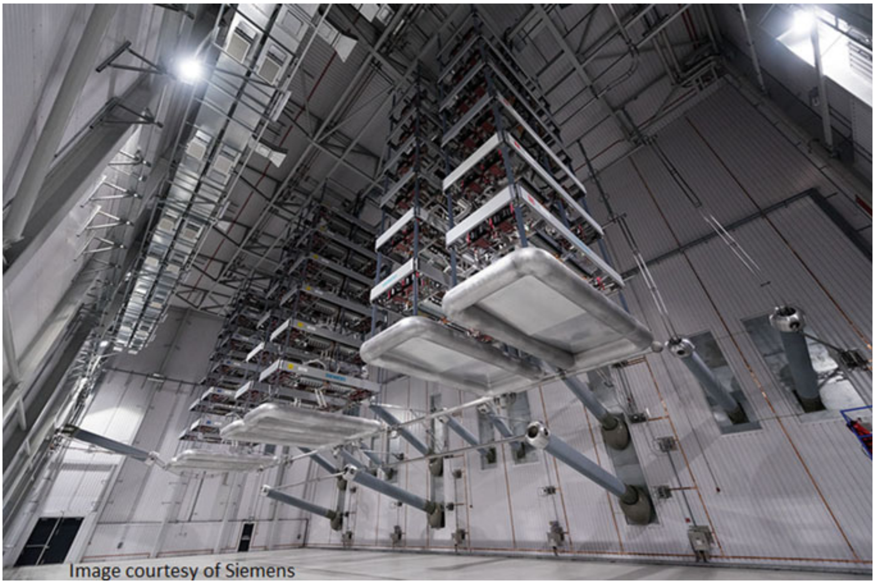


Image courtesy of Siemens

Fig. 2 Converter hall

2.5 Future Analysis Requirements in EMC/EMI

On the product side, product standards are compiled specifying emission limits and immunity requirements for different types of grid-connected converters (both generation-side and user-side) [see IEC 62920 [2] for the converters used in PV systems, IEC 61800-3 [3] for the converters used in variable speed drives and IEC 62040-2 [4] for the converters used in uninterruptible power supplies (UPSs)].

Most product and generic standards do not cover the conducted voltage disturbance immunity medium-frequency range from 2 to 150 kHz since it was previously thought that testing only above 150 kHz was required to cover the voltages induced in cable connections by external radio transmitters.

This situation has now changed with grid-connected converters switching at kHz frequencies and generating conducted voltage disturbances in the 2–150 kHz range. Immunity requirements in this frequency range must be covered by future product and generic standards. Therefore, from the emission viewpoint, to avoid interference with radio transmission, conducted voltage disturbance (emission) limits in the frequency range 2–150 kHz will need to be covered by future product and generic standards.

With the introduction of 5G cellular transmission, immunity requirements will have to be extended to 86 GHz (note that IEC 62920 [2] tests up to 6.4 GHz—the upper limit of the long-term evolution (LTE) cellular frequency band).

While the product standards usually specify emission limits for individual converters, the emission where there are multiple converters remains unknown. There may therefore be a trend towards more in-situ measurements (see IEC 61800-3 [3] where this is specified—but only for large variable speed drives).

Furthermore, with the trend towards cost-reflective tariffs, generators and users may be financially penalised for the disturbances they generate. There may also be an increased use of filter circuits to control voltage disturbance levels.

2.6 Research and Development Needs

Research is required into the immunity of equipment to high-frequency radiated electromagnetic fields up to 86 GHz, the immunity of equipment to medium-frequency conducted voltage disturbances (from 2 to 150 kHz), the immunity testing using voltage waveforms actually found in practice (rather than immunity testing at single frequencies) and the general effect of high-frequency conducted voltage disturbances and high-frequency radiated electromagnetic disturbances on non-converter equipment.

From the emission point of view, research is required into converter emission behaviour up to 86 GHz.

Where mitigation involves filtering, research is required into improved methods of filter design (especially where adjacent filters are present) as well as filters that maintain their filtering behaviour up to very high frequencies (many do not because of parasitic inductances and capacitances).

Knowledge of the grid impedance at very high frequencies including grid resonances will allow the design of improved line impedance stabilisation networks (LISNs) used for conducted voltage disturbance emission testing.

Research is required into the interaction of multiple sources of conducted voltage disturbances and the interaction of multiple sources of radiated electromagnetic disturbances.

Next-generation converters would include resonance-responsive converters (converters that change their switching frequencies to avoid exciting grid resonances), PLC-responsive converters (converters that change their switching frequencies to avoid interference with PLC), co-ordinated operation of multiple converters to reduce emissions and converter switching strategies that do not produce high-amplitude high-frequency spectral lines (spread-spectrum switching strategies).

3 Power Quality

3.1 Power Quality and Its Importance in Electricity Supply Systems of the Future

PQ concerns the range of voltage disturbances on electricity networks that can interfere with the intended operation of systems and equipment connected to those networks. Disturbances may originate in the generation, operation of other customers' equipment, utility operation or atmospheric events or even from within the affected installation itself. Disturbances of interest include frequency, voltage magnitude (long-term voltage, dips/sags, swells and interruptions, voltage unbalance, voltage fluctuations) and voltage wave shape (harmonics including DC, subharmonics, interharmonics, supraharmonics, transients) [5, 6].

PQ is of increasing interest and importance due to several factors:

- Growing use of power electronics (PE) and digital control systems in power systems and customer equipment and installations leading to increased PQ immunity requirements;
- Increased instances in the management of voltage distortion with the growing use of PE in power systems and customer equipment;
- Increase in voltage distortion due to the use of power electronic systems associated with renewable energy, especially when connected at remote locations where the system strength [7] is already low; and
- Modification of existing harmonics due to frequency shift of resonances with the increased use of power factor correction capacitors and underground cables.

Furthermore, a precise description of the supply characteristics given in standards and utility codes and increasing emphasis of this by regulators give customers greater expectations. This has become more significant because of the availability of inexpensive monitoring allowing customers to check the quality of their supply against utility objectives.

3.2 State of the Art

The management of PQ originally has been reactive, with individual customer complaints being addressed as they arose. Later, as the specification of PQ became more precise, benefits were seen in more proactive approaches [8, 9], with the management of PQ as an integral part of the planning, operation and maintenance of the power system. Financial losses associated with PQ problems are a further justification to pay attention to such efforts [10]. At present, some countries are still at the reactive stage, but the great majority are engaged in making the transition to a proactive approach. This involves adherence to standards, and long-term PQ monitoring of a sample of sites to feed back into the PQ management process [11, 12].

The key guides to PQ management are PQ standards, with major influences being the IEC and IEEE. There are other regional or national codes, for example, UK, Germany and Australia, but these are mainly based on the IEC and IEEE documents and aim to address specific regional or national variations and issues. The basic approach in the IEC documents is compatibility between disturbance levels on the network and equipment immunity so that all equipment can operate within their electrical environment, including interaction with each other, and the inevitable effects of planned operations and unexpected incidents happening within the network. Compatibility levels are the boundaries between acceptable network emissions and equipment immunity. They are chosen to minimise the cost of EMC to the community: too high a value leads to expensive equipment immunity costs; too low a value leads to expensive mitigation costs.

IEC PQ standards/documents can be roughly divided into five types:

(a) Specification of compatibility levels,
(b) Specification of equipment immunity requirements and immunity requirement test methods,
(c) Specification of equipment emission limits (usually at LV),
(d) Principles for determining the allocation of disturbance allowance to different MV-HV-EHV customers (there is also a trend to allocation of disturbance limits to larger LV installations),
(e) Specification of monitoring and statistical indices for different PQ disturbances.

There are some difficulties with IEC standards/documents, and many utilities have difficulties in using them. These difficulties include:

- Choice of compatibility levels—these are sometimes not rigorously determined but are based on values known to have been acceptable in the past. The immunity

level of equipment is sometimes not known well with the possibility of an unnecessarily large margin between planning levels and equipment immunity level. The effect of supraharmonics and voltage fluctuations on CFLs and LED lighting systems need further investigation.
- Allowance for the disturbance impact of renewable generation because of the uncertainty in its future installed level and the emission characteristics of different generation technologies.
- Some analysis methods depend on assumptions which need to be re-examined, e.g. allowance for diversity, transfer coefficients between different voltage levels and efficient methods for allowing for numerous scenarios in meshed transmission system-related calculations.
- In determining customer allowances, there is an implicit assumption that the power system under study is evolving to a well-known final state. This ignores that power systems are continually evolving, with substations and transmission lines being upgraded as demand increases.

There could also be an increase in DC distribution networks which would come with their own PQ issues.

3.3 Aspects Influencing Power Quality

The global trends on the integration of RES to existing power systems through power electronic converters can be expected to continue [13, 14]. Increasing capacities and the number of such power electronic converters, both at transmission, distribution and in micro-grid environments are already evident. The majority of the large capacity wind and solar energy generating systems are connected at remote and offshore locations, and this trend can be expected to continue into the future [15, 16]. At the same time, HVDC transmission systems that are power electronic converter based will also continue to grow [15]. There is evidence to the effect that the power electronic-based variable speed options will take prominence in large pump storage schemes in new capacity developments [17].

The increased dispersion of RES at the distribution level, e.g. domestic PV and energy storage systems, all of which depend on power electronic interfaces can be expected to grow. At the utilisation level, trends in the use of power electronic systems can be expected to continue to grow, e.g. EVs, small and large devices including variable speed drives, active power filters, energy-saving devices including lighting systems and consumer electronics [6, 18].

In summary, future power systems will have a strong dependency on power electronic interfaces and can be expected to transform into systems that demonstrate an increasing complexity ‘both in terms of technical performance and system operability’ [15] where PQ will become increasingly important compared to that of electricity systems of the past.

3.4 Potential Future Impacts

In electricity supply systems of the future with increased penetration levels of power electronic converters, it is vital to pay attention to ensure that the connected equipment continues to operate without being disturbed and does not experience accelerated ageing.

Large-scale power electronic systems associated with wind and solar farms may be of the voltage source converter (VSC) type and their high-power semiconductor devices are switched at a relatively low frequency such as around 3 kHz as illustrated in Fig. 3.

Governed by the modulation strategies adopted, inherent non-ideal nature of the switching of the semiconductor devices, component sizing and the controller structures used, these converters tend to inject a full spectrum of low- and high-order harmonic currents into the connected grid, and hence, low-order harmonic voltage

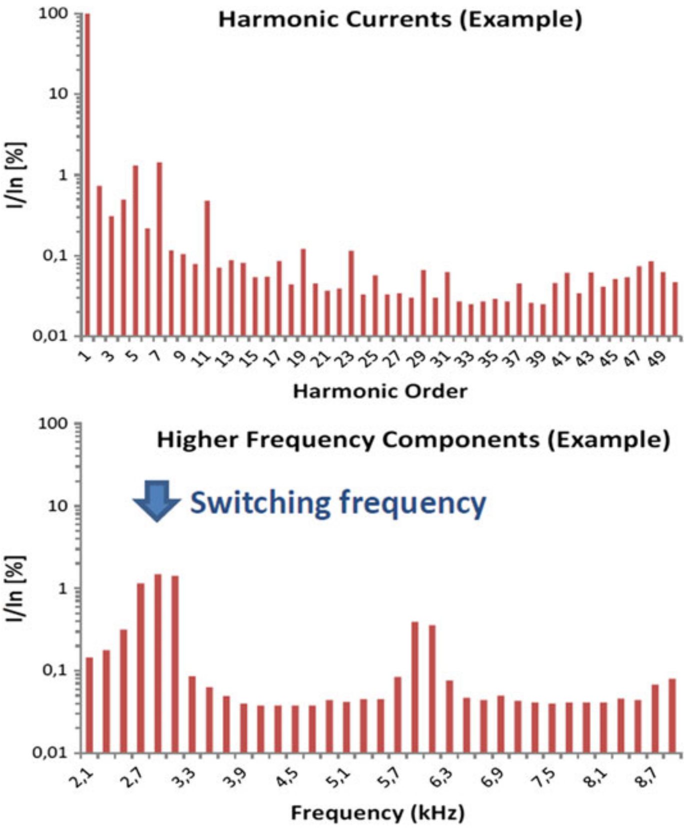


Fig. 3 Example harmonic currents and switching frequency. Image courtesy of Fraunhofer Institute for Solar Energy Systems, ISE

distortion levels at the point of common coupling can increase, especially at locations where the system strength [7] is low. The high-order harmonic distortion levels are influenced strongly by local network resonances. Harmonic resonance issues within wind and solar farms can become problematic as the collector systems of such farms are based on underground cables. Such harmonic resonance issues have already been reported in relation to offshore wind farms which employ considerable lengths of cables [19].

At the transmission level, with the proliferation of large-scale PE-based generation there is an imminent threat to system strength [20, 21] due to the replacement of conventional synchronous generators. This reduction in system strength can impact on a range of power system operational issues including PQ. In general, the associated PQ problems can manifest into generating system instability issues especially under contingency conditions. For example, power electronic-based generating systems, while requiring a minimum system strength for their normal operation, can have their control systems affected by network harmonic voltages leading to undue interactions between the control systems of such generating systems. These ‘harmonic instability’ concerns (traditionally associated with line commutated converters in HVDC systems [22]) can become more prevalent in future electricity networks, and hence, necessary assessment needs to be undertaken [21]. At the same time, step voltage changes, commonly identified as rapid voltage changes (RVCs) that are associated with network switching operations which violate acceptable limits have the potential to trigger system instability.

Generators with power electronic grid interfaces that inject active and reactive power into the grid usually behave as positive-sequence sources. Considering the remote locations of such generators connected to long un-transposed transmission lines, negative-sequence voltages at remote ends can develop due to line asymmetry, thus requiring voltage unbalance mitigation at strategic locations such as using dedicated STATCOMs.

Voltage fluctuations which arise as a result of the intermittency or variations of wind and solar generating systems can be expected and these can be managed using dynamic reactive power sources (e.g. STATCOMs).

With the proliferation of rooftop solar PV inverter systems in LV networks, one of the major concerns is the management of the steady-state voltage [23, 24], which often leads to inverter shutdown. Network operators around the world are quite active in this regard developing a number of voltage management strategies, including the use of smart inverters [25].

Considerable interest has already been shown in high frequencies beyond the traditional 2 kHz limit, often referred to as ‘supraharmonics’ [6]. As is evident from Fig. 4 [26], these frequencies are quite prominent with domestic solar PV inverters [26] as they switch at relatively higher frequencies compared to larger inverters. It is unlikely that these harmonics will propagate significant distances since they are absorbed by adjacent customer equipment in LV systems. The level of impact on the connected equipment is yet to be quantified. Preliminary studies tend to indicate extra heating and possible lifetime reduction in components such as electrolytic capacitors that are an integral part of switch-mode power supplies [27].

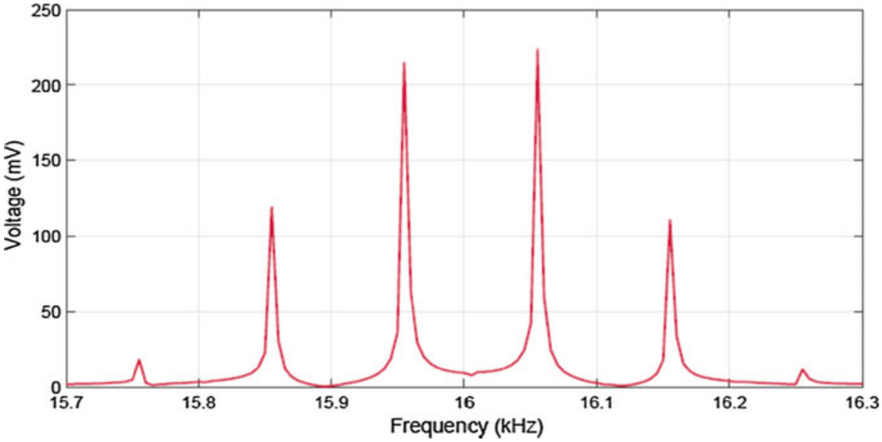


Fig. 4 First emission band of a domestic solar inverter [26]

3.5 *Future Analysis Requirements*

Proactive PQ management is based on three main activities:

a. Understanding the requirements of relevant standards and embedding appropriate practices into power system planning, operation and maintenance
b. Long-term PQ monitoring to understand system PQ performance at an appropriate range of sites at all voltage levels
c. Using results from (b) and from analysis of network incidents and individual customer complaints to improve PQ management practices.

PQ standards need development to allow them to deal with future grid evolution and hence:

- Standards and guidelines need to be developed for PQ disturbance types not yet allowed for, such as supraharmonics and transients [5, 6].
- Standards will need to be introduced regarding the performance of inverters used with renewable generation [23], possibly using IEEE 1547 as a guide [25].
- Some existing PQ standards will need to be improved—e.g. harmonic standards will need to allow for an allocation to power electronic-based generation in terms of the particular disturbances they generate and the uncertainty of their future installed capacity.

PQ monitoring will need to be further developed to give a more comprehensive view of all relevant PQ disturbances. This will require the development of new sensors such as high-frequency voltage transducers to give useful measurements of supraharmonics [6]. Better methods of top-down reporting will be required to simplify the interpretation of large amounts of data that this surveying will generate.

New issues can be expected to arise in planning and operation which will need to be adapted to meeting PQ requirements. For example, in LV networks voltage control will be impacted by distributed generation and there may be voltage unbalance issues due to single-phase PV generation units and single-phase electric vehicle charging [6]. Advanced distribution automation and the growth of micro-grids may be a useful tool to improve reliability and PQ [6]. The use of more extensive cable systems will impact on the management of harmonics [6].

There will be a need for greater information sharing both between different electricity supply organisations and also within the organisation [28]. A particular issue is the sharing between transmission and distribution companies since large renewable generation (solar and wind farms) is often connected near the transmission/distribution interface. It is important that all relevant organisations follow the same practices, and this may require more credible enforcement by regulators [28].

A particular case of information sharing occurs between utilities and customers. Customers are largely unaware of PQ issues until there is a problem. There is an obligation on utilities to prepare appropriate factsheets giving essential PQ information to customers so that many PQ problems can be addressed at the plant design stage, for example, by the specification of appropriate emission limits and immunity requirement levels for equipment.

3.6 Research, Education and Development Needs

A range of aspects can be considered with regard to research:

- The adequacy of existing PQ equipment standards could be explored further.
- The immunity of equipment in general to some types of PQ disturbances which have come to prominence recently, such as interharmonics, DC components, subharmonics and supraharmonics, needs to be better understood.
- New inverter designs (topologies and control) need to be examined to see if they comply with existing EMC/PQ standards.
- The appropriate management of supraharmonics.
- Electromagnetic transient (EMT) models need development which can represent the harmonic emission and network resonance behaviour of power electronic-based generating systems. System assessment studies involving harmonic instability and resonance studies will need to be facilitated using such high-fidelity models where root mean square (RMS) models are insufficient.
- The term ‘PQ data analytics’ has been coined for the effective use of high-volume PQ monitoring data [29]. This study has the aim, among others, of identifying the root cause of PQ problems, determining levels at unmonitored sites by state estimation techniques and determining the condition of equipment which might be approaching the end of life where this results in increasing PQ effects.

In terms of training and education, the following are areas where effort could be placed:

- Many of the topics considered above are too detailed for incorporation into already crowded undergraduate degree programs. It would be more effective to have undergraduates with a solid traditional power engineering education with electives in supporting areas such as power systems, PE, data analytics and digital signal processing, for example, who are equipped with a suitable background to work in areas related to PQ.
- Engineers employed in the electricity industry can expect to meet a wide range of new problems when they move into the area of PQ since the topic encompasses the whole of the power system and the operation of customer equipment. Growth in the number of continuing education courses to meet the needs of the apprentice PQ engineer will be desirable.

4 Insulation Co-ordination

4.1 Insulation Co-ordination and Its Importance in Electricity Supply Systems of the Future

Insulation co-ordination can be defined as the 'selection of the dielectric strength of equipment in relation to the operating overvoltages which can appear on the system for which the equipment is intended and taking into account the service environment and the characteristics of the available preventing and protection devices' [30].

The origins of voltage stresses are various with the most common ones being lightning, switching, fault or load rejection. Those associated with lightning are described in the next section, while this section focuses on on-site transient measurements and insulation co-ordination in connection with network undergrounding at the transmission level, UHV AC lines and the impact of dispersed generation (especially large PE-connected generation facilities), which requires further research and development.

The installation of underground and submarine cables at the transmission level has seen a steady increase in the last decade. This tendency is expected to continue due to the need for network reinforcement and transfer of renewable energy. Added to this is growing public opposition to the installation of overhead lines (OHLs) due to visual and environmental concerns. Switching and lightning overvoltage characteristics and propagation are different for cables compared to OHLs. For comparison purposes, Fig. 5 shows the voltage traces at the open ends of a 10-km cable and OHL, for single-pole energisation at peak voltage at 0.105 s. The propagation speeds are approximately 300 m/μs and 190 m/μs for the OHL and cable, respectively. The small oscillations in the cable voltage are caused by the intersheath mode, which has a propagation speed of 75 m/μs. This necessitates detailed simulation studies using electromagnetic transient programs with validated and detailed models of underground/submarine cables. The larger capacitance of the cables when compared with

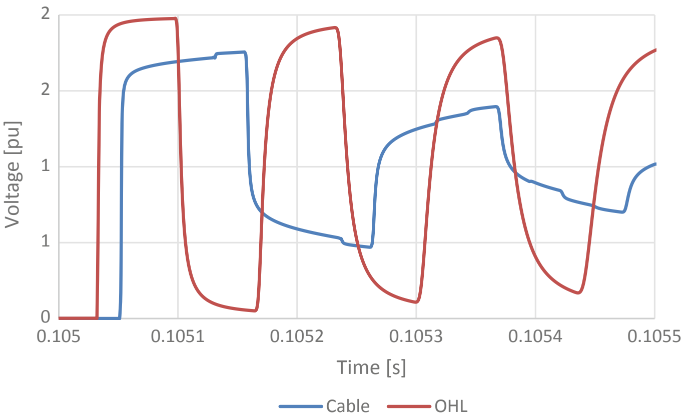


Fig. 5 Voltage waveform propagation comparison between a cable and an OHL

OHLs also leads to resonance frequencies lower than usual, leading to a large overvoltage if these resonances are excited by a transient phenomenon (e.g. transformer energisation). As a result, proper insulation co-ordination when installing new cables or new lines in areas with a substantial number of existing cables is of utmost importance. It may become a more common task in future, as the number and length of cables to be installed continue to increase.

Currently, UHV AC lines are limited to China, Japan and countries that were once part of the Soviet Union. The advantages/disadvantages of these lines are a topic of discussion and future tendencies regarding their expansion and further voltage increases are not currently clear. For insulation co-ordination, the lower insulation margins and scarce experience lead to very detailed custom studies. As the number of installations and associated operational experience increases, the development of standard procedures is expected.

The replacement of large, centralised synchronous generation by dispersed generation is an increasing trend. The associated reduction in the short-circuit power level leads to more severe temporary overvoltages (TOVs) if no other actions are taken. Additionally, the decrease in the load demand seen from the step-down transformer represents lower damping of these same TOVs. The estimation of this load for the studies is also a challenging task, but the impact is considerable for some of the phenomena. Finally, as most new generation is connected via PE, new control features able to reduce TOVs are being developed by manufacturers together with system operators. This is currently a topic of considerable work and new solutions are expected in the near future.

Lastly, the expected increase of HVDC links (point-to-point or multi-terminal) might lead to new study cases relating to transients, harmonics or TOVs. Some operators plan to have HVDC and high-voltage alternating current (HVAC) lines mounted on the same tower, which might require specific insulation co-ordination guidelines. All this should become clearer in the near future with the expansion of HVDC links.

Concurrently, measurement technology has developed sufficiently for more affordable on-site measurement of transient phenomena. The evaluation of transient stress in HV transmission and distribution networks plays an important role in terms of modern insulation co-ordination. It is necessary to provide reliable and precise measurement results in the field, which are used as reference values for transient simulation studies. Insulation co-ordination studies have certainly become more complex tasks as the transmission system is challenged to accommodate the changing patterns of generation and consumption caused by the transition from centralised power plants towards renewable-based generation.

4.2 State of the Art

4.2.1 Impact of Network Undergrounding

The voltage limits for insulation co-ordination are still defined by the transformer and surge arrester rated data for the majority of cases, even for studies involving HVAC cables. However, lightning is a special case. Although cables are naturally protected from lightning, their impact must be considered in lines containing multiple sections of OHL and cable and in cables adjacent to OHLs. The difference between the surge impedances means that the magnitude of a voltage wave decreases when propagating from an OHL to a cable, increasing in the opposite case. This has a positive impact in terms of the protection of the cable in the case of lightning striking an OHL if the cable is long enough. It may, however, be dangerous if the cable is short and multiple reflections occur at its terminals, thereby building up the voltage. Surge arresters or other voltage-limiting devices must be considered for installation at the OHL—cable transition points, and their rated data dimensioning must account for this potential voltage rise as well as the associated energy.

The solid insulation of cables introduces a large shunt capacitance when compared to OHLs, leading to low resonance frequencies that may result in larger TOVs: e.g. the energisation of a transformer, whose inrush current contains harmonic and DC components that are injected into the system in addition to the fundamental component. These TOVs have already been observed during the design stage for long radial connections between offshore wind farms and the respective onshore substation, during fault clearance or in cases of system islanding. As the amount of installed cables increases, the system capacitance also increases, as well as the likelihood of resonance at low frequencies, increasing the probability of TOVs.

Other phenomena are also analysed when performing insulation co-ordination studies in systems using underground cables: cable switching, fault clearance, zero-missing, circuit breaker stresses, etc., but these are well known and of less concern, and are therefore not considered in this section.

4.2.2 Ultra-High-Voltage Lines

UHV lines have a higher capacitance and transport large amounts of power. As a result, TOVs originated by load rejection might be larger and longer, making it a phenomenon of great concern and an important input for the choice of surge arresters and of insulation equipment. The installation of controllable shunt reactors or the trip of the line might be used as mitigation measures to minimise the consequences of load rejection. However, the latter must be assessed in relation to further grid impacts. Another important TOV case is that encountered as a consequence of the higher capacitance of UHV lines, which lowers the resonance frequency, with challenges similar to those mentioned for long cables.

The allowed switching overvoltages for UHV lines are lower in p.u. (typically between 1.3 and 1.7 p.u., depending on equipment and country), meaning higher requirements for limiting these overvoltages. The usage of a pre-insertion resistor is one possible solution. Additionally, it can be used as an opening resistor to provide support in cases of load rejection, but the energy absorption requirements are a limiting factor. The switching overvoltages associated with three-phase auto-reclosure should be carefully considered, because of the higher overvoltages.

Auto-reclosure failure has a higher probability for UHV lines, because the secondary arc current is larger and longer, leading to a higher transient recovery voltage (TRV). Moreover, given the long lengths of these lines, crossing several different areas with different meteorological conditions, as well as stronger capacitive coupling between phases, the secondary arc characteristics can change (when compared to usual experience) and might depend on the fault location. Special procedures to extinguish the secondary arc might be required (e.g. high-speed grounding switches or a neutral grounding reactor as part of shunt compensation).

Finally, lightning is of special concern, as the probability of shield failure is relatively higher. Very fast transient overvoltages (VFTOs) associated with gas-insulated substations (GISs) are topics requiring further research, because of uncertainties in different parameters that possibly lead to erroneous simulations. In addition, due to the very high frequencies involved in VFTOs in GISs, accurate simulation may not be possible in cases where these frequencies exceed the applicable limits of the admittance and impedance formulae used in commercial software [31]. Improved modelling is required to achieve accurate results.

4.2.3 On-Site Transient Measurements

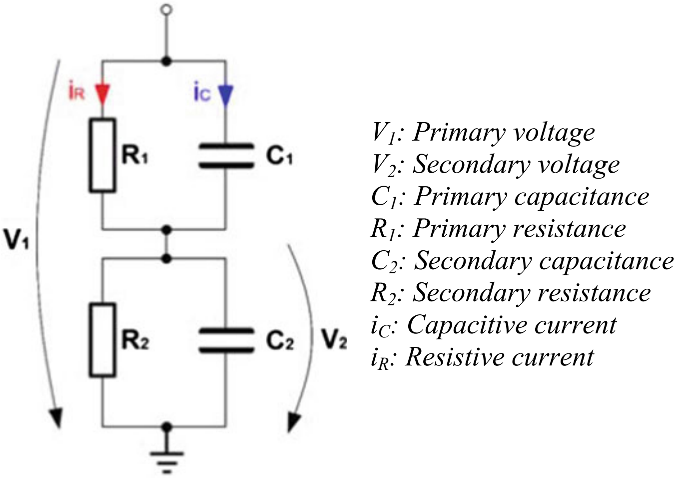
Currently, reduced design margins mean an increased requirement for accurate voltage and current measurements, in order to validate simulation models and to guarantee the proper operation of protection equipment. Higher-frequency phenomena are of particular concern, both because of associated inaccuracies in existing instrumentation transformer technology and the decrease in the frequency of the first resonance point. The increased emphasis on transients necessitates accurate measurements in order to understand transients and hence this section illustrates the transient behaviour of currently installed voltage transformers, compared to a non-conventional measurement system for the future [32].

Inductive Voltage Transformer (VT)

The VT belongs to the group of conventional instrument transformers and is currently in common use. The critical aspect of VTs is the frequency response behaviour. The first resonance peak ($\geq$1 kHz) depends on the main inductance and typically on the capacitance of the primary windings. At or close to the resonance point, the ratio error can increase to several hundred per cent. Therefore, only the frequency range beginning from the rated frequency up to the maximum specified ratio error of the first resonance peak is of value. Publications indicate that the first resonance point is moving closer to the rated frequency with increasing system voltage [33, 34].

Resistive Capacitive Voltage Divider (RC-VD)

The RC-VD belongs to the group of non-conventional instrument transformers. Resonance frequencies must be avoided by the correct selection of the resistances and capacitances (Fig. 6). The RC-VD shows a linear frequency response with high accuracy over the frequency range of operation (e.g. up to 10 kHz). This creates the possibility for reliable transient measurement values in AC and DC UHV systems. The phase displacement of the RC-VD is low enough for the identification of the direction of the spurious signal sources. The secondary measurement set-up must have a low inductance design [32, 35].



V_1: *Primary voltage*
V_2: *Secondary voltage*
C_1: *Primary capacitance*
R_1: *Primary resistance*
C_2: *Secondary capacitance*
R_2: *Secondary resistance*
i_C: *Capacitive current*
i_R: *Resistive current*

Fig. 6 Simplified equivalent circuit diagram of an RC-VD [35]

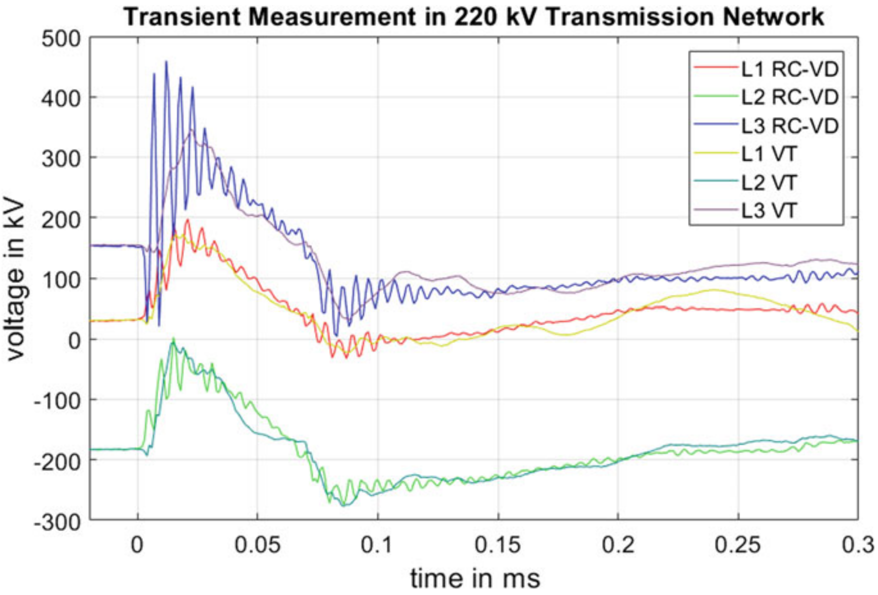


Fig. 7 Comparison between VT and RC-VD in the case of an atmospheric discharge [32] (L1, L2 and L3 refer to phase voltages)

Figure 7 shows an on-site measurement example, performed by the Technical University of Graz, during simultaneous data recording of a VT and an RC-VD. The measurement concerns a 220 kV line-to-ground transmission network during a high-frequency indirect lightning stress, which reaches up to 250 kHz. For these frequencies, the measured voltage is affected by the VT characteristic. In comparison, the RC-VD makes high-frequency measurements possible [32].

4.3 Aspects Influencing Insulation Co-ordination

As the number of HVAC cables continues to increase, resonances at low frequencies will become more common and represent a challenge due to excitation by inrush currents that may lead to unacceptable overvoltages and require the installation of special equipment. Additionally, the high rate-of-change of the impedance around the resonance frequency means that small variations in the simulation model may have a large impact on the simulation output if resonance occurs close to a harmonic frequency.

Another aspect influencing insulation co-ordination today is the use of UHV where links up to 1100 kV are already being built for commercial operation [36]. Besides having some similar issues to cables due to high capacitance, to operate at such high voltages is a new challenge that will affect the procedures and methods used in insulation co-ordination. As the trend to have very large generation remote from consumption areas continues to increase in some parts of the world, the number of UHV lines is expected to increase and new tools and standards must be developed.

4.4 Potential Future Impacts

Sustainable development goals inherently link the transition of traditional production of power towards a sustainable alternative. This challenges not only the generation systems, but equally the transmission and distribution of electrical energy. Furthermore, public acceptance in an increasingly densely populated environment demands power infrastructures with less environmental impact. New solutions including gas-insulated lines (GILs), UHV lines for long distances, submarine and underground cables, power electronic inverter-based generation, as well as hybrid AC1/AC2/DC solutions where two different AC voltage levels connect to a DC link, all require new approaches in order to ensure proper insulation co-ordination and thereby a level of reliability and economy when compared with traditional systems.

- Underground cable systems require the same basic approach for insulation co-ordination as OHLs. However, due to the very different electrical characteristics of cable systems, modelling and analysis is not as well established. The state-of-the art for such studies is still in development, and the complexities grow with the extent of cables used. Modelling tools are developed and available, but some grey areas with regards to the range of validity and applicability still exist. Furthermore, the non-self-restoring properties of cable systems suggest enhanced risk assessment when checking the levels to which the cables and their surrounding equipment are assessed.
- Combining several AC and DC systems via OHLs produces new and very complex cases related to transient studies. Identifying a standard analysis approach is typically not easy. If such systems also include cables, this challenge increases.
- Presently, the modelling of power electronic converters for insulation co-ordination studies is troublesome because of the lack of suitable data. As the relative number of such devices increases, their impact and the need for model accuracy also increases, with special relevance for the assessment of TOVs.
- Generally, surge arresters are a solution to limit lightning and switching overvoltages. The increase in the magnitude and duration of TOVs due to different causes makes the respective energy absorption capability and overvoltage withstand curve important selection parameters.
- Protection of such new systems must be rethought with the changing insulation threats. Insulation co-ordination not only reveals which levels of security against failures can be achieved, but also the risk of certain types of failures. The types and characteristics of faulted conditions and their associated consequences emphasise the need to rethink the way in which protection, as the next link in the chain, must protect future power systems.

4.5 Future Analysis Requirements

The main challenge is the ability to be able to build up the experience needed to conduct insulation co-ordination studies as a standard engineering design task with the same confidence as for traditional systems. Typically, insulation co-ordination decisions have required several more or less standardised study cases, some performed using transient simulation tools, but many based on recommendations from various standards. The complexity of future power networks will yield numerous cases requiring careful examination with many combinations to analyse in order to reach a sufficient safety margin for the insulation. Artificial intelligence methods are considered a possible way towards a more efficient insulation study methodology. The improved use of computational power as an alternative to the usual laptop/workstation-based case-by-case studies is foreseen as being able to better facilitate insulation co-ordination of a complex power system in such a way that design engineers can concentrate on the principal outcome of various approaches of co-ordination. Such a thorough approach will also make an economical assessment of the various solutions (which will have various consequences for economy and reliability) more transparent.

5 Lightning

5.1 Lightning and Its Importance in Electricity Supply Systems of the Future

Lightning current is a primary source of physical damage, disturbances, and malfunctions in power systems. Lightning is one of the most common geophysical phenomena in nature and has a wide spatial and temporal distribution. The study of lightning is a challenging task due to its randomness and complex discharge mechanism. Although the understanding of lightning has increased considerably to-date, there are still many areas requiring further research. Lightning can be defined as a transient electric discharge in the air with the length of electric arc measured in kilometres and accompanied by a high current that could have values from a few kiloamperes up to tens or hundreds of kiloamperes. The lightning discharge is usually termed a ‘lightning flash’ and most lightning flashes (about three-quarters) do not involve ground [33]. These are termed ‘cloud flashes’ (discharges) that include intracloud and cloud-to-air discharges and are referred to as ‘IC’. Lightning discharges between cloud and earth are relevant for research concerning the power systems since they can hit objects in the system and threaten power system reliability. They are termed cloud-to-ground discharges and are referred to as ‘CG’. The discharges, i.e. the lightning flashes, are usually composed of multiple strokes, and can be downward, or upward when initiated from tall objects, in which case they are referred to as ‘GC’. These two principal types are pictured in Fig. 8. At the time of writing,

Fig. 8 Downward (CG) lightning on the left and upward (GC) lightning on the right

lightning currents are measured on several towers in the world, as well as monitored and analysed by lightning location systems (LLSs).

The effective lightning protection of transmission and distribution lines and substations directly affects the reliability of the power system. The height of transmission line towers has increased significantly with the use of EHV and UHV. These high towers are becoming increasingly common in regions where UHV/EHV is used to overcome the large physical distances between energy resources and load centres, including in countries such as China where UHV/EHV is seen as an important part of the future decarbonisation process [37]. The primary cause of a (UHV/EHV) transmission line trip is a direct lightning strike causing an increase in the proportion of total lightning shielding failures. The analysis of striking distance and lightning shielding failure deserves more attention in order to prevent line outages.

The effects of lightning protection of transmission lines are directly influenced by the impulse grounding impedance of the transmission line tower. At the time of writing, research on the subject mainly includes experimentation and calculation of the impulse characteristics of grounding devices, the frequency-dependent characteristics of soil [38] and the optimisation of grounding structure design.

The improvement in lightning protection of OHLs with the application of the line surge arresters (LSAs) is continuing as the technology improves.

Induced overvoltages caused by lightning are the main risk for LV and MV lines, converter stations and substations.

Lightning protection of renewable energy systems is attracting increased attention due to the increased penetration of renewable sources of generation in order to meet stringent future targets. The damage to wind turbines caused by lightning is currently one of the main causes of unplanned downtime responsible for the loss of power generation. Understanding the effects of lightning strikes has become increasingly important as the size and rated power of wind turbines increase. In addition, they are often installed in locations where repair is difficult and costly. Lightning is also one of the main causes of failures in solar electric systems and components which require protection against a direct lightning strike and against the effects of lightning's electromagnetic pulse. For these reasons, lightning protection of future power systems with a large penetration of renewable generation requires further research and development.

Further developments of LLSs and their application in power systems are very important in assisting system operators with early warnings of lightning so that harmful effects can be minimised.

5.2 Lightning Parameters and Their Effect on Lightning Protection Systems

Lightning current is the primary source of physical (thermal and mechanical) damage, disturbances, and malfunctions. In order to protect the power system from lightning, knowledge of the lightning waveshape, amplitudes, etc., is important. According to IEC 62305-1 (2010) [39], the lightning threat is associated with specific current parameters.

The distributions of these parameters that are presently adopted by most lightning protection standards are largely based on direct current measurements on instrumented towers. One of the measured lightning waveforms at Lovcen tower, Montenegro, is shown in Fig. 9. Estimation of lightning peak currents is derived from measured electric and magnetic fields. The currents are also measured for triggered-lightning strokes that are similar to subsequent strokes in natural lightning.

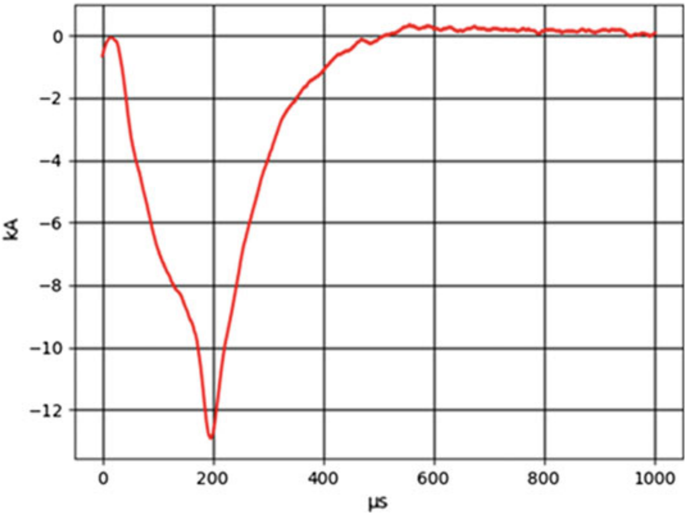


Fig. 9 Measured lightning waveform of a negative downward strike

5.3 Aspects Influencing Lightning Protection

Failure of an OHL can be caused by lightning directly striking the phase conductor, by the lightning striking the tower or to the shielding wire followed by the flashover to phase conductors.

When lightning strikes the tower or the overhead ground wire, the current in the tower and ground impedances cause the rise of the tower voltage. The tower and shield wire voltages are much larger than the phase conductor voltages. If the voltage difference from phase to tower exceeds a critical value, a flashover occurs, called ‘back-flashover’. Lightning may cause flashovers on distribution lines from both direct strikes and nearby flashes. Direct lightning strikes to power distribution lines cause insulation flashover in the great majority of cases. However, experience and observations show that many of the lightning-related outages of low-insulation lines are due to lightning that hits the ground in close proximity to the line. Due to the limited height of MV and LV distribution lines compared to that of the structures in their vicinity, indirect lightning strikes are more frequent than direct ones, and for this reason, the literature on this subject (see the bibliography of [40]) focuses mostly on such types of lightning events.

HV OHLs are protected by a shield wire, and use of the electro-geometric model (EGM), introduced by Armstrong and Whitehead in 1968 [41], provides an equation for the striking distance as well as the stroke angle. The EGM is widely used for estimating the lightning performance of transmission lines [42, 43].

To estimate the threat from lightning and vulnerability of OHLs, LLSs are used. Today, applications of LLSs are well known in electric power systems and other industries as a standard tool to analyse power systems. Application in transmission and distribution networks and systems is mostly encountered in one or more of the following areas [44–50]:

- Correlation of outages and faults in networks with lightning strokes
- Control and management of the power system
- Early warning of approaching lightning fronts
- Power system design, OHL route planning and line protection.

The LLS detects and locates atmospheric discharges, e.g. lightning strokes, in the atmosphere and serves as an important source of valuable lightning-related data. Currently, lightning data collected with LLSs (based on various location technologies) is used for the analysis of energy systems. In general, these LLSs typically have a flash detection efficiency (DE) of more than 90%, a stroke DE of more than 80% and a location accuracy better than 200 m if the network exhibits sensor baselines less than 250 km and if they are well maintained and operated (see [51–56]). The various technologies differ primarily in their accuracy in terms of (i) estimating the lightning peak current; and (ii) classifying individual events as either cloud-to-ground or cloud pulse. Often not all strokes of a flash hit the same ground strike point. This is important for all risk analyses because, if a flash exhibits two ground strike points on average, the risk of being struck by lightning doubles. Therefore, the risk of any structure being struck by lightning should be estimated using the ground strike point density, NSG, which was first introduced in IEC62858. At the time of writing, there is ongoing research to analyse different algorithms to identify individual ground strike points from LLS data. Various algorithms are currently used [57–62], each of which has advantages and disadvantages.

After applying one of these algorithms to LLS data, the ground strike point density can be determined spatially.

5.4 Future Aspects

The EGM equations are being adapted to reflect the observations made in practice. For example, in Japan [63, 64] it was observed that the actual lightning stroke rate to ground wires of UHV and 500 kV transmission lines was about five and about three times higher, respectively, than the rate calculated by the above described EGM method. An improved EGM based on these observations was proposed by Taniguchi et al. [65]. The improvement mainly relates to the striking distance and distribution of current waveform.

In addition, there has also been some recent progress in the correlated observation of lightning currents and final breakdown distances through the increased use of high-speed cameras in lightning research (see e.g. [66, 67]).

The leader progression model is gradually playing the same important role as EGM in the analysis of lightning shielding failure. The key problem with the leader progression model is the upward leader initiation criterion. In future, in-depth experimental observation and modelling of leader initiation will need to be studied further in the research of lightning protection.

In order to reduce the number of failures of OHLs caused by lightning, it would be convenient to increase the insulation level of the transmission line or to reduce tower grounding resistance, but such measures are often difficult to implement on existing OHLs. Installing an LSA is a measure becoming more popular due to the development of metal oxide (MO) surge arrestor technology with a polymeric housing, which neither causes significant additional mechanical stresses to the construction of the transmission lines, nor reduces their affordability. Recent application of line arresters showed significant improvement in the lightning performance of OHLs.

Metallic oxide arrester (MOA) installation was performed on lines of different voltage levels and configurations [68]. Field performance of the installed line arresters over the past several years has been very good for the most part [69–73] although mechanical failure rates in some regions are high.

In addition to improvements to MOA technology, the procedure for their optimal selection and maintenance should be advanced.

5.5 Future Analysis Requirements

Developments in lightning diagnostic techniques have enabled a deeper understanding of lightning phenomena. Lightning is one of the key factors threatening the safe and reliable operation of power systems, and there are still many issues related to lightning and lightning protection that need to be addressed. Some of the topics that should be examined, and activities undertaken are:

- Direct measurement of lightning currents using instrumented tall structures:
  Besides the measurements of lightning current, the observations of upward lightning or upward leaders is important in order to prevent lines outages in UHV/EHV power systems with significantly increased heights of transmission towers.
- Development, application and monitoring of lightning protection elements for OHLs, substation equipment and underground and submarine cables:
  The effective application of line arresters has been demonstrated in distribution and transmission systems. They do not cause significant additional mechanical stresses to the construction of the existing transmission lines and their price is decreasing, making them more accessible.
- Numerical simulations in lightning-related studies, including lightning shielding, induced lightning and overvoltage protection:
  Improvement of existing models for numerical simulations, obtaining parameters and model validation. Analysis of future power systems will see an increased application of EMT simulation, and the development of new EMT models will be required in order to accurately capture the abovementioned aspects.
- Electrical grounding including towers of transmission and distribution systems:
  The impulse tower footing grounding impedance directly influences the effects of lightning protection of OHLs. The study of the transient behaviour of grounding devices, considering the nonlinear frequency-dependent characteristics of the soil, would lead to a deeper understanding of the transient characteristics of a grounding system.
- Lightning protection in renewable power systems:
  The damage caused by lightning is one of the main causes of unplanned downtime responsible for the loss of power supply in wind and solar power generation farms in hybrid wind–solar power generation and in energy storage systems.
- Improvement of LLS operating principles by removing present limitations and optimising the performance of the existing systems:
  Exploitation of data provided by LLSs for improved lightning protection of system components and their optimal maintenance.

6 Power System Dynamics

6.1 Importance in Electricity Supply Systems of the Future

Power system dynamics investigations have traditionally revolved around preventing ‘angle instability’ or ‘voltage instability’ and in some cases also frequency instability [74]. It can be reasonably expected that future power systems will exhibit more frequent, faster and less damped dynamic phenomena than has previously been experienced [15].

An example of the new kind of dynamic phenomena has been reported in a small island system consisting of Ireland and Northern Ireland, which aims to develop the highest penetration of wind power on a synchronous system in Europe [75]. According to the Irish study on high wind penetration levels, the integrity of frequency response and dynamic stability of the power system is compromised at high instantaneous penetrations of wind power. It is reasonable to assume that a high penetration is where more than 50–60% of the instantaneous load demand of the network is supported by energy sources interfaced through PE, most commonly wind, solar and HVDC. Also, in adding significant volumes of wind power onto the system, it is reported that the online reactive power available to the system operator to manage voltage will be fundamentally altered. Dynamic phenomena are strongly influenced by the size of the power system; the consequences and resulting needs will be different for large networks compared to smaller, islanded systems such as Ireland. Specific studies on each system will be needed.

A conventional ac system runs at a common frequency with all rotating masses synchronised to that single reference frame. The kinetic energy stored in the rotating masses of conventional synchronous generators provides inertia to the power system. Synchronous inertia is extremely useful in situations where the frequency is forced to deviate (i.e. due to a system imbalance) in that it opposes the change naturally. Power electronic inverter-based generation does not provide synchronous inertia, but rather relies on the response of control systems to respond to the measured frequency disturbance. Measurement and control system often include unavoidable time delays of varying significance. Hence in the presence of increased power electronic inverter-based generation, there is an increased emphasis on reduced or practically non-existent synchronous inertia and how to manage system dynamics under such conditions.

As a practical example, consider Fig. 10 which shows the measured frequency disturbance following the fast runback and trip of a large generating unit in Tasmania, Australia. The active power response of a medium-sized hydro-generating unit and wind farm is overlaid for comparison. While the wind farm output remains relatively constant during the frequency disturbance, the inertial and governor response of the hydro-unit can be clearly identified, helping support the control of network frequency.

Figure 11 shows different simulated wind power control responses to support the system frequency [76]. The two curves with synthetic inertia have shapes similar to the inertial response of synchronous generators. The cases with fast frequency

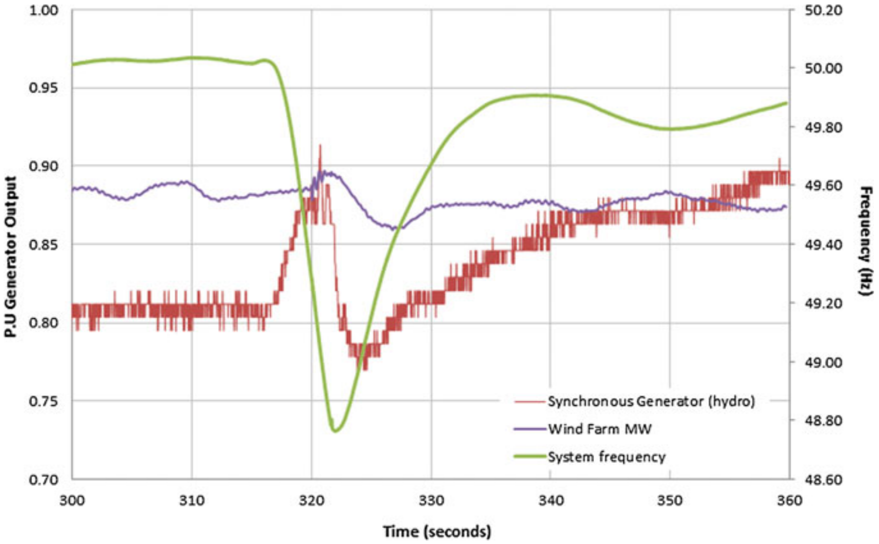
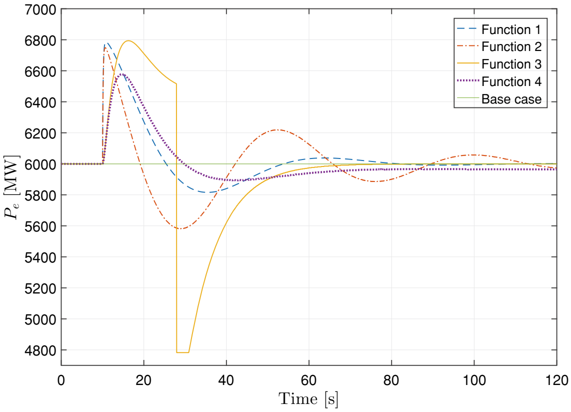


Fig. 10 Measured response of hydro generation and wind to fast-moving frequency disturbance in Tasmania, Australia

Fig. 11 Simulated electrical power from wind power for different combinations of wind power control. Simulated cases had a 30 GW system load and 20 % wind power production [76]



response show slower power response. With no frequency support, the wind turbine shows a negligible response to a frequency disturbance in the grid. The dynamic response of the wind turbine differs depending on the wind power control method, as does the system frequency recovery.

6.2 Potential Future Impacts

The future electricity supply system is expected to transition from one based primarily on synchronous machines to one dominated by power electronic interfaced energy sources and loads. There will be increased reliance on transmission solutions to solve power system dynamics problems that will also be based on PE (i.e. HVDC and flexible AC transmission systems (FACTS)).

Transmission interconnections will be used also to gain access to various ancillary services and capacity reserves in times of local area shortages. There will be increased use of HVDC technology in order to improve controllability and provide access to remote sources. HVDC and power electronic equipment have a very different dynamic response and performance compared with conventional generation and AC transmission. HVDC import from other synchronous areas reduces inertia and short-circuit levels compared with the situation when the same amount is produced locally with synchronous generators. Reduced inertia and low short-circuit levels negatively impact power system dynamics.

The delivery of fast frequency response from PE, coupled with the development of converter control systems capable of emulating synchronous machine behaviours (virtual synchronous generator), is likely to complement a resurgence of synchronous condenser installations in coming years.

Prices of many emerging technologies have decreased and are forecast to decrease further, and as a result, there will be an increasing wide-spread penetration of distributed energy resources (DER) such as rooftop PV embedded in the distribution grids. High penetration levels of many small generators and intelligent loads (including such things as ‘smart’ thermostats as well as charging devices for electric vehicles and embedded energy storage modules) will require the emergence of an active distribution grid that will need to have improved observability and controllability for the operators responsible for system security. This will require the ongoing development of communication systems and data management systems so that system operators not only have the tools to assess the state of the network but can also actively manage various aspects of power system security when needed.

Energy storage comes in many forms [77] in order to provide services such as frequency regulation, mitigating transmission congestion, smoothing out the variability of wind and solar installations or for supplying peaking capacity. Increased penetration of energy storage is expected in both distribution and transmission networks as prices of technology decrease and new ancillary service markets emerge. Managing charging and discharging will be challenging in order to ensure sufficient capacity and reserves are available.

Simulation software and positive-sequence models are mature for conventional power systems (i.e. where synchronous generators provide a large share of electricity, the system has relatively high inertia and the distribution grids are passive). Existing tools and models will still have their place in the future to a certain extent, but their limitations need to be understood as fast-acting, power electronic-based equipment has an ever-increasing impact on the performance and dynamic response characteristics of the electricity supply system.

6.3 Future Analysis Requirements

Many areas of the world are beginning to examine the effects of the changing electricity supply system. In North America, studies are focusing on the increase of renewable energy penetration (up to 100%) on the grid partly to get ahead of the curve and partly because of emerging renewable portfolio standards. California, for example, recently passed a 100% carbon-free bill in 2018 that plans to eliminate carbon emissions from the state by 2045. Many islanded networks like Ireland [75] have aggressive plans to approach being 100% renewable. In other areas, like Australia, favourable policies have resulted in high penetration levels of rooftop solar PV and grid-connected wind generation that have led to stability challenges [78]. In Europe, studies are also underway to find solutions for the technological challenges the future grid may be faced with [79, 80]. One of the ways to find solutions to these challenges is to modify existing simulation tools and analysis techniques.

In general, there is an increasing need for three-phase EMT simulations to accurately predict the dynamic behaviour of fast-acting PE. Computing power has improved dramatically, but EMT simulations are still relatively slow compared with traditional positive-sequence-based transient stability tools unless large areas of the network are reduced and replaced by an equivalent representation. There is a potential loss of accuracy if network reduction is not undertaken appropriately. To some extent, real-time simulators (RTSs) bridge the gap between model accuracy and speed of response. Although, for extensive contingency analysis, faster than real-time tools will be required. The use of hybrid simulations which enable EMT and positive-sequence models to be interfaced and run together in parallel is another already available tool, but which may see increased relevance going forward to address the various issues which have been outlined.

With more converter-interfaced generation in the system, together with a lack of experience about the system's actual dynamic behaviour, it may be impossible to know what simulation model parameters give the correct results. It follows that specialised grid tests may be needed in future for model and parameter verification. Where tests are not practical to implement, there is likely to be an increased reliance on model verification using high-speed measurement data coming from phasor measurement units (PMU) and other such transient recording equipment. The ability to identify and extract meaningful data from large volumes of accumulated measurements will require improvements in data mining techniques as well as efficient tools to work with 'big data sets'.

There is a growing need to better represent sub-transmission and distribution networks where significant DER (distributed energy resources) and energy storage may be connected. Among other issues, this includes the ability to analyse (as well as possibly test) fault-ride-through capability and the resulting risk of sympathetic tripping for upstream transmission disturbances. Better co-operation between distribution system operators (DSOs) and transmission system operators (TSOs) is needed to share model information, especially when the dynamic response characteristics of DER can impact the broader grid.

To address these challenges, it is important to recognise the need to develop new skill sets in conjunction with the required analysis tools. The operation of power systems is becoming increasingly complex and will require the ongoing upskilling of current practitioners as well as the development of appropriate training courses for the next generation of engineers. Traditional power engineering study programs and courses will need to adapt and/or expand to maintain relevance and ensure that contemporary issues (e.g. PE and control systems) are being taught. This includes opportunities for research and development at post-graduate levels. The need for specialised analysis and modelling skills are only likely to increase as the complexity of the power system grows.

6.4 Future Issues

The dynamic behaviour of the power system is observed over a wide time-scale ranging from steady state to seconds or minutes following a disturbance. Specific dynamic phenomena that may result in a system operating limit (e.g. voltage stability, angle stability, frequency stability [81]) being exceeded can differ depending on the particular load or generator dispatch. Increasing intermittent generation gives rise to more variable dispatch scenarios over shorter time periods meaning that system dynamics can change quickly as the different plant is taken offline or committed into service. This makes predicting the dynamic behaviour of the system much more difficult and has the potential to increase the likelihood of ‘local’ network issues occurring. Frequency stability, voltage stability as well as other non-traditional areas, e.g. control interactions between multiple power electronic converters and weak grid operation of power converters at low short-circuit levels, are likely to become areas of increasing concern as renewable penetration levels increase within both transmission and distribution grids.

6.4.1 Frequency Stability

Frequency stability is the ability of the power system to restore an acceptable steady-state frequency following a large disturbance that results in a significant imbalance between load and generation.

Generally, system inertia, mainly existing in the rotating kinetic energy of synchronous generators, decreases as power electronic converter-based generation increases. This can lead to a higher rate of change of frequency (ROCOF) as well as a lower frequency nadir. Frequency-ride-through capability of existing equipment may be inadequate, which will exacerbate the frequency decline if generators trip unexpectedly. In such a situation, under-frequency load shedding (UFLS) relays could activate and trip large amounts of load. Low voltage and high voltage-ride-through capability of converter-connected generators may also be insufficient and lead to additional generation tripping during a disturbance, further impacting frequency performance. The impact of reduced inertia levels can be seen in the simulation results shown in Fig. 12. The ability to adequately control frequency following both credible and non-credible contingency events is likely to become more challenging for many power systems. It can be expected that real-time management of inertia, fast frequency response capabilities (from converter-connected generating systems as well as energy storage) and more traditional frequency control ancillary services will become increasing relevant going forward. The mandatory dispatch of minimum inertia requirements is already a feature in the Australian National Electricity Market (NEM).

Provision of frequency control services, such as fast frequency reserve (FFR) and primary frequency reserve, is expected from new resources such as wind, solar and energy storage systems (including PE interfaced batteries, supercapacitors and pumped hydro) as well as traditional devices such as loads, FACTS and HVDC systems to counteract high ROCOF and prevent undesirable UFLS operation. Detailed modelling and analysis will be required to ensure frequency stability. The more

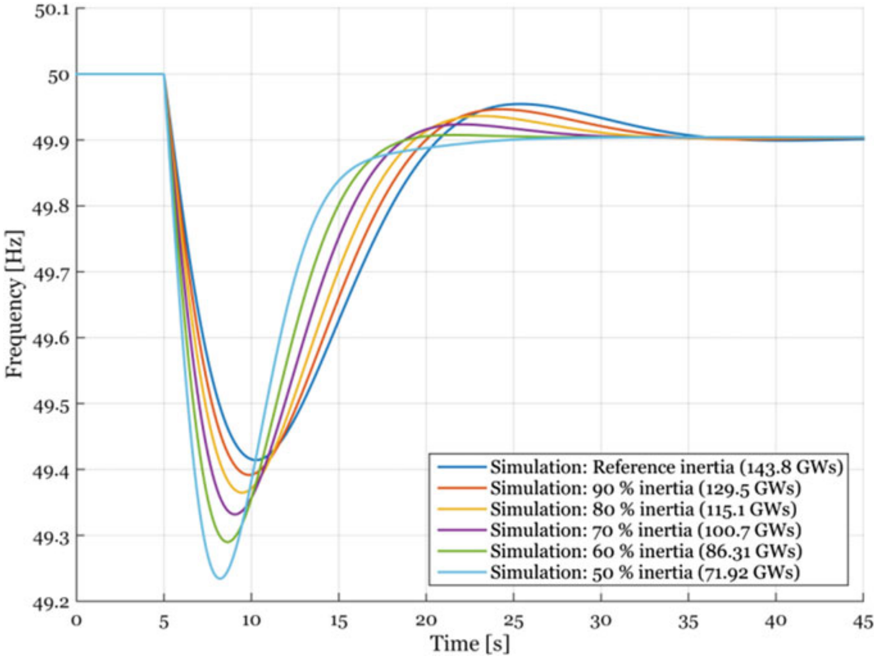


Fig. 12 Simulated frequency variations with different amounts of kinetic energy and inertia in the system [80]

rapidly frequency changes, the more important it is to have a sufficient amount of very fast reserves, which can come from sources other than synchronous generators. According to a study in Texas, during low inertia periods, 1 MW of load resources is up to 2.35 times more effective than 1 MW of primary frequency reserve from the generators [82]. While the use of carefully co-ordinated switchable load can deliver benefits for the control of low-frequency events, care must be taken to ensure that sufficient 'continuous control action' remains available to stabilise frequency and avoid any subsequent over-shoot. This is particularly the case where the size of available load blocks does not allow for fine adjustments, making it more difficult to 'match' load tripping to the size of the contingency event. In such cases, the use of centralised control systems for arming and disarming of switchable loads can deliver benefits especially where the control scheme has access to power system measurements for decision-making purposes. A switchable load scheme exists in Australia whereby the volume of contracted frequency control ancillary service that is armed depends on calculated system inertia, contingency size and the expected load relief. In this case, switchable loads provide a useful supplement to, but do not replace, the continuous control action provided by generating systems and HVDC.

6.4.2 Voltage Stability

Voltage stability is the ability to maintain acceptable voltages and reactive power balance following a disturbance such as a generator trip or a line fault followed by a circuit trip.

Voltage stability in future power networks may actually improve as FACTS devices become more common including VSC-based HVDC transmission systems. However, the rapid speed of voltage regulator response can give rise to control instability (e.g. 10–30 Hz oscillations) if not properly tuned or designed for weak system or low short-circuit systems. Traditional FACTS devices typically monitor the local system strength or detect expected oscillations and automatically adjust the voltage regulator gain [83]. Weak systems (i.e. short-circuit ratio of three or less) can affect the performance of HVDC converters and other power electronic connected equipment. Post-fault recovery rates following fault clearing may need to be decreased to prevent voltage collapse or increased to ensure frequency stability.

The role of synchronous condensers is likely to be revisited in the future power system—a return to the past in some ways—in order to provide voltage and reactive power control, inertia and/or short-circuit current (i.e. system strength) support where needed.

A geomagnetic disturbance (GMD) can induce relatively large DC currents to flow in the power system. This DC current is characterised as being quasi-DC with an ultra-low frequency between 1 mHz and 1 Hz. It could saturate transformers resulting in harmonic concerns as well as increased reactive power demand, thereby causing low voltage concerns potentially leading to voltage collapse. The future power system is expected to remain resilient against these types of disturbances even as low short-circuit levels become more common.

6.4.3 Transient Stability

Transient stability or rotor angle stability is the ability to maintain synchronism following large disturbances such as a multi-phase fault followed by the disconnection of a transmission line. With fewer synchronous machines that might also be more electrically dispersed across the power system, there is a need to consider how transient stability could be degraded due to reduced levels of synchronising torque and inertia. While generation connected via a power electronic converter is immune to classical rotor angle stability, the phase-locked loop (PLL) within a converter will still need to track the local voltage angle and remain synchronised during and following fault clearance. Where the local rate of change of voltage angle is high, consideration should be given to both the fault-ride-through capability of power converters as well as the transient stability of nearby synchronous generating units.

6.4.4 Small Signal Stability

Small signal stability is the ability of the power system to maintain synchronism beyond ‘first swing’ as well as adequately control the damping of power oscillations following network disturbances. Instabilities of this type have traditionally been due to insufficient damping torque being provided by synchronous generating units, often remedied through excitation system tuning modifications or the installation of power system stabilisers (PSSs).

Depending on dispatch outcomes, high penetration levels of renewables will result in fewer synchronous machines being online and may result in less ‘traditional’ damping torque being available within the network. This could be due to synchronous generators fitted with PSS equipment being dispatched less often, potentially leading to a higher probability of poorly damped low-frequency oscillations. It will be important to understand what generating units are fitted with stabilising equipment and are likely to remain part of future generation dispatch scenarios. Potential mitigations could be provided from power oscillation damping controls installed on strategically located FACTS, HVDC and other power electronic devices.

6.4.5 Non-traditional Dynamic Behaviour

Historically, sub-synchronous oscillation (SSO) is defined as a condition when the electric power system exchanges significant amounts of energy with a turbine generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system following a disturbance [84].

A more specific definition of sub-synchronous resonance (SSR) was then accepted to cover the oscillatory attributes of electrical and mechanical variables associated with turbine generators when coupled to a series compensated transmission system. The oscillatory interchange of energy can be lightly damped, undamped or even negatively damped and growing [84].

Three specific interactions between a generator and the electric power system have been commonly investigated and reported in the literature:

- Induction generator effect (IGE)
- Torsional interaction
- Torque amplification or transient torque effect.

In addition to the interactions between a series compensated system and turbo generator, other device-dependent sub-synchronous oscillation cases can also be observed. These devices range from PSSs to HVDC converter controls, static VAR compensator (SVC), high-speed governor controls and variable speed drives. These are mainly fast power regulation devices and although in the past the issue was referred to as device-dependent sub-synchronous oscillation, it is nowadays more commonly referred to as sub-synchronous torsional interactions (SSTI).

A most recent addition to the above phenomena is the control interaction that occurs between any power electronic device and a series capacitor compensated system [85]. This is referred to as sub-synchronous control interaction or instability (SSCI) and is often confused with SSR. However, the main difference of SSCI is that it does not involve any mechanical interaction and has no fixed frequency of concern (as is the case with fixed mechanical torsional modes in SSR). It should be noted that the IGE may also have some impact on exacerbating SSCI, but this is not reported as a major concern [86].

SSTI is the interaction between the mechanical torsional masses in a turbine generator unit such as a wind turbine generator and a power electronic device such as HVDC or FACTS. The power electronic device can exhibit negative damping to sub-synchronous frequencies. SSCI is the interaction between a power electronic device (e.g. Type 3 wind turbine generator) and a series-compensated transmission line. In 2009, wind projects in Texas and North Dakota experienced SSCI [86].

Multiple power electronic inverters connected in close proximity can lead to a multi-infeed configuration. Conventional HVDC systems with line commutated converters are known to have the potential for control interactions if the system is weak [87]. It is expected that similar concerns could result in other power electronic converters in close electrical proximity.

System flexibility has traditionally come from synchronous generators (e.g. spinning reserves from hydro-power and from flexible thermal power plants). System flexibility is becoming scarcer as thermal-based synchronous generators are turned off and the flexibility must come also from other sources (e.g. demand, HVDC systems connected to other synchronous systems, batteries and via new controls on wind and solar plants). Unforeseen control interactions could result if controls are not properly designed and implemented.

Loads have traditionally been represented by a static load model commonly referred to as a ZIP model, and it may be comprised of constant impedance (Z), constant current (I) and constant power (P) characteristics. The load dynamics of the future power system are not well known. Composite static and dynamic load models reflecting high penetration levels of power electronic loads may become necessary in order to capture the dynamic behaviour.

6.5 Research and Development Needs

The scope of power system dynamics within Study Committee C4 includes the development of advanced tools, new analytical techniques for assessment of power system dynamic performance, security, design of controls and modelling of existing and new equipment, real-time stability evaluation and control. The system technical performance of the future electricity supply system could be improved by further research in the following keys areas.

6.5.1 Modelling

Development of improved load, storage and distributed generator models noting that the characteristics of some of these devices have evolved rapidly in recent years (i.e. LED lighting, dominance of inverter interfaced motor loads and generators, very high concentration of switched-mode power supplies, storage batteries able to serve several purposes such as providing fast frequency reserves and reactive power). As an example, two recent disturbances in the USA highlighted potential concerns with the current models of solar generation [88, 89]. The frequency and voltage ride-through capability were not known to the grid operator and an additional 900–1200 MW of generation was lost unexpectedly following a grid disturbance, which primarily affected frequency response. Similar operational experiences are being accumulated in Australia with the output of embedded PV noted to reduce by substantial amounts (hundreds of MW) following fault events in the transmission network [27, 90].

Given the significance of small-scale solar generation in Australia with approximately 9.4 GW of PV now installed [91], the Australian Energy Market Operator (AEMO) is currently supporting research activities to develop improved composite load models which will include the critical dynamic performance characteristics of embedded PV generating systems. Other system operators have also expressed similar ambitions in response to the increasing penetration of distributed energy resources in their networks [31]. Notably, CIGRE has supported the development of methods for accurately representing the aggregate response of active distribution networks (inclusive of embedded generation and storage) as well as the aggregate response of network loads for grid studies [92].

Both individual and aggregate model development will require sensors and measurements in order to confirm the accuracy of parameter values and their robustness as load and generation changes over time. In some cases, synchronised measurements in each phase may need to be considered using PMU techniques. As penetration levels of inverter-based generation increase, it is becoming increasingly important that the dynamic models used to represent all generating resources accurately match the performance of equipment installed in the field.

Synchronous generator dynamics and how they interact with the power system, for example, the shaft rotational speed and its variations, are largely dictated by the laws of physics. However, even conventional synchronous generators have control systems which can be used to vary the response of a machine within practical limits, i.e. excitation and governor control systems being two of the most important. Such control arrangements have a long history, with generic simulation models readily available which provide sufficiently accurate simulation results in many circumstances.

Modern converter-connected generators are connected to the grid via power electronic converters and not via the magnetic flux linkage in a generator's air gap. Therefore, the interaction between the generator and power system becomes quite different, with the network interaction being more dictated by the rating of the power electronic converters and the tuning of multi-layered control systems rather than the pure physics defined through a magnetic coupling.

The change from physics-driven dynamics (with some contribution from controls) to purely control-driven dynamics has changed various aspects of modelling. Modelling is now more dependent on the manufacturer and on the way the controls have been specifically designed. Different manufacturers have different control strategies to suit various applications and equipment designs. Therefore, using generic models does not necessarily give the correct simulation results, especially when protection functions must be adequately represented. While manufacturers may have detailed models available for design and in-house testing purposes, they can be too complicated and laborious for use in simulating the complete power system. An ongoing challenge for the industry is therefore to develop models which can replicate the key performance characteristics of all network-connected plant and equipment, but which are simple enough to be combined and used for practical analysis of the interconnected power system.

In general, transmission planners and operators want to have publicly available or generic models with parameters specific to the original equipment manufacturer. The second-generation generic models have evolved from work in the US and by the IEC [90].

Figure 13 shows an example of the differences that exist in the simulation results between a detailed vendor model and a generic full-converter decoupled generator representation.

Simulation Methods

Ongoing development of methods to simulate large portions of the power system on electromagnetic transient and real-time simulators can be expected. This is to enable the effects of power electronic interfaced equipment to be properly considered in the appropriate time frames. Developments should consider techniques to speed up simulations, such as by using hybrid or multi-rate simulation, while maintaining high accuracy [93].

The role of real-time monitoring (measuring) and stability analysis systems to complement offline simulations that are used to predict stability limits will also need to evolve. With various aspects of the power system getting harder to predict and simulate with known accuracy, better online tools to monitor the 'real' performance or state of the power system will be needed, such as inertia or short-circuit level.

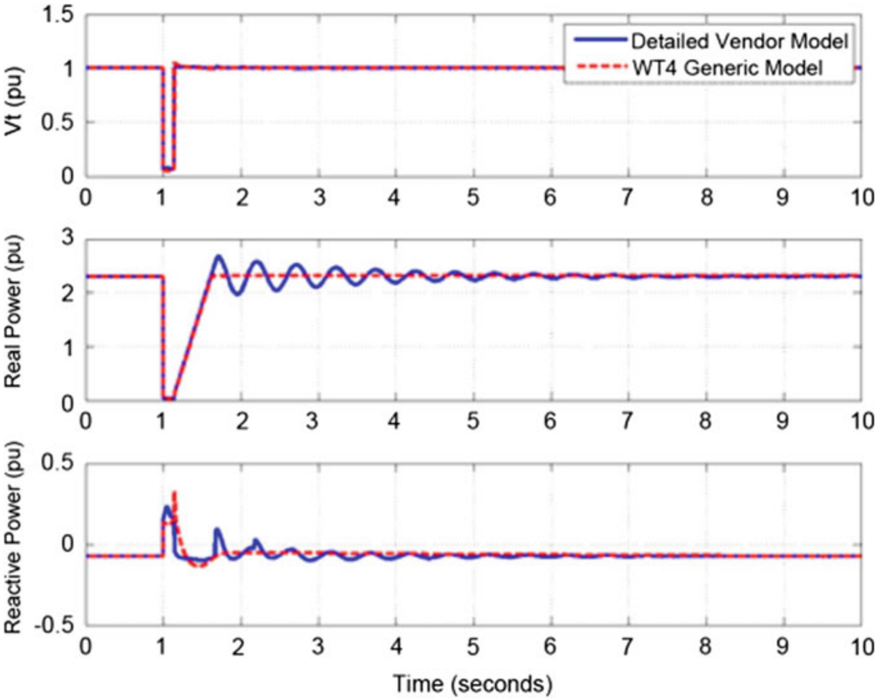


Fig. 13 Example of the validation results when comparing the full-converter decoupled generic generator model (WT4) and a detailed vendor model [91]

Once the concepts of wide-area protection and control (e.g. based on PMUs) further mature, they are expected to play a more significant role in improving dynamic performance.

Planning typically involves testing the system at only a few points such as peak load or light load conditions. New methods will be needed to find the critical cases in future power systems.

Traditional resource adequacy methods determine if sufficient capacity is available to meet the loss of load expectation (LOLE) or equivalent unserved energy (EUE) metric. The future power system is expected to be more energy limited rather than capacity limited. Probabilistic methods and tools will need to evolve to capture the new characteristic of the future power system. This will incorporate ongoing developments in wind and solar forecasting as well as processes to efficiently and economically manage reserves to cater for any residual errors in those forecasts. In this case, the simulation time window goes beyond the micro- and milliseconds relevant for fast power system dynamics, and extends to days, weeks and months with the objective of ensuring that all energy needs can be satisfied.

Acknowledgements CIGRE Study Committee C4 gratefully acknowledges the main contributors to this work (in alphabetical order): Claus Leth Bak (Aalborg University), John van Coller (University of the Witwatersrand), Gerhard Diendorfer (OVE), Vic Gosbell (University of Wollongong), Liisa Haarla (Fingrid), Andrew Halley (TasNetworks), David Jacobson (Manitoba Hydro), Stephan Pack (Technical University of Graz), Sarath Perera (University of Wollongong), WH Siew (University of Strathclyde), Wolfgang Schulz (OVE), Filipe Faria da Silva (Aalborg University) and Ivo Uglesic (University of Zagreb).

References

1. IEC 61000-6-5:2015, Electromagnetic compatibility (EMC)—Part 6-5: Generic standards—Immunity for equipment used in power station and substation environment
2. IEC 62920:2017, Photovoltaic power generating systems—EMC requirements and test methods for power conversion equipment
3. IEC 61800-3:2017, Adjustable speed electrical power drive systems—Part 3: EMC requirements and specific test methods
4. IEC 62040-2:2016, Uninterruptible power systems (UPS)—Part 2: Electromagnetic compatibility (EMC) requirements
5. Dugan, R.C., McGranaghan, M.F., Santoso, S., Beaty, H.W.: Electrical Power Systems Quality, 3rd ed. McGraw-Hill (2012)
6. CIGRE TB 719, Power Quality and EMC Issues with Future Electricity Networks, March 2018
7. Australian Energy Market Operator, AEMO, Fact Sheet: System Strength, Dec 4, 2016
8. Sabin, D.D., Grebe, T.E., Sundaram, A.: Preliminary results for eighteen months of monitoring from the EPRI distribution power quality project. In: Proceedings of 4th International Conference on Power Quality: End-Use Applications and Perspectives (PQA'95), New York, New York, May 1995
9. Gosbell, V.J., Smith, V.W., Barr, R., Perera, B.S.P.: A methodology for a national power quality survey of distribution networks. J. Electr. Electron. Eng. **21**(3), 181–188 (2002)
10. https://copperalliance.org.uk/knowledge-base/resource-library/power-quality-utilisation-guide/
11. Elphick, S., Gosbell, V., Barr, R.: The Australian power quality monitoring project. In: EEA Annual Conference, Auckland, New Zealand, June 2006
12. Elphick, S., Ciufo, P., Drury, G., Smith, V., Perera, S., Gosbell, V.: Large scale proactive power-quality monitoring: an example from Australia. IEEE Trans. Power Delivery **32**(2), 881–889 (2017). https://doi.org/10.1109/TPWRD.2016.2562680
13. Global Wind Energy Council, Global Wind Report, Annual Market Update 2017. Available at: https://theswitch.com/2018/04/25/global-wind-report-annual-market-update/ (2017)
14. Solar Power Europe, Global Market Outlook For Solar Power/2018–2022
15. Halley, A., Martins, N., Gomes, P., Jacobson, D., Sattinger, W., Fang, Y., Haarla, L., Emin, Z., Val Escudero, M., Almeida De Graaff, S., Sewdien, V., Bose, A.: Effects of increasing power electronics based technology on power system stability: performance and operations. CIGRE Sci. Eng. No 11 (June 2018)
16. Emin, Z., Almeida de Graaf, S.: Effects of increasing power electronics based technology on power system stability: performance and operations. In: CIGRE Electra No 298, p. 10 (June 2018)
17. Appleyard, D.: Pumped storage hydropower round-up. Hydro Rev. **23**(6) (2015)
18. Ronnberg, S.K., et al.: The expected impact of four major changes in the grid on power quality—a review. CIGRE Sci. Eng. No 8, pp. 85–97 (June 2017)
19. Jensen, C.F., Kocewiak, L.H., Emin, Z.: Amplification of harmonic background distortion in wind power plants with long high voltage connections. CIGRE Sci. Eng. No 7, pp. 109–116 (February 2017)

20. Australian Energy Market Operator, AEMO, System Strength Requirements Methodology System Strength Requirements & Fault Level Shortfalls, Final, July 1, 2018
21. Australian Energy Market Operator, AEMO, System Strength Impact Assessment Guidelines, Final 1, July 1 2018
22. Bodger, P.S., Irwin, G.D., Woodford, D.: Controlling harmonic instability of HVDC links connected to weak AC systems. IEEE Trans. Power Delivery **5**(4), 2039–2046 (1994)
23. CIGRE TB 672, Power Quality Aspects of Solar Power, December 201)
24. CIGRE TB 586, Capacity of Distribution Feeders for Hosting DER, June 2014
25. Impact of IEEE 1547 Standard on Smart Inverters, IEEE PES Industry Technical Support Task Force, Technical Report PES-TR67, May 2018
26. Darmawardana, D., Perera, S., Meyer, J., Robinson, D., Jayatunga, U., Elphick, S.: Development of high frequency (Supraharmonic) models of small-scale (<5 kW), single-phase, grid-tied PV inverters based on laboratory experiments. Electr. Power Syst. Res. **177**, 105990-1–105990-18 (2019)
27. Darmawardana, D., Perera, S., Meyer, J., Robinson, D., David, J., Jayatunga, U.: Impact of high frequency emissions (2–150 kHz) on lifetime degradation of electrolytic capacitors in grid connected equipment. In: Proceedings of the IEEE PES General Meeting, Atlanta, 4–8 Aug 2019
28. CIGRE TB 527, Coping with Limits for Very High Penetrations of Renewable Energy, February 2013
29. Xu, W.: The future of power quality research. Presented at Plenary Session, 18 International Conference on Harmonics and Quality of Power, ICHQP2018, Ljubljana, Slovenia, May 13–16, 2018
30. IEC 60071-1: 2006-01, Insulation co-ordination—Part 1: Definitions, principles and rules, Edition 8.0
31. Xue, H., Ametani, A., Mahseredjian, J.: Very fast transients in a 500 kV gas-insulated substation. IEEE Trans. Power Delivery **34**(2), 527–637 (2019). https://doi.org/10.1109/TPWRD.2018.2874331
32. Plesch, J., Sperling, E., Achleitner, G., Pack, S.: Measurement of transient voltages in a substation. In: CIGRE Symposium, Lund/Sweden (2015)
33. Meier, J., Stiegler, R., Klatt, M., Elst, M., Sperling, E.: Accuracy of harmonic voltage transformers in the frequency range up to 5 kHz using conventional insulation transformers. In: 21st. International Conference on Electricity Distribution, CIRED, Frankfurt/Germany, Paper 0917 (2011)
34. IEC TR 61869-103: 2012-05, Instrument transformer—The use of instrument transformer for power quality measurement
35. Sperling, E., Schegner, P.: A possibility to measure power quality with RC-divider. In: CIRED Conference Stockholm/Sweden, Paper 0195 (2013)
36. CIGRE TB 704, Evaluation of Lightning Shielding Analysis Methods for EHV and UHV DC and AC Transmission lines, October 2017
37. Fairley, P.: A grid as big as China. IEEE Spectr. **56**(3), 36–41 (2019)
38. CIGRE TB 781, Impact of soil-parameter frequency dependence on the response of grounding electrodes and on the lightning performance of electrical systems, October 2019
39. IEC TR 62305-1:2010, Protection against lightning—Part 1: General principles
40. IEEE Std 1410-2010: IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines (2010)
41. Armstrong, H.R., Whitehead, E.R.: Field and analytical studies of transmission line shielding. IEEE Trans. Power Apparatus Syst. **PAS-87**(1), 270–281 (1968). https://doi.org/10.1109/tpas.1968.291999
42. IEEE Std 1243-1997: IEEE Guide for Improving the Lightning Performance of Transmission Lines (1997)
43. CIGRE TB 63, Guide to procedures for estimating the lightning performance of transmission lines (1991)

44. Diendorfer, G., Schulz, W.: Ground flash density and lightning exposure of power transmission lines. In: Power Tech Conference Proceedings, IEEE, Bologna, Italy, 2003. https://doi.org/10.1109/PTC.2003.1304476
45. Bernstein, R., Samm, R., Cummins, K., Pyle, R., Tuel, J.: Lightning detection network averts damage and speeds restoration. IEEE Comput. Appl. Power **9**(2) (1996). https://doi.org/10.1109/67.491513
46. Cummins, K., Krider, E., Malone, M.: The US national lightning detection network/sup TM/ and applications of cloud-to-ground lightning data by electric power utilities. IEEE Trans. Electromag. Compatibility **40**(4) (1998). https://doi.org/10.1109/15.736207
47. Nag, A., Schulz, M.J.M.W., Cummins, K.L.: Lightning locating systems: Insights on characteristics and validation techniques. Earth Space Sci. **2**(4) (2015). https://doi.org/10.1002/2014EA000051
48. Finke, U., Kreyer, O.: Detect and Locate Lightning Events from Geostationary Satellite Observations (Report Part I): Review of existing lightning location systems", Institute fürMeteorologie und Klimatologie, Universität Hannover, Hannover, Germany (September 2002)
49. Rodrigues, R., Mendes, V., Catalao, J.: Lightning data observed with lightning location system in Portugal. IEEE Trans. Power Delivery **25**(2) (2010). https://doi.org/10.1109/tpwrd.2009.2037325
50. Bourscheidt, V., Jr., Pinto, O., Naccarato, K.: Improvements on lightning density estimation based on analysis of lightning location system performance parameters: Brazilian case. IEEE Trans. Geosci. Rem. Sens. **52**(3) (2014). https://doi.org/10.1109/tgrs.2013.2253109
51. Nag, A., Murphy, M.J., Schulz, W., Cummins, K.L.: Lightning locating systems: insights on characteristics and validation techniques. Earth Space Sci. **2**(4), 65–93 (2015). https://doi.org/10.1002/2014EA000051
52. Schulz, W., Diendorfer, G., Pedeboy, S., Poelman, D.R.: The European lightning location system EUCLID—Part 1: performance analysis and validation. Nat. Hazards Earth Syst. Sci. **16**(2), 595–605 (2016). https://doi.org/10.5194/nhess-16-595-2016
53. Cummins, K.L., Murphy, M.J.: An overview of lightning locating systems: history, techniques, and data uses, with an in-depth look at the U.S. NLDN. IEEE Trans. Electromagn. Compat. **51**(3), 499–518 (2009). https://doi.org/10.1109/TEMC.2009.2023450
54. Mallick, S., et al.: Performance characteristics of the ENTLN evaluated using rocket-triggered lightning data. Electr. Power Syst. Res. **118**, 15–28 (2015)
55. Zhu, Y., et al.: Evaluation of ENTLN performance characteristics based on the ground-truth natural and rocket-triggered lightning data acquired in Florida. J. Geophys. Res. Atmosp. **122**(18) (2017). https://doi.org/10.1002/2017JD027270
56. Betz, H.-D.: Lightning location with 'LINET' in Europe. In: International Conference on Lightning Protection (ICLP), Cagliari, Italy (2010)
57. Cummins, K.L.: Analysis of multiple ground contacts in cloud-to-ground flashes using LLS data: the impact of complex terrain. In: International Lightning Detection Conference and International Lightning Meteorology Conference (ILDC/ILMC), April 2012 Broomfield, Colorado, USA
58. Pedeboy, S.: Identification of the multiple ground contacts flashes with lightning location systems. In: 22nd International Lightning Detection Conference and 4th International Lightning Meteorology Conference (ILDC/ILMC), Broomfield, Colorado, USA (2012)
59. Schulz, W., Pedeboy, S., Saba, M.M.F.: LLS detection efficiency of ground strike points. In: 2014 International Conference on Lightning Protection (ICLP), Shanghai, China. https://doi.org/10.1109/iclp.2014.6973097
60. Pédeboy, S., Schulz, W.: Validation of a ground strike point identification algorithm based on ground truth data. In: International Lightning Detection Conference and International Lightning Meteorology Conference (ILDC/ILMC), Tucson, Arizona, USA (2014 March)
61. Campos, L.Z.S., Cummins, K.L., Pinto, O.J.: An algorithm for identifying ground strike points from return stroke data provided by Lightning Location Systems. In: Asia-Pacific Conference on Lightning (APL) (2015)

62. Campos, L.Z.S.: On the mechanisms that lead to multiple ground contacts in lightning, Ph.D. Thesis, Instituto Nacional de PesquisasEspaciais INPE, Brazil (2016)
63. Takami, J., Okabe, S.: Characteristics of direct lightning strokes to phase conductors of UHV transmission lines. IEEE Trans. Power Delivery **22**(1), 537–546 (2007). https://doi.org/10.1109/TPWRD.2006.887102
64. Taniguchi, S., Tsuboi, T., Okabe, S.: Observation results of lightning shielding for large-scale transmission lines. IEEE Trans. Dielectr. Electr. Insul. **16**(2), 552–559 (2009). https://doi.org/10.1109/TDEI.2009.4815191
65. Taniguchi, S., Tsuboi, T., Okabe, S., Nagaraki, Y., Takami, J., Ota, H.: Improved method of calculating lightning stroke rate to large-sized transmission lines based on electric geometry model. IEEE Trans. Dielectr. Electr. Insul. **17**(1), 53–62 (2010). https://doi.org/10.1109/TDEI.2010.5412002
66. Saba, M.M.F., PAlva, A.R., Schuman, C., Ferro, M.A.S., Naccarato, K.P., Silva, J.C.O., Sigueira, F.v.C., Custodio, D.M.: Lightning attachment process to common buildings. Geophys. Res. Lett. (2017). https://doi.org/10.1002/2017GL072796
67. Wang, D., Takagi, N., Gamerota, W.R., Uman, M.A., Jordan, D.M.: Lightning attachment processes of three natural lightning discharges. J. Geophys. Res. Atmosp. **120**(20) (2015). https://doi.org/10.1002/2015JD023734
68. Tsuge, K., Yamada, H.: Application technology of lightning arrester for 275 kV transmission lines. In: 28th International Conference on Lightning Protection ICLP 2006, September 18–22, Kanazawa-Japan (2006)
69. Kawamura, T., et al.: Development of metal-oxide transmission line arrester and its effectiveness. In: CIGRE 1994 Session, Reference 33-201
70. Kawamura, T., et al.:"Experience and effectiveness of application of arresters to overhead lines. In: CIGRE 1998 Session, Reference 33-301
71. Shigeno, T.: Experience and effectiveness of transmission line arresters. In: IEEE PES Transmission and Distribution Conference and Exhibition: Asia and Pacific, 6–10 October 2002, Yokohama, Japan. https://doi.org/10.1109/TDC.2002.1178504
72. Tsuge, K.: Design and performance of external gap type line arrester. In: IEEE PES Transmission and Distribution Conference and Exhibition: Asia and Pacific, 6–10 October 2002, Yokohama, Japan. https://doi.org/10.1109/TDC.2002.1178505
73. Enriquez, G., Velzquez, R., Romualdo, C.: Mexican experience with the application of transmission line arresters. In: CIGRE Session 2006, Reference C4-106-2006
74. Kundur, P.: Power System Stability and Control. McGraw-Hill (1994)
75. O'Sullivan, J., Coughlan, Y., Rourke, S., Kamaluddin, N.: Achieving the highest levels of wind integration—a system operator perspective. IEEE Trans. Sustain. Energy **3**(4), 819–826 (2012). https://doi.org/10.1109/TSTE.2012.2201184
76. Eriksson, R., Modig, N., Elkington, K.: Synthetic Inertia versus fast frequency response—a definition. IET Renew. Power Gener. **12**(5), 507–514 (2018). https://doi.org/10.1049/iet-rpg.2017.037
77. International Energy Agency (IEA), Energy Storage—Technology Roadmap (2014). Available at: https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergystorage.pdf
78. Maisch, M.: AEMO well-prepared for summer, renewables to help manage peak periods. PV magazine, November 17, 2018
79. European Union project, The Massive Integration of Power Electronic Devices (MIGRATE). https://www.h2020-migrate.eu/
80. Future System Inertia, ENTSOE Report, 2017
81. CIGRE TB 231, Definition and Classification of Power System Stability, June 2003
82. Du, P., Matevosyan, J.: Forecast system inertia condition and its impact to integrate more renewables. IEEE Trans. Smart Grid **9**(2), 1531–1533 (2018). https://doi.org/10.1109/TSG.2017.2662318
83. de Oliveira, M., Jacobson, D.: System interaction studies in real-time for the Birchtree SVC. In: IEEE Power and Energy Conference, Winnipeg (2011). https://doi.org/10.1109/EPEC.2011.6070178

84. IEEE Committee Report, Terms, definitions and symbols for subsynchronous oscillations. IEEE Trans. Power Apparatus Syst. **PAS-104**, 1326–1334 (1985). https://doi.org/10.1109/mper.1985.5526631
85. Lawrence, P., Gross, C.: Sub-synchronous grid conditions: new event, new problem, and new solutions. In: Western Protective Relay Conference, Spokane Washington, October 2010
86. Irwin, G.D., Jindal, A.K., Isaacs, A.L.: Sub-synchronous control interactions between type 3 wind turbines and series compensated AC transmission systems. In: IEEE Power and Energy Society General Meeting (2011). https://doi.org/10.1109/PES.2011.6039426
87. CIGRE TB 364, Systems with Multiple DC Infeed, December 2008
88. NERC, 1200 MW Fault Induced Solar PV Resource Interruption Disturbance Report, NERC, June 2017
89. NERC, 900 MW Fault Induced Solar PV Resource Interruption Report, Joint NERC and WECC Staff Report, February 2018
90. NERC, Reliability Guideline Power Plant Model Verification for Inverter-Based Resources, September 2018. https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/PPMV_for_Inverter-Based_Resources.pdf
91. Asmine, M., Brochu, J., Fortmann, J., Gagnon, R., Kazachkov, Y., Langlois, C.-E., Larose, C., Muljadi, E., MacDowell, J., Pourbeik, P., Seman, S.A., Wiens, K.: Model validation for wind turbine generator models. IEEE Trans. Power Syst. **26**(3) (2011). https://doi.org/10.1109/tpwrs.2010.2092794
92. CIGRE TB 457, Development and Operation of Active Distribution Networks, April 2011
93. Zhang, S., Zhu, Y., Ou, K., Guo, Q., Hu, Y., Li, W.: A practical real-time hybrid simulator for modern large HVAC/DC power systems interfacing RTDS and external transient program. In: IEEE Power and Energy Society General Meeting (2016). https://doi.org/10.1109/PESGM.2016.7741596

Genevieve Lietz received the Bachelor of Engineering from the School of Electrical and Computer Engineering, RMIT University and her Ph.D. in analysis and modelling of power systems from the University of Melbourne, Melbourne, Australia, in 2001 and 2007, respectively. She worked at DIgSILENT Pacific, Australia, before relocating to Germany in 2007 to work as a power system engineer and software developer at DIgSILENT GmbH. She is in the Power Systems and Modelling department and works with all aspects of overhead line and cable modelling, power quality and modelling and analysis of harmonics. She is a member of the IEEE and contributed to CIGRE JWG C4/B4.38 Network Modelling for Harmonic Studies. She is currently Secretary of CIGRE Study Committee C4 System Technical Performance and is active in other CIGRE working groups.

Zia Emin received his B.Sc. in Electrical and Electronics Engineering from the Middle East Technical University, Ankara, Turkey, and M.Sc. and Ph.D. degrees from The University of Manchester, Manchester, UK. He has worked as a specialist power system engineer with many years of experience in power quality and switching studies initially with National Grid and later with Parsons Brinckerhoff (later WSP) and PSC. He has extensive knowledge in all aspects of power system modelling including steady-state, frequency- and time-domain modelling and substantial experience in harmonic performance specification for HVDC converter stations, renewable generation connections and the connection of traction supply points. He is Fellow of the Institute of Engineering and Technology (IET-UK), Senior Member of IEEE, Distinguished Member of CIGRE and a Chartered Engineer in UK. He is member of GEL/210/12 Committee at the British Standards Institution and of WG8 in IEC SC77A. He is active in many CIGRE working groups as member, task force leader and convener within system technical performance area related to power quality and insulation co-ordination. He was the past UK representative on CIGRE SC C4 System Technical Performance and is currently the Chairman for the same Study Committee. He received the CIGRE Technical Committee Award in 2013, the Distinguished Member award in 2014 and the Senior and Principal Professional Associate title within Parsons Brinckerhoff reflecting recognition on his technical and professional level. He has served in several colloquia, symposia and conference technical committees and continues to do so. He has over 50 technical publications and is a reviewer in many technical journals of IET, IEEE and other publishers.

Electricity Markets and Regulation

Alex Cruickshank and Yannick Phulpin

The operation of markets and regulations is difficult to predict for 2050 because:

- *There is no uniform starting point between countries and markets; and*
- *The political and social structures of communities differ, which impacts the development of the grid, from a markets and regulation perspective, toward 2050.*

That said, the current markets are discussed in terms of liberalization, cross-zonal and temporal integration, and integration of DER. These categories are further broken down by management of risk, price and cost efficiency, and ability of trading to occur outside of the formal markets.

The extension of the current approach, option 1, where the current overall structure is retained but increasing interconnection between systems, even between continents allows a broader market to develop. The highly interconnected system will allow transfers of energy from areas with good renewable resources, such as hydro and stable low emission resources, such as nuclear, to balance the increased amounts of intermittent, renewable energy and distributed energy. A major development in this option is the integration of existing markets as is currently occurring in Europe and could be expected more in other regions. These are significant changes, which will require new pricing techniques for network and markets. We note that the concepts for these developments are already beginning to occur in advanced markets and that monopoly markets will have increased customer participation under this option.

Option 2, with a reliance on distributed markets and grid structures, is a radical change from the current design and requires the development of complete trading and settlement at the local grid level with net trading between the local grids. The

---

On behalf of CIGRE Study Committee C5

A. Cruickshank (✉)
Oakley Greenwood Pty Ltd, Margate, Australia
e-mail: acruickshank@oakleygreenwood.com.au

Y. Phulpin
EDF, Saint-Denis, France

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_14

use of distributed and local sources of energy rather than reliance on centralized supply is a complete change to market structures and the management of risk, where end users will directly support a significant share of the investments. An approach is included in the chapter. We note that option 2 is less likely than option 1, even with the long lead time of this book, where the social and political structures support and encourage monopoly or government provision of electricity.

This limitation and the nature of market development that currently occurs mean that there is likely to be a variety of market and regulatory forms in 2050, both in the remaining vertical structures and in the operation of the distributed structures.

1 Introduction

This chapter is to examine potential market designs and operations and the regulatory environment for the two potential future states of electricity provision in 2050 described in Chapter "Introduction and Overview":

- A highly connected grid with globalized grid provision of electricity and a high proportion of renewable energy; and
- A system dominated by loosely connected microgrids, which are largely self-contained and contain a large proportion of renewable energy.

This chapter deals with the potential market arrangements for the two future states and related regulatory issues.

While the underlying physics and technologies of the grid will impact the form of the markets and regulation that is required, this chapter does not deal with:

- The economics of system development, which is covered in Chapter "Power System Development and Economics" (SC C1);
- Market and system operation, which is covered in Chapter "Power System Operation and Control" (SC C2);
- The technical aspects of distributed energy resources (DER), which are covered in Chapter "Active Distributed Systems and Distributed Energy Resources" (SC C6); nor
- The information systems and requirements, which are covered in Chapter "Information Systems and Telecommunications" (SC D2).

In addition, other chapters have described the advances in energy market equipment and technology, including the increase in distributed and intermittent, the impact of this increase and the more general advances in the engineering and technical aspects of electricity. While the pace of technical advances can vary, the direction is generally forward (cheaper, better, faster) with occasional leaps as new technologies are developed.

The development of markets and regulation does not always "improve"[1] the electricity service from an end-customer perspective, while there is generally move forward as technology, particularly communication, monitoring, and measurement tools improve. By forward, we mean toward open markets, innovation, and competitive supply. Community faith in markets as a means of reliable supply can, however, reverse. This can lead to an increase in political intervention or substantial reduction in market freedoms. The trade-off between reliable supply, open markets, least cost, and safe supply is not always straightforward.

The recent World Energy Outlook 2018 [12] reports:

> While fully regulated markets with vertically integrated utilities tended to face over-investment, leading to excess capacity, market upheaval was apparent in countries that rely on competitive markets (competition drives about 54% of the world's electricity consumption, it notes). Several jurisdictions—for example, in Colombia, France, and the UK—that rely on markets to attract investment are shifting from markets where energy is the only source of revenue toward the inclusion of a firm or dispatchable capacity product. In the changing business environment, U.S. vertically integrated utilities for the most part kept hybrid generation-retail models, though competitive generators are also moving in that direction.

With increasing availability of technology and increasing retail prices for energy, there is a movement to more distributed supply of energy, increasing self-reliance on the provision and management of energy and a desire to trade locally with or without central supply. While some consider leaving the grid, the need for backup and efficient outcomes generally requires a level of interconnection. This means that we need to consider markets and also non-market actions of connected parties.[2]

Energy markets are in place to optimize the price paid for secure supply of energy. When the security of supply is low or reduced for some reason, communities generally expect more government or regulatory intervention. When supply is highly secure, the question of price dominates, and markets become more competitive.

1.1 Optimizing Energy Supply

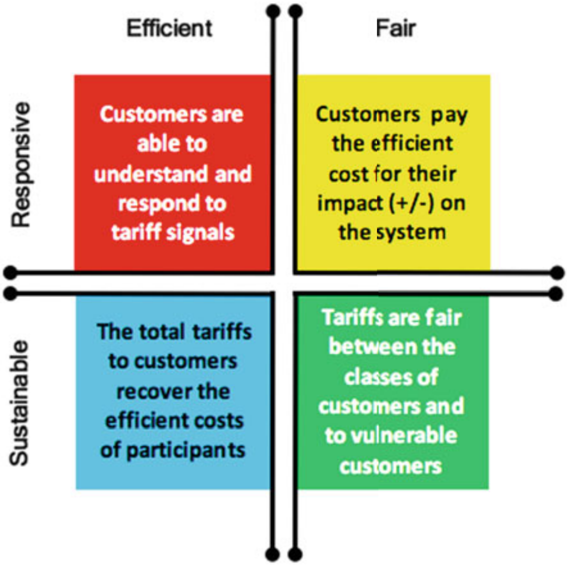
At all levels, the efficient provision of electricity is the aim of all forms of electricity supply systems, whether liberalized or not. The question of efficiency, in terms of the prices paid by customers and their ability to respond to those prices, is central to consideration of the future of the grid.

---

[1] The term "improve" is used for want of a better word. The key requirements of a market are the reliable supply of electricity at minimal cost, while ensuring the safety of the community and the industry theory, competitive markets are seen as the solution by economists but in practice, governments and communities may not always seek the best outcome but rather a good outcome.

[2] For example, one response to high prices is the fitting of LED lights or other energy use reduction, which is economically efficient. Another response is the adoption of PV generation, which can, in the absence of correct charging (see [9]), reduce costs to an individual connection while increasing costs overall.

Fig. 1 Efficient prices from TB 747



When Working Group C5.16 examined retail pricing, discussed in Sect. 2.2 below, they prefaced their technical brochure (29) with a discussion of the efficiency of the entire grid in its supply to end use customers.

The working group noted that efficient supply systems had been described by many authors, for example, Bonbright [20], Simshauser [21], and Farugui [22]. The working group summarized the discussion into Fig. 1, noting that the essential features of efficient supply are that:

- Efficient costs of the entire system are developed and fully recovered for a sustainable and efficient system;
- Tariffs should be fair between customer classes, noting the need to support vulnerable customers, so that system was sustainable and fair;
- All customers should pay or be paid the total efficient cost of the impact of their connection and use of electricity for a fair allocation of system costs and to allow customers to gauge their impact when they make decisions; and
- Customers should be aware of their impacts and be able to be rewarded if they act to minimize their impact, when compared to other costs, allowing efficient use of energy.[3]

The technical brochure noted that efficient tariff, according to the literature cited above would comprise four elements:

- A **fixed charge** to recover costs that were nor specifically related to the actions of customers but that were efficiently occurred, e.g., systems costs;

---

[3] This is the subject of a review by Oakley Greenwood on economic integration of DER [24].

- **Demand charges** to recover costs that were incurred due to the need for fixed assets to generate and transfer the capacity required by customers;
- **Variable costs**, possibly time of use based, to recover costs that were related to the energy consumed at a site; and
- **Policy levies** to recover the imposts of regulators and governments for environmental, social, and other policy reasons.

The technical brochure noted that few tariff regimes clearly delineate these four elements at the small customer level with commercial and industrial customers having more efficient tariffs. Some, particularly European tariffs, contained a measure of demand in the fixed charges, which allowed some measure of efficient recovery.

1.2 Markets to Be Considered

There are two levels of markets to be considered:

- Wholesale—the dispatch of supply to meet demand. These markets dispatch large-scale (usually >10 MW) generation and other electricity supply sources to meet the net operational demand.
  The role of the market and system control is to set the price of electricity that is consistent with an optimal dispatch of energy while ensuring system security. They are also a driver for many investment decisions. The role is both economic and operational; and
- Retail—the trading of energy to and increasingly between customers. Traditionally, the role of retail supply has been to break up wholesale supply to the smaller packages for supply to customers. Beyond supply-cost recovery, retail contracts also aim at delivering economic signals that end users can assess to take efficient investment and operational decisions. Increasingly, smaller-scale distributed generation[4] resources are providing supply within the distribution network and are part of the retail market.
  Some markets are developing for direct sales between customers or to purchase supply from customers. The retail supply is therefore a combination of energy purchased via wholesale markets and from customers with the intent of optimal pricing and efficient supply. This is best summarized:

  > From a regulatory perspective, retail models should ensure affordability and sustainability while maintaining reliability of electricity supply; they should enable customers' empowerment, energy transition policies encouraging higher integration of Distributed Energy Resources (DER) or energy efficiency and better access to the market to new actors such as aggregators, local authorities and consumers. Bialecki et al. [1]

The role of markets is also influenced by community expectations for services. Electricity has become an essential service, which means that its reliable supply is

---

[4] Larger generation, although within the distribution network, may be settled in the wholesale market.

considered to be part of a developed community and the lack of supply, whether at the personal level or for a community, is considered a serious problem.[5]

Note that not all countries or regions within countries use markets for electricity, optimizing dispatch using other criteria and ensuring reliable supply. Working group C5.17, which was investigating capacity remuneration, found that 5 of the 31 markets they surveyed (16%) were not liberalized,[6] that is open to competition for supply.[7] The World Energy Outlook 2018 [12] reported that 46% of regional electricity supplies are not liberalized, suggesting that countries and markets reporting to CIGRE surveys are not always representative of energy supply systems generally.

Working groups C5.16 [9] and C5.19 [5], which were examining retail pricing and demand response found that 85% and 73% (respectively) of surveyed markets had retailer choice for their customers. These figures relate to primarily liberalized markets, where supply competition is also available. While WG C5.16 reported on all of the EU countries and some other markets, markets not covered by CIGRE membership were not included.

We note that environmental policies are tending to increase the imposts on the electricity bills, again leading to higher priced energy for consumers. The imposts can be in the form of obligations to use specific technologies, such as low emissions, but also can restrict the technologies, such as restrictions on the use of nuclear or coal technologies.

1.3 Causes of Market Development

As noted above, the development of markets and regulations in electricity are therefore governed not only by changes in available technology but also by government policies, community expectations, and social factors. Working group C5.20 examined market changes and their drivers and noted that, while environment and technology influence the changes, the market operator and governments actually tend to make the changes, not consumers and participants, who provide the pressure for the changes.

They noted in their conclusions[8]:

---

[5] For example, in Australia, a recent rapid increase in prices combined with a lowering of market reliability has resulted in the threatened reintroduction of price regulation in some states and the introduction of reliability obligations on market participants—a retreat from the pure economic market to a more centrally planned market.

[6] TB 647 [4], page 6. "Not liberalized" includes multiple vertical monopolies service areas within a country or region as well as single monopolies and government owned suppliers.

[7] While all but two members of the EU have liberalized markets and there are some liberalized markets in Asia, North America and South America, many countries retain monopoly suppliers. Only markets and countries that are members of CIGRE respond to these surveys and, therefore, the sample will contain a larger proportion of liberalized markets.

[8] Based on the conclusions in the executive summary of Technical Brochure 709 [7].

- Although one objective of markets is to disaggregate decision making and allocate risks away from central parties to where the risks can be better handled, it appears major changes are driven by central authorities;
- Consultation is very valuable in ensuring development of workable rules but can also be a barrier to reform if market actors are faced with repeated calls for input;
- Consumers will ultimately hold governments and their agencies responsible for poor electric reliability, insecure power system operation and affordability. Therefore, governments and their agencies are likely to be conservative by promoting change, perhaps ahead of other actors (e.g., generators/retailers) who are not held directly accountable; and
- It is inevitable that major change is complex and that the changes in physical or financial operation can lead to unintended outcomes. The Working Group sees merit in designing markets for typical conditions (which of course may change) and protecting against extremes rather than designing for worst case but providing no mechanism to respond to extreme conditions.

The current developments in the grid, with accelerated increases in renewable and intermittent generation due to environmental policies, are leading to higher prices (including levies related with the achievement of policy targets) and reduced grid resilience leading to reduced confidence in pure markets[9] where they currently exist to address the energy transition challenges. This will be noted in the description of the current state of affairs in markets and regulation but not in the description of the end states described under the two scenarios.

The need and volume of subsidies and regulations promoting some technologies and restricting others is usually transitionary and not an issue for the long term. Nevertheless, it is not always clear how these developments will progress where they are subject to political processes[10] rather than economic factors.

This chapter therefore notes political and social influences but assumes that economic drivers and the advances in technology will be the primary factors for consideration for the grid of the future.

---

[9] Note that this chapter, while noting the impacts of environmental policies and legislation, including Anthropomorphic Global Warming (or Human Caused Climate Change), will not address this issue directly. This is the role of Study Committee C3 Power System Environmental Performance and is included in Chapter "Power System Environmental Performance".

[10] For example, while most developed countries have signed the Paris Accord on emissions reductions, the USA a large emitter and a developed country has not. It is, however, significantly reducing its emissions due to the structural shift to gas fired generation, driven by low cost sources as well as significant state level actions on renewables. In addition, other countries, such as France and Australia that are both signatories to the Accord, are facing difficulties at the social/political level from implementing the necessary reforms. The outcomes of the Accord are also heavily influenced by other countries emissions reductions, particularly high emitters that are not signatories.

1.4 The Structure of This Chapter

In this chapter, we will examine the current issues with the change to the mix of supply types, including an increase in embedded supply and demand response. Other chapters will cover the issues of technical integration of new technologies. We outline the current market and regulatory states at a general level and examine what market and regulatory features are required to achieve the two end states postulated in this book based on general reviews, such as the Australian Future Grid Forum.[11]

1.5 Sources of Information

This chapter contains original ideas from members of SC C5, but sections and data have been drawn from relevant papers to the CIGRE Session in 2018 and technical brochures developed by recent working groups. These technical brochures are listed in the bibliography, and specific references will be noted in the text, including the relevant working groups.

2 Current Markets and Regulatory Approaches

There are a number of criteria to compare the potential future of the grid to the current grid operations. For markets and regulation, this is complicated as there are a number of forms in countries and regions. Key characteristics are:

- Monopoly or liberalized wholesale market;
  - Form of the market and management of risk;
  - Mechanisms for ensuring capacity;
  - Integration of renewables; and
  - Efficiency of pricing;
- Retail competition and the form of the retail competition;
  - Form of the retail markets, including "beyond the meter"[12];
  - Efficiency of pricing and management of risk; and

---

[11] The Future Grid Forum [15] examined the future market and grid in Australia using four potential end states (discussed later), two of which are similar to the potential end states in this book. Other countries have also conducted similar reviews, each considering, like this book, how technical, industry and political changes will impact the future of the electrical system.

[12] Beyond the meter operations refers to trading within unregulated networks, known as embedded networks in Australia and private networks in some countries. The increasing role of these networks as effective microgrids is being increasingly reported, for example [1, 2].

  - Integration of distributed energy resources, including demand response and the used of storage (DER).
- Interconnection and trading between markets and countries.

These factors are discussed in the following parts of this section as well as in the discussion of the two options. They are also referred to in the discussions of country developments but less directly.

2.1 Markets and Reliability of Supply

Where market exists,[13] they have the role of ensuring resources are available to operate and efficiently dispatched to optimize and maintain the grid. How markets do this varies depending on their forms and future markets, whether centralized or distributed will need to meet these requirements.

For this chapter, we will define markets by:

- How the pool or balancing market is operated and settled;
- Whether capacity is remunerated separately; and
- How ancillary[14] services are provided.

2.1.1 Market Balancing and Settlement

Gross Dispatch and Settlement

In the Australian NEM, all energy is traded via the wholesale market and the market operator dispatches and settles all of the energy traded. This approach is sometimes referred to as a "gross" market as the gross value of the energy traded is transacted via the market operator.

In this market, all generators offer their plant to the market and are dispatched by the market operator. Each retailer is then required to pay the market operator the full value of the energy purchased during a trading period (in the NEM it is a week). The market operator, having collected the monies from the retailers, pays the generators for the energy dispatched.

As large amounts are potentially owed by retailers at the end of each trading period, there are prudential arrangements to ensure that there will be sufficient funds

---

[13] As discussed in Sect. 1.1, half of the energy systems do not have markets. In these systems planning and the development of capacity is done by the grid operator or government. This chapter will assume that the forms of market in 2050 are mostly competitive.

[14] Frequency control, system restart, voltage support services. These can also be referred to as spinning reserve and other terms. The concept of system strength is being is being incorporated as well.

to pay the generators and defined approaches to manage participant risk [10] and retailer default [11].

In this form of market, participants establish financial contracts between themselves to manage their risk exposures. These contracts may be directly established between participants, termed “over the counter contracts (OTC)” or traded via an exchange such as the Australian Stock Exchange (ASX) or the European Energy Exchange (EEX). These arrangements are discussed in TB 667 [10].

Net Dispatch and Settlement

Other markets, like PJM[15] and the GB balancing market,[16] only trade balancing amounts. In these markets, participants establish physical contracts for supply between themselves and supply the grid operator with generation and demand schedules for each trading day. Prior to the delivery period, the grid operator sums the various generation and schedules as the basis for dispatch and then adjusts the generators, including some that only participate in balancing, to meet demand in real time.

Retailers pay the net difference between their lodged schedules and their actual demand on the day, and generators are paid the net difference between their lodged schedules and their generation on the day. Note that the settlement amounts for each party can be positive or negative.

As the amounts transacted by the market operator are dramatically smaller than in gross settled markets, the prudential arrangements are often less formal in net markets. Technical brochure 667 describes these arrangements in more detail.

In net markets, participants often do not contract to cover their exposures to the balancing market as they can be quite small[17] since the bulk of the energy value is traded bilaterally. If they do want to manage their exposures, they use the same tools, OTC and exchange products, that are used in gross markets.

2.1.2 Remuneration of Capacity in Markets

Markets can be also described in terms of how they remunerate capacity. This was the subject of technical brochure 647 [4], which found that, while there were energy-only markets, like the Australian NEM and ERCOT, and long-standing markets with separate capacity remuneration, like PJM, markets in Europe that had been focusing on energy and balancing reserve were now starting to separately remunerate capacity.

A general characterization is that markets that evolved, like PJM, where existing entities start sharing reserves and that morphs into a market, tend to have separate

---

[15] PJM is a transmission interconnection based market for seven states in the North Eastern part of the United States of America. It is centered on Pennsylvania, New Jersey and Maryland.

[16] There are some differences between the markets. Some, like PJM, dispatch all generators on the day based on a common price established in a day-ahead market. In the GB market, generators opt to participate in the balancing market, which has a separate price.

[17] There are examples of parties in net markets only operating in the balancing market. In these cases, they would utilize contracts to manage their risks.

capacity remuneration. Markets that are designed, like the Australian NEM and the UK market, tended to be energy only. This was based on:

> … under ideal conditions, electricity spot markets provide efficient outcomes in both the short and the long term, meaning that they lead to optimal investment in generation capacity, both in terms of volume and generation technology portfolio. This theory stands; the question is whether it applies in practice, or whether real market conditions deviate too much from the ideal situation. The belief that unregulated markets in electricity generation can produce an optimal outcome in the long term used to be widely shared …—TB 647 page 16 [4]

The increase in the withdrawal of thermal resources due to high levels of renewable generation penetration, and price caps in some markets, has led to general adoption of separate capacity remuneration schemes in Australia, the UK and some European countries as the proportion of reliable, dispatchable plant has decreased. This trend can be expected to continue. In addition, if the trading group size reduces, as option 2 suggests, the need to explicitly fund capacity increases.

2.1.3 Ancillary Services

To maintain reliable supply, there are a number of services that are required by the electricity system that need to be funded via the market. These will have been discussed in Chapter "Power System Operation and Control", particularly the increasing requirements for services that maintain the strength of the system, which used to be provided routinely by synchronous plant.

Funding these services is an essential component of markets. Where possible, these services are incorporated into markets and purchased in conjunction with capacity and energy, ether in parallel with these open offer markets or separately via tenders. Some services, however, are not capable of market provision and have to be purchased through regulatory requirements.

It is beyond the scope of this chapter to deal with the range of ancillary services other than to note that the range of services required is changing due to the increase in intermittent and asynchronous resources in the grid and that all of the services will need to be funded. Chapters "Power System Development and Economics" and "Active Distributed Systems and Distributed Energy Resources" will cover the changing nature of ancillary services provision.

For this chapter, we will assume that the necessary range of services will be defined, and that funding of those services will be part of the market design.

2.2 Retail Contestability and Pricing

Many working groups in market areas note that full retail contestability is not universal. As discussed in the introduction, 46% of markets are not liberalized and

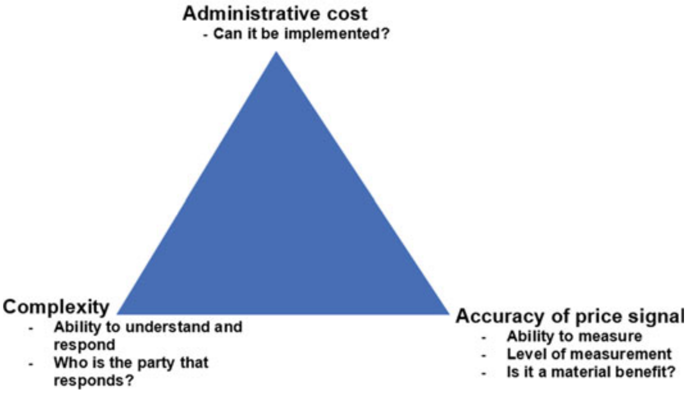


Fig. 2 Tariff trade-offs for customer pricing [24]

of the 54% not all are fully liberalized. Liberalized markets may still have non-competitive prices, but where they do, the combination of efficient wholesale pricing and competitive retail prices should yield the most efficient price for customers.

Working group C5.16 [9] looked at retail pricing, particularly small customer pricing, noting that it was often inefficient. This was independent of the liberalization of the market, although competition for customers should drive efficient prices.

A key consideration is that efficient pricing should provide the optimal use of any system and that efficient tariffs should empower customers to make the best use of the grid and to invest appropriately so that they are part of optimizing the system as whole.[18]

In establishing prices, however, there is almost always a range of potential price signals that could be used to facilitate more efficient outcomes, but these have to be adjusted to meet the circumstances and customer size [24] (Fig. 2).

Generally, developing efficient pricing structures involves making trade-offs between efficiency and:

- **Complexity**. Are the tariffs and rules too complex for the customer to be able to understand them and respond?
- **Accuracy**. Is the tariff element able to be measured so that the tariff is accurate? and
- **Administratively feasible**. Can the tariff be efficiently levied or is the cost of recovery greater that the pricing benefit achieved?

The trade-offs are impacted by the size of the customer. Industrial customers tend to have staff to manage their costs, and suppliers are likely to be able to cope with complexity. In addition, they will normally have higher level metering, and the profit margins on their supply would support more complex tariffs.

---

[18] Paraphrased from Farugui “Bonbright Revisited” [23].

Smaller customers are increasingly being targeted by intermediaries and aggregators [2], who build up portfolios of customers so that better pricing options are available. The does not necessarily mean the use of microgrids, but microgrids may assist in better pricing.

The key point for retailers, intermediaries, and end use customers is that the efficient cost needs to be available at the retail level and be couched in form that allows empowered customers to interact efficiently with the grid.

2.3 Distributed Energy Resources

Distributed energy resource (DER); PV generation, standby plants, co-generation, storage and responsive loads are increasingly part of electricity systems as their costs reduce, the unit sizes match smaller loads, and integration tools become available.

DER from industrial and larger commercial sites has always been available and incorporated into the electricity market to a greater or lesser degree. The key factors causing their increased penetration now include:

- Reduced prices, allowing them to be cost effective as part of a customer energy package;
- Smaller unit sizes that allow their integration into customer sites, often without export to the grid and the complications that entails;
- Better control systems that allow more efficient control of DER as part of site operation; and
- Renewable energy subsidies.

Not all of these factors are present for all installations. A key factor for many sites is the subsidies for both the capital costs and the prices paid for renewable generation and, in many cases, responsive loads.

Regulation of these installations has so far lagged behind the installations and many countries are reporting issues, particularly with high penetrations of PV generation, as most of the current inverters are not controllable.

These issues are, however, being addressed technically (with better inverters) and through improved pricing. As mentioned in the previous section, improved pricing could cause better decision making for PV installation. The issue of subsidies (see next section) needs to be addressed, however, before efficient integration can occur.

Working group C5.19 [5] examined the regulatory issues with DER and noted that some countries were effectively integrating DER. The key factors were the use of specialized resources (aggregators or demand-response providers) and fitting the type of demand response to the relevant market.

It was noted that uncontrolled DER did not increase economic welfare in general after a defined point (that differed for each market) but that controlled DER can add significant value.

2.4 Market Distortions

In Sect. 2.1.2, above, we noted that energy-only markets are very efficient in developing and remunerating capacity, *under theoretical conditions*. We also noted that some markets are abandoning the concept of energy-only markets due to real-world impacts of increased variability in supplies, lower rates of capacity formation, and higher investor risks related to political intervention.

2.4.1 Price Caps

One of the well-known market distortions to efficient markets is price capping. To work effectively, energy markets need to allow the price to range freely from the value that will cause unnecessary generation to depart (or load to increase) to the value that will cause investment in generation (or load reduction). Price caps and floors restrict the range of prices causing the need for additional mechanisms for managing capacity.

In theory, the maximum price in markets should be unlimited, but at least the value at which energy users will voluntarily stop using energy. In Australia, this is known as the Value of Customer Reliability (VCR) and in other countries the Value of Lost Load (VoLL). In practice, this is rarely achieved as the risk for market participants can be too high, leading to some restrictions.

Working group C5.23 [12] examined this issue. They noted that the market arrangements, discussed above in Sect. 2.1, were a key factor as well as participant structure issues, such as vertical integration and ownership of the assets. A summary of the findings is on page 6 of their technical brochure (TB 753 [12]):

> It was found that for the vast majority of countries and regions surveyed, market price caps are implemented for market power mitigation and to protect load from supply resources being able to raise the price in situations when they have market power. Very few markets set caps that reflect the VoLL to the customer, nor do they even have any information of what the VoLL is for their region.
>
> Current trends across all countries and regions are that market price caps are rising over time. In addition, price caps in Europe are converging toward common values with the recent Agency for the Cooperation of Energy Regulators (ACER) decision No. 04/2017 for single day-ahead coupling (SDAC).[19] It is likely that these trends will continue as wholesale electricity markets continue to evolve and regulators and government authorities become more assured with their operations.

That being said, the working group noted examples of regulators and governments using modeling and other tools to ensure reliable supply and that this was included in decision making for price caps.

---

[19] Single day-ahead coupling (SDAC) is a coordinated electricity price setting and cross-zonal capacity allocation mechanism, which simultaneously matches orders from the day-ahead markets per bidding zone, respecting cross-zonal capacity and allocation constraints between bidding zones.

2.4.2 Subsidies

A large, emerging issue, driven currently by environmental policies, is the impact of subsidies on investments in other competitive assets. While government and other subsidies are not new as various industries have been subsidized for job creation or other reasons (e.g., biofuels have been subsidized to support the production of corn by farmers), the impact on energy markets has been significant.

Subsidies on renewable investments are often hidden away, and the impacts not well understood. For example, in South Australia, the Renewable Energy Target has led to a very high penetration of intermittent energy leading to a reduction in grid stability. While not directly responsible for the recent blackouts in SA, the reduction in system strength was a contributing factor.

The subsidies to renewables have a more direct impact causing a loss of thermal plants, which has been noted in many countries, for example, in the USA:

> I have solar on my house. I've supported wind generation. But, we cannot underestimate the escalating costs as we more deeply penetrate the market with [renewables]. So, where Indiana is now is where Texas was a decade and a half ago, making decisions about really big, weighty, costly things; and, I'd simply ask, look to Texas and learn the lessons from it. …
>
> … The biggest miss, other than transmission, the impact of subsidization. I think you all know this but when you get $23 a megawatt hour for putting wind on the grid, in the form of a subsidy, and the price of electricity drops low, and you only get that subsidy if you generate, you bid the price of electricity negative.
>
> You literally, in the Texas market, see one out of every three bids negative. In other words, paying to stay on the grid. So, that has two effects. One, it destroys and distorts the marketplace and, two, it erodes the capital of existing thermal: nuclear, coal, and I will tell you new gas. …
>
> … people and banks are not going to invest in a marketplace where a subsidy is driving the price of electricity to below zero. Guthridge et al. [17]

Subsidies are political/social impact on markets and always create distortions in markets. Many, such as low-income rebates in some countries, are supported by the community. The key issue is to ensure that their existence and impacts are understood, and the benefits outweigh the market impacts and costs.

3 Future Scenarios and Their Market and Regulatory Requirements

A key consideration is, if we are looking at two potential futures,[20] what market and regulatory conditions would be required to support those futures. The chapter will therefore also consider whether there are preferred regulations and market

---

[20] We note the discussion in Sect. 1.1, that noted that some regions and markets are not pursuing competition and where there may be little scope for fully decentralized approaches. There will still be, however, opportunities for distributed control within centrally operated markets.

approaches. The two scenarios will be covered in Sects. 3.2 and 3.3, with a summary in Sect. 3.4. The two scenarios will, however, have a common set of general factors, which are covered in Sect. 3.1, below.

A Continuum of Outcomes

The key parameters will be whether control and settlements are focused on the center of the market or grid, or if they are decentralized with the focus at the edge of the grid. The two scenarios will require different regulatory approaches to support the focus required for the two cases.

As will be seen, it is not necessarily a choice between two stark options but rather a description of two sides of a single market design, differentiated by how the markets are managed and settled. In fact, it is likely, that both approaches will be used for different countries and markets and, potentially, even regions within countries.

The regulatory approaches in countries and regions should be sufficiently advanced to allow variations of the two options to coexist and potentially move between the options as technology, pricing, and reliability varies.

3.1 General Developments

There are general developments in technology that are occurring and will continue, forcing changes in all markets. Some may be covered in other chapters, but a summary of key changes that will impact markets and regulation is summarized in this section.

3.1.1 Microgrid Development

Microgrids are becoming more common as DER costs and control systems are reducing. Navigant have recently published a report [19] showing that:

> The cost of microgrid technologies continues to drop and the controls continue to improve in functionality. And although regulatory barriers and the long project development cycle still frustrate efforts to move this market into the mainstream, significant progress has been made since Navigant Research first sized this market a decade ago. Different market segments have shifted in prominence over that time period, but what has remained consistent is overall growth across all five major regions profiled.
>
> Among the high level regional findings, Asia Pacific is expected to continue to be the largest overall market for microgrids, with remote segments making up the majority opportunity. North America remains the top market for grid-tied microgrids, as a flurry of projects identified in 2019 increased starting point capacity levels in 2019 beyond those previously forecast. Latin America is the fastest growing market due in part to the major island-wide microgrid program in Puerto Rico.
>
> This Navigant Research report forecasts regional capacity, implementation spending, and business model type by six primary market segments: campus/institutional, commercial and industrial (C&I), community, remote, utility distribution, and military (US only). The study provides an analysis of market drivers, barriers, and technology issues. Global market

> forecasts, segmented by region and market type, extend through 2028. Capacity is expected to grow by more than 22% over the forecast. Navigant 2019 [19]

Both of the potential futures described in this book will include microgrids to a greater (option 2) and lesser (option 1) extend. In fact, the development of Distributed Services operators can be viewed as a form of grid connected microgrid.

The development of technical controls is covered in Chapters "Power System Operation and Control" and "Active Distributed Systems and Distributed Energy Resources", but each microgrid will require:

- A means for valuing energy and capacity. Given their small size, it is likely that the two will be priced separately, but if the end user pricing is efficient, energy only may be an option.
- Provision of ancillary and related services to allow the microgrid to operate islanded, if necessary, or to contribute to the larger grid.
- A trusted means of settlement. Parties must be able to be assured that the market will work effectively as a means of trade. Developments of distributed ledgers, like Blockchain, are increasingly allowing for distributed and isolated markets, and it is interesting to note that Southeast Asia is also leading the adoption of Blockchain-based markets.

As noted in the Navigant report, the technologies are advancing and only being hampered by regulatory constraints and the long project lead times. Like the penetration of Blockchain and the adoption of mobile phones versus landlines, the lack of existing infrastructure and rules is a benefit to the development of microgrids and the business case is clearer as the adoption of microgrid approaches can be weighed up against establishing a full, widespread market.

3.1.2 Metering and Measurement

One of the limitations of trading in electricity is the ability to measure the key characteristics; demand,[21] energy, power quality, etc. At the level of the discussion in this chapter, the two key parameters are demand and energy.

For settlement purposes, the meter for each connection (usually for each site but not always) is the key measure and the "source of truth" for trading. Currently, the quality of metering is low across many markets; from incomplete coverage to simple meters that accumulate energy across periods as long as three months. This form of metering limits the ability of customers to interact with the grid as the impact of their actions cannot be accurately assessed.

Increasingly, grids are being equipped with more advanced meters. These can:

---

[21] This discussion relates to small-scale supplies and loads. Bulk energy supplies use SCADA to assess sent out energy and therefore the capacity being supplied. With increased use of advanced metering and relaxation of some metering standards, it is possible that this level of detail will be available for all forms of supply. This discussion, therefore, focuses on loads and, in later sections, pricing for loads.

- Allow measurement of energy across shorter periods, typically half-hourly but in some cases as finely as five minutes;
- Provide a better estimate of the maximum demands at a site, possibly with a specific measurement;
- Measure import and export separately. This can include separate measurement of generation, consumption, and storage at a site;
- Assess key power quality metrics at the supply point, such as voltage or power factor;
- Include control tools such as:
    - Circuit switching under local or remote control; and
    - Capacity limiting, to limit demand under certain criteria;
- Provide communications between the meter and the meter provider/operator and possibly the customer. This can allow:
    - Remote reading of meter information for settlement and control;
    - Communications between the parties registered to the meter;
    - Remote operation of controls; and
    - Upgrading of meters without attending the site.

Currently, many countries and regions have programs to extend advanced metering to all customers. It is assumed for this chapter that this effectively completes by 2050.

Metering and measurement have extended to device or control system level allowing more granulated trading and tariffs within sites and for EVs and other mobile systems. For example, electric vehicles could meter their own demand and energy at any connection they make with the network and the enhanced communication would allow trading of the energy via the using Web/cloud-based platforms like (e.g., Blockchain) making trading more flexible.

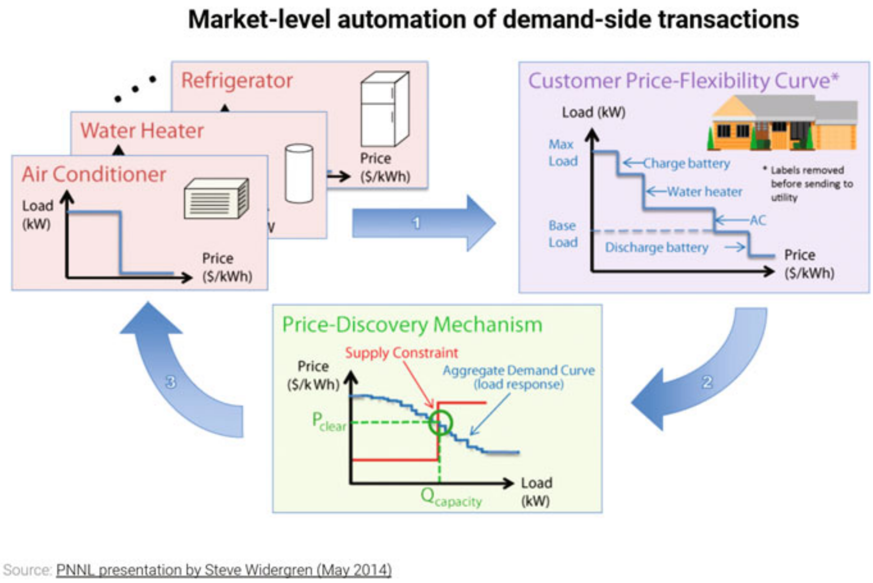
3.1.3 Information Systems and Automation

The automation of control systems for industry, commercial installations, and even to household is gathering pace. It is already possible to control devices in people's homes (and has been for some time), but the use of AMI now allows two-way communications. This aspect of IT development will be covered more in Chapter "Information Systems and Telecommunications".

An example of the use of automation (at a simple level) is provided by the Olympic Peninsula Trial. Households,[22] see Fig. 3, were given access to a simple range of options covering from increased comfort to reduced cost. The households were able to adjust the settings at any time, although most set it once. Household bills reduced around 10%, while the utility noticed an average of 15% reduction in peak demand,

---

[22] From Smart Grid Demonstration: Olympic Peninsula Project (PNNL, 2007), energyinnovation-project.com.



Source: PNNL presentation by Steve Widergren (May 2014)

Fig. 3 Olympic Peninsula trial

with 50% on some days. There have been many trials of this form, and they are well documented in the literature.

The key point is that allowing end users to interact with grid participants will allow a more optimal system, given effective pricing. By 2050, this can be expected to be routine and coordination between the energy system and uses will be routine and algorithm based using machine-to-machine interactions (M2M) rather than requiring human oversight of the details.

For example, a person might have a control system that interacts with their load serving entity. They have set a rule that requires their car[23] to be at least 80% charged by 8 a.m. (the minimum to do the days tasks) and to pay no more that 55c for energy prior to 4 a.m. at which time charging becomes the priority. This rule allows the person to be sure that their car is ready for use in the morning at minimum cost.

As part of the either option, the choices that the person makes could be included in the estimates of cost outcomes and impact forward price estimates. All other parties would have similar rules, and as each price perturbation occurs, the system would oscillate and return to a new optimum price for the dispatch/load configuration.

Communication and control ubiquitous. Allow ready interaction between sites and local and centralized dispatch and settlement.

Alternatively, end users may prefer a simpler interface, like that used in the Olympic Peninsula trial, where their energy supplier or aggregator (or Microgrid operator) provides cost minimization services through control devices at the user's

---

[23] By 2050, it can be assumed that EVs are the norm either for airshed or other emissions reasons.

site. This would still allow two-sided market optimization where DER is included in the dispatch and pricing calculations.

The key point is that ubiquitous communication and control systems, combined with efficient pricing, allow the users to manage their own costs and the market to fully optimize.

3.1.4 Network Constraints

Efficient network pricing means that customers and suppliers fund the efficient development of networks that networks can handle two-way flows of energy, and constraints are at the efficient level that balance generation (local or remote) with appropriate levels of network. The planning and other considerations to achieve this are covered in Chapter "Power System Development and Economics".

3.2 Option 1—A Highly Connected Grid Incorporating Renewables at All Levels

The thinking in this section is based on Transactive Energy[24] in the USA, supplemented by work by CIGRE SC C1 [13] and Task Team 4 from ACTAD (IEC) on Global Electricity Interconnection.

This option is an extension of the current approaches to markets as:

- The grid still has supply side and demand side;
- Pricing of DER is competitive but not reliably cheaper; and
- Large-scale supplies are still needed for industry and large commercial operations.

The developments are the use of communications and DER, possibly via some micrograds, but mainly TSO and DSO operations will provide a two-way market and allow for efficient prices at all levels.

In addition, the current approaches for Global Electricity Interconnection (GEI), being pursued by SC C1 [13] and other parties [26, 27], are expected to have come to fruition by 2050. This would mean that not only would regions like North American and Europe be interconnected but also that there would be interconnections between continents and regions.

---

[24] Transactive energy is a concept for integrating grid operations. There was a trial, called the Northwest Trial, that tested the concepts across a variety of technologies and a number of states. The trial ran for 5 years and spanned 5 states, involving 11 Utilities (112 MW of assets) a number of technology participants and 60,000 metered users. The study was supported by two universities. The results of the study were collated by Brattle. www.gridwiseas.org.

In almost all cases, the global interconnections are expected to be UHVDC,[25] which will allow cross-border exchanges driven by comparative wholesale market prices. These developments, on top of increasing integration at the regional level, would mean:

- Common pricing across regions with interconnected AC grid, allowing efficient charging within regions; and
- Harmonized (or aligned) regulatory frameworks and pricing mechanisms at the international level allowing price differentials across the UHVDC networks to drive cost-efficient transfers of energy.[26]

At the wholesale level, then, the wide interconnection of energy sources would allow competitive dispatch (competitive markets permitting) of all sources of supply, providing efficient outcomes in terms of pricing. The improved incorporation of DER would ensure that the price was related to consumers value of supply.

In addition, wide interconnection would allow full reserve sharing and a larger grid to absorb intermittent supplies and ameliorate the reliability and system strength concerns. One of the aims of Global Electricity Interconnection[27] is to allow the wide transfer of reliable renewable energy from rich sources (Western China, Northern Europe, Canada, etc.) to areas with high demand but less capability to access reliable renewables.[28]

At the retail level, efficient tariffs based on efficient wholesale prices would allow customers at all levels to efficient invest in local DER and to make efficient decisions on its use. In this way, the grid will allow best use of assets and energy from empowered participants and end users.

The mechanisms for centralized supply will require efficient exchanges for capacity and energy to be in place and for the settlement of those exchanges to be linked in real time so that the true value of energy is known across the entire system. Major developments are expected in terms of governance of electricity markets to achieve the targeted scheme.

The key point is that efficient exchanges and pricing will allow value not technical standards to drive the efficient delivery of energy.

---

[25] HVDC is common now as a means of transferring energy. Ultra-High Voltage Direct Current (UHVDC) links are being developed for even longer distances, with some success. In twenty years, this should be standard technology.

[26] It can be expected that some form of efficient charging for networks will develop, including nodal pricing and financial transmission right. For this paper, a solution is assumed, although fully efficient network pricing has been an intractable problem to date.

[27] IEC whitepaper, page 3 [26].

[28] The author recalls a concept developed by EDF to use the, then promising, development of superconductivity to the same end. Like Global Electricity Interconnection, the EDF concept linked continents electronically to allow transfer of, mainly, solar power to provide continuous, renewable supplies. GEI serves the same purpose.

3.2.1 Operation of the Centralized Approach

As discussed above, the centralized concept, termed “Transactive Energy,” has been trialed in the USA, via a US-government-funded project, the North West Trial.

The Transactive Energy approach implemented a unique distributed communication, control, and incentive system. The combination of devices, software, and advanced analytical tools gave homeowners more information about their energy use and cost and allowed them to act on the information. The project expanded upon the region’s experience in the 2006 Demonstration Project on the Olympic Peninsula, also discussed above, which successfully tested demand-response concepts and technologies.

In the Transactive Energy model,[29] shown in Fig. 4, the Transmission System Operator (TSO) manages the larger grid (and in our model, between the larger grids), while distribution system operators (DSO) manages the local grid, which may include microgrids, power producers, and various types of customers. The network operators provide and manage information flows between all participants in the grid, including market operators, TSOs and DSOs, and retailers if their operations are separated from DSOs (together referred to as MSORs) (Fig. 4).

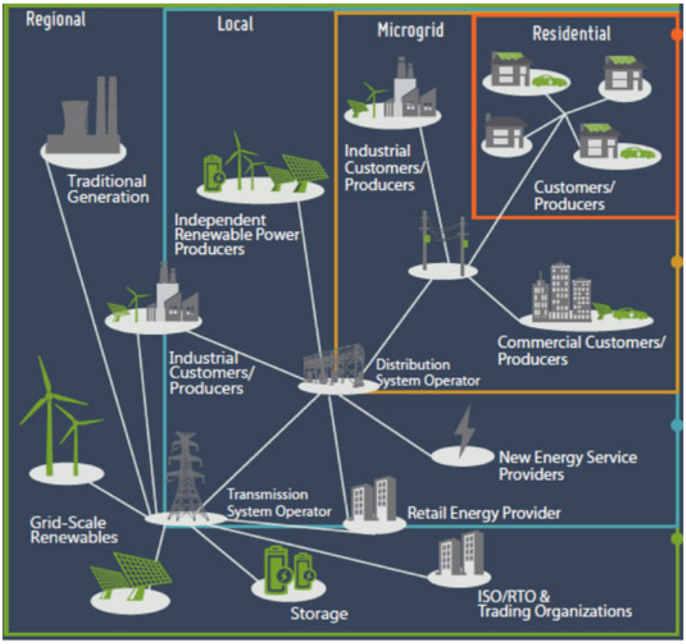


Fig. 4 A model for a highly centralised approach

---

[29] From www.gridwiseac.org. Adapted from diagrams developed by Battalle, Pacific North West Smart Grid Trial, 2015.

The MSOR systems provide load and the effective local price at each level and site connection point for all parties in the system and, like now, would also provide a forecast of prices for a set of future intervals.

Customers can choose to buy, sell, or store their energy based on dynamic prices and forecasts. The customer chooses how they use their own energy based on their own priorities between comfort, control, and cost. Importantly, they can adjust their plans based on new information.

MSORs in the transactive control area have more resilient grids due to improved DER response and better information for dispatch of grid-based resources. They are also incentivized to provide accurate price forecasts, so that decentralized decision making is efficient.

The trial reported that 97% of participants were happy with the system and technology, and reduced outage times were observed for networks in the trial.

3.2.2 Price Iterations

Prices for customers in this form of grid will be based on the latest information on market and network loadings.[30] While this is common in wholesale exchanges, and conceptually applied for vertically integrated systems, this will be new for all but the largest of customers. This will require improved control systems and automation described in Sect. 3.1.3.

Some examples:

EV Charging

A person arrives home at 6 p.m. and plugs in their car. They tell the system that they intend to charge their EV commencing in 5 min and it will require 4 h of charging.[31] The system responds that the price for the supply at that time, based on the current usage by others and adding the EV load, will be 65c per kWh reducing to 60c at 8 p.m. The system also predicts that the price will be 40c at midnight and remain at that level until 8 a.m.

Based on the prices, the person decides to commence charging at midnight. The system then recalculates and responds that, with that change, the price now will be 55c reducing to 50c at 8 p.m. but rising to 45c at Midnight and reducing down to 40c at 4 a.m. The person is happy with that outcome as it is probably optimal and leaves the system to run.

Optimizing Demand

A person puts on an electric toaster, the control system notes the additional loading

---

[30] Note that the market price for dispatched energy could still dominate unless a grid element is stressed or there is an outage but energy price fluctuations in the longer timeframe will assist in moderating peak loadings due to more efficient dispatch and investment.

[31] Recalling the discussion in Sect. 3.1.3, that this would probably be a M2M discussion not an actual human interaction.

and, knowing that a toaster only loads for a few minutes, signals the fridge and air conditioner to not cycle during this period, therefore minimizing site demand.

Similarly, at an industrial site that uses electric presses for manufacturing, when the presses operate during periods signaled by the grid as high demand, the site control system would reduce non-essential supplies to minimize cost and site demand.

3.2.3 Requirements

The range of functions required to manage distributed services was examined by the New York Market Design and Platform Technology Working Group[32] that noted:

> DSP operational functions include real-time load monitoring, real-time network monitoring, enhanced fault detection/location, automated feeder and line switching, and automated voltage and VAR control. The DSP will commit and dispatch market-based DER and integrate net load impact information… thereby providing greater visibility and control of the grid. The monitoring and dispatch of DERs will complement the increased use of intelligent grid-facing equipment such as sensors, reclosers, switched capacitors, and voltage monitors.

The MDPT report[33] identifies a set of core technologies to support the functionalities identified with respect to system planning, grid operations, market operations, and data requirements. The identified technologies include:

- Geospatial models of connectivity and system characteristics, sensing and control technologies needed to maintain a stable and reliable grid;
- Optimization tools that consider demand-response (DR) capabilities and the generation output of existing and new DERs in the grid.

These tools will need to be supported by a secure and scalable communications network and a system that provides forecast as well as current pricing to allow all participants to respond to prices and system demands. This information is already available at the wholesale level, often termed predispatch, day-ahead prices or balancing prices. For fully two-sided markets, the necessary communication and pricing will need to extend to every end user.

3.2.4 Development of New Assets and Governance

The large interconnected system will allow efficient development of large-scale assets based on their cost including the transmission assets to transfer the energy to the regions that need the energy. These will compete with local supplies of energy and

---

[32] Market Design and Platform Technology Working Group (MDPT) in support of the New York State Public Service Commission's (PSC) Reforming the Energy Vision (REV) proceeding, 17 August 2015.

[33] The report also notes that the North West trial has developed the protocols for DSO interactions as well as the necessary equipment and software to allow these transactions to occur in real time.

DER where there are resources and the ability to use local supplies, potentially augmented with storage for intermittent resources.

The range of technologies and the large number of permutations supply and demand alternatives will need coordination and control. Full optimization of the larger system will need an expansion and development of the coordination that has developed in Europe and North America.

Markets, states, and governments are coordinating developments of networks now, and this coordination will need to extend to the examination of generation and transmission options versus local supplies. The decision making that is currently being done at the country level may need to be centralized into regional districts, like used in North America now. Also, the allocation of risks between generation companies, end users, and system operators may evolve significantly.

This development is important if the benefits described at the beginning of Sect. 3.2 are to be realized.

3.3 Option 2—Loosely Connected Microgrids

The option where the future grid comprises many loosely connected microgrids is predicated on an extension of current developments where:

- The price and availability of DER have increased so that central supplies are needed less and small-scale gas, PV generation, co-generation, and local wind power provide most of the supply;
- Local microgrids develop at the town/community scale using their own range of energy sources and site-based DER to meet the local demand;
- A local MSOR manages the exchange in value and the operation of the grid at the local level; and
- Local markets exchange energy and capacity, not to balance their local grids but purely to optimize the value of grids.

  This approach could allow for long-term supply arrangements between the local grids, but the supplies between grids are managed as if they were generators or load on the edge of the local grid and not essential to the management of the local grid.

The reasons for this form of future grid could be:

- Economic, where economies of scale have reversed and the cost of transferring energy across large distances is greater that the local production, storage, and use of energy;
- Community based, where a values-based[34] approach for sharing energy causes the development of local markets either isolated from the grid or only loosely connected to it; or

---

[34] A review into the operation of embedded network in Australia by Oakley Greenwood established that some of these partially self-contained networks existed for community reasons.

- Technical, where there are benefits from the ability to separate the grid into separate sustainable sections due to physical disruptions that can cause loss of supply in some areas, for example, in Japan [29, 30].

Many trials of microgrid operations and small-scale grids are used for remote communities and islands [28]. Therefore, the technical requirements are known and can be managed. Other chapters will detail how these capabilities are being developed toward 2050.

For this chapter, it is sufficient to establish how the market will:

- Attract and remunerate the supply of energy, including DER so that the microgrid is able to balance the supply and demand for energy. This is for both:
  - Capacity to meet peak demands (including managing demand); and
  - Energy for meeting dispatch requirements;
- Remunerate the ancillary services necessary to support islanded operation if the microgrid is to truly be self-sufficient and trading and not just a subsidiary grid;
- How prices can be developed for customers and suppliers that meet the economic requirements described in Sect. 1.1, above.

This section will expand on the concepts of microgrid trading to a greater extent than required in the discussion of option 1 because this is a more radical departure from current approaches.

3.3.1 Roles in Providing Microgrid Services

To examine potential market operation within a distributed model, it is necessary to define the roles required to provide the various services. Figure 5 shows a hierarchical system embedded within a smart grid.[35] The system uses five levels from transmission through to the control systems within a facility. This is a complicated scheme covering all layers from processes to market. For our purposes, a simpler, three-level model is sufficient, like that shown in Fig. 6.

The layers, shown in Fig. 6 are suitable for this chapter, since the focus is on customers and the market arrangements. The three layers are:

- The technology layer, which deals with metering, network operations, and security of the distribution system or local network;
- The market operation layer, which deals with dispatch and pricing of energy for the participants of the local grid market; and
- The customer service layer, which deals with interactions between the customer and the market.

---

[35] Xanthus International Consulting—SIWG Phase 3 Advanced DER Functions—November 2015.

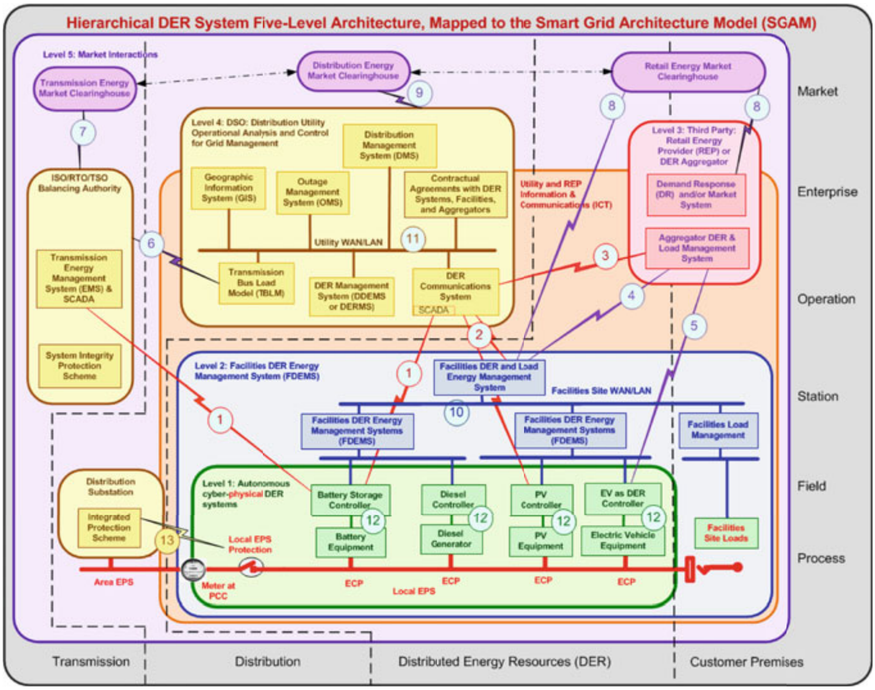


Fig. 5 DER systems based on Smart Meter models

Fig. 6 Simplified operation of distributed market

3.3.2 The Technology Layer

The essential operation of the network must be maintained in any market. The technology layer in microgrid operation therefore covers all of the current grid operations, namely:

- Security of the grid, including management of new connections;
- Switching and load balancing;
- Outage management and maintenance planning and execution; and

- Customer operations requested by retailers and third parties.

The technology layer also supports the market layer. This requires:

- Short-term load forecasting to identify congestion and network issues. This function would take weather[36] and load forecasts and assess critical network elements for congestion and other stresses. It would also use planned outage information to create a network capability map for a defined future period. This information would be updated as circumstances, such as unplanned outages or weather, change.
- Recording distributed energy resource—embedded generation and demand management—(DER) "on" and "off" plans and operations. The planned and actual DER activity timings and quantities are required to forecast loads and for predispatch pricing.
- The network congestion shadow price, which would be combined with the value of supply, calculated in the energy layer, to calculate a price for each connection point for dispatch of energy into the system or purchase of energy from the system. The price would vary from:
    - A negative price, where there is excess supply, to create incentives for parties to reduce supply or increase demand; to
    - A maximum price, up to the Value of Unserved Energy, where supply, including DER, would reduce the network constraints or maintain supply. This price would be communicated to the market layer for incorporation into the customer connection price.
- Metering information on a five to fifteen-minute basis (for dispatch and demand response). The actual metering would be used for settlement, although probably aggregated into settlement blocks.

Advanced metering means that more than one party could be providing metering data at the small customer level, it would be expected that metering would be provided on a competitive basis. This may mean that the actual provision of meters is part of the customer layer rather than the technology layer. This would require some standardization or regulation to coordinate between the market and system operators, if they were separate parties, complicating the operation of the technology layer unless all connected parties are required, as part of their connection agreement, to ensure that necessary data is made available to the technology layer provider.

3.3.3 The Market Layer

The market layer involves:

---

[36] The exact management and location of forecasting will depend on the model/options chosen. If a fully integrated DSO is used, it would be efficient for all forecasting—load, solar output etc.—would be done in a single group. If the layers are to be separated, then it is likely that the technology layer would be confined to network load forecasting.

- Registration and communication with participant market players. The market operator would record all of the necessary details for participants, including settlement information and prudential obligations. The nature of connected DER and any limitation on its use would need to be recorded much like performance standards are required for generating units now;
- Recording of all supply consumption and other participant actions. Any planned operations of DER and significant (responsive) loads would interact with the market in the same way as major generators to optimize the system operation, to reduce the cost of supply by:

  - Optimizing the dispatch of generation
  - Allowing participants to either to reduce the cost of energy consumed at their site or to maximize the value of energy exported from a site.

  Note that this is recording for dispatch and forecasting purposes, and would be shared with the technology layer operator, not settlement information. Settlement would be based on actual 15-min data provided after the event;
- Calculation of the price at supplier and customer connection points. The market operator would calculate the current and expected price[37] for the microgrid based on:

  - Expected loads;
  - Network congestion and pricing;
  - Expected DER operation and charges; and
  - Regional market operators provide additional schemes to manage security of supply at least cost.

- Publication of current and forecast prices. The market operator will publish the current and forecast prices to participants. The price would be available electronically to all participants and will also be sent via M2M channels to support dispatch and allow DER. The price and forecast of prices would be recalculated when significant changes occur; and
- Settlement of the customer prices. The market operator would need to provide data for settlement between the parties. Settlement could be gross or net, depending on the particular microgrid and their choices of market forms.

Systems to provide these services could be extensive, but the bulk of the necessary protocols and the underlying IT systems are in use in the USA and in Europe now.

Operation of a market, using registered parties, is a form of “exclusive dealing,” and therefore, some regulatory and legislative approvals will be required. This will involve defining the rules and operation of the market and seeking authorization from relevant regulatory bodies for the arrangement or gaining legislative support from governments.

---

[37] Treatment of losses will have to be considered if material in the microgrid. All markets adjust for losses either by varying the price at the connection points or by adjusting physical quantities.

3.3.4 The Customer Layer

The customer layer is similar to the current retail regimes. The parties provide equipment, sales and billing services, and contract with end use customers for the provision of services. In the DSO model, participants in the customer layer could be:

- Retailers or load serving entities (LSE). These licensed entities would provide energy at a price. The contract may include some form of cost reflective pricing (not directly price responsive), pricing for responsive loads using prevailing prices and pricing for DER. The DER pricing would be contract based with prices for reducing a site and prices for export into the grid;
- Beyond the meter providers—exempt sellers or energy providers, where DER equipment is provided to meet the customer needs but they are not the retailer. The DER equipment could be set up to be price responsive or simply to provide on-command DR;
- Demand or generator aggregators. These are parties that split out the responsive load or the DER from the normal loads at a site and aggregate that into marketable quantities. This group of participants would actively work to maximize their income using the price at the customer sites and may contract with retailers to assist them to manage normal risks; and
- Network entities seeking to use DER to manage network issues. In a microgrid, the ancillary services necessary to operation the market could either be contracted directly or purchased in the market.

The customer services layer is where participants would take advantage of the advances in technology, for example:

- Storage, which allows the control and dispatch of other generation sources[38] as well as allowing price arbitrage of energy supplies. Storage would operate based on the price at the node to consume or export energy to minimize cost or maximize profits over a defined period.
  As storage is an energy constrained supply, the key aspect is to store or export at the appropriate times. The provision of forecast prices would therefore allow the use of storage to be optimized;
- Electric vehicles. A special form of storage with both some limitations and also the ability to be located at different parts of a network at different times. The DSO environment will allow flexible pricing for both electric vehicles as a load and as moveable storage.

The participants in this layer will require sophisticated management systems that:

- Allow visibility of loads, DER, and market prices;
- Active and rule-based control over all devices at a site; and
- The ability to interact with prices and forecast prices that come from the market layer of the DSO.

---

[38] While initially focused on Solar PV or wind, the use of storage on co-generation would allow optimal use of these generators.

These systems and devices are now available in Europe and the USA. Preferably, the systems will use open-source software, to maximize interoperability and minimize the cost of changing providers.

3.3.5 Operation of the Layers

These three layers are currently required for many familiar markets, for example

Service/Operation	Technology layer	Market layer	Customer layer
Central markets, e.g., Australian National Electricity Market, PJM	Grid operations, communication systems, metering, protection systems	Market dispatch engine, systems access. Web publication of prices. Settlements	Customer registration and transfers and related processes, retailer customer systems. Trading rules
Ride-sharing services, such as Uber or Ola	Internet, Web access for operations	Customer and car registration, trip matching algorithm, collections from customers and payment to drivers	Phone apps to allow access, information on car locations, and contract formation tools
Hotel and home share services, such as AirBnB, Booking.com	Internet, Web access for operations	Customer and accommodation registration. Site and customer matching and reservation process. Settlement services	Web site and phone apps for access, review service, contract formation, additional venue services (local guide information)
Distributed System Operations	Distribution utility operation and control systems. Metering providers	Participant registration, forecasting and dispatch, settlements	Retail, beyond the meter services, provision of home energy management equipment and customer billing

The layers for a service can be provided by a single party where the industry is not competitive or by a combination of parties. In the examples shown:

- For the current energy markets, the technology layer is provided by the networks, predominantly, in conjunction with the grid or a system operator. The system operator may also provide the market layer in some countries (e.g., the Australian Energy Market Operator).
- For Web-based services, on the other hand, the technology layer is provided by multiple parties using a cooperative standard, while the Web provides both the market and customer layers. Increasingly, tools such as Blockchain are allowing distributed settlement systems for smaller-scale markets.

For a microgrid, it may be possible to operate without formal competition that some or all of these layers could be provided by one party. Logically, the layers would be provided by:

- The technology layer would predominantly be provided by the distributor or local network provider in the microgrid area;
- The market level is open to a number of parties and could be different for each microgrid. It is likely, however, that standard forms could be developed and provided by a single or a small number of market system providers; and
- The customer layer should be competitive allowing various parties to interact, including LSEs, aggregators, customers, generators, with some regulated oversight to ensure anti-competitive activities do not occur.

It is hard to be prescriptive, but the market layer could be cooperatively owned by the members of the customer layer. This is how markets such as PJM developed. If this was the approach, then, subject to some regulatory oversight, each market would be able to develop their own rules.

The operation of the layers for the DSO model would evolve as the concept is more widely adopted and could involve many parties at the technology level as well as the customer level.

3.3.6 Market-Based Trading Across the Region and Between the Microgrids

Given each microgrid is self-contained, or able to be self-contained, to the point of operating in isolated mode, then trading between the grids is for economic purposes, that is to minimize the overall cost of each grid. For example:

- Two or more local grids trade via a range of collectivization platforms, possibly sharing large-scale generators, such as nuclear facilities or large-scale PV generation. This could be via cloud-based exchanges;
- Local markets with attributes that complement each other, say a hydro-based microgrid and a largely solar/storage grid, agree to share some balancing duties to reduce costs to both grids. This could be season or weather condition specific to manage winter periods; or
- If the purpose of the microgrid is technical resilience, the grids could operate as a combined unit for normal periods but be capable of separate operations when necessary. Each microgrid would be able to operate independently, but the most economic operation would be as a combined unit.

Once there are microgrids operating independently and interdependently, the forms will vary according to the needs of participants. As discussed above in Sect. 3.3.5, there could be standardization if that is economic, but the regulation should be such that a wide range of options is possible. This means that regulation should focus on minimizing anti-competitive outcomes.

3.3.7 Development of New Assets

In this option, assets would be developed cooperatively between the communities and the microgrid operators. The balance between supply from microgrid and shared resources and distributed or customer resources would be based on economic choices of the customers and community rather than central planners. From this perspective, investors may request specific risk mitigation measures.

Of course, like trading between microgrids, it may be possible for two or more microgrids to pool resources and share assets. This would include joint development of network interconnections to allow trading between the microgrids. This is being done between countries and markets and will be possible at the more local scale as well. This is discussed in the next section.

3.4 A Range of Potential Outcomes

In the introduction, it was noted that a large number of markets are not liberalized at all. For these markets, some movement down the option one approach is possible, depending on political developments. It is unlikely, however, that, given the time required to develop current markets, the full microgrid outcome is possible.

In addition, the range of trading between microgrids described in Sect. 3.3.6 suggests that options One and Two are just the ends of a continuum. If efficient pricing is adopted for wholesale markets and current technologies are allowed to develop, the only barrier to the efficient aggregation or fragmentation of markets is regulations that prevent efficient outcomes.

This issue was described in the introduction; political concerns, reliability concerns, and monopoly concerns can all derail efficient market designs and outcomes.

The outcomes in Europe, for example, where efficient markets already exist, would tend toward option one with large-scale interconnection already in place. For Asia (not counting China), the more fragmented approach could be more suitable where large-scale integration is not already underway and it is possible to adopt lower-cost renewable approaches supported by local storage without abandoning expensive infrastructure.

It is therefore likely that describing the two options in this chapter is simply describing the intermediate steps to the longer-term outcomes, shown in Fig. 7.

This was discussed at the recent Microgrid Conference in Newcastle, Australia,[39] where potential future outcomes were discussed and one participant (ABB) gave its own projection of the future, shown in Fig. 8, which mirrors CIGRE's ideas in this chapter and the work of many of the working groups.

---

[39] Both Figs. 7 and 8 are drawn from the ABB presentation to the Microgrid conference, September 2017, Newcastle.

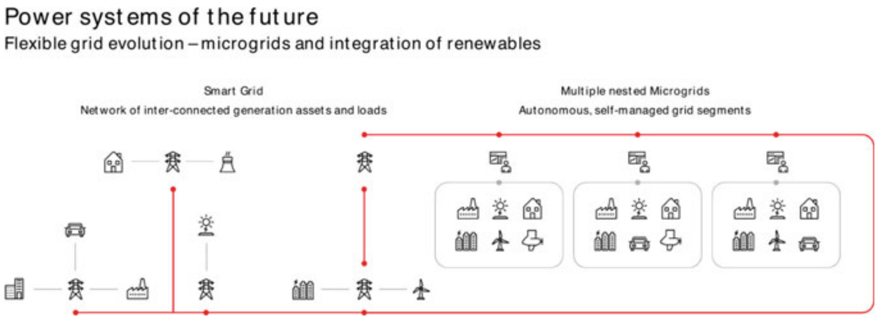
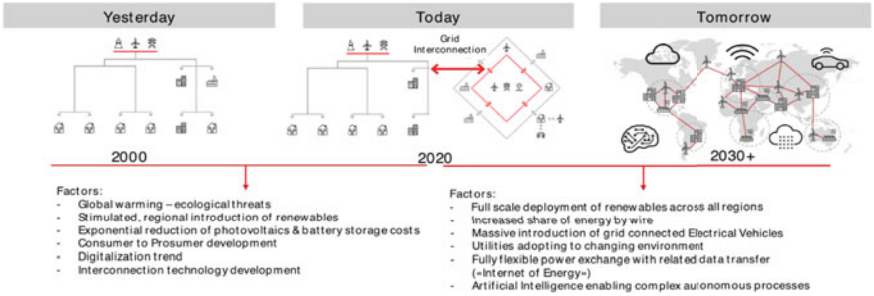


Fig. 7 A range of smart grids and microgrids (ABB)



Factors:
- Global warming – ecological threats
- Stimulated, regional introduction of renewables
- Exponential reduction of photovoltaics & battery storage costs
- Consumer to Prosumer development
- Digitalization trend
- Interconnection technology development

Factors:
- Full scale deployment of renewables across all regions
- Increased share of energy by wire
- Massive introduction of grid connected Electrical Vehicles
- Utilities adopting to changing environment
- Fully flexible power exchange with related data transfer («Internet of Energy»)
- Artificial Intelligence enabling complex autonomous processes

Fig. 8 The future of the grid

Contributors **Country material provided by**

David Bowker, AU
Adam Keech, US
Yannick Phulpin, FR

Editorial panel members for this chapter

Versions of the chapter were reviewed by members of SC C5:

Praveen Agarwal
Kankar Bhattacharya, CA
David Bowker, AU
Al DiCaprio, US
Adam Keech, US
Stefan Linder
Konrad Purchała
Patricio Valenzuela
Jarrad Wright, ZA

References and Bibliography

CIGRE Papers

1. Bialecki, A., et al.: A comparative analysis of existing and prospective market organisations at the retail level: role modelling and regulatory choices. In: CIGRE: 2018 Session Papers and Proceedings (C5-308), e-cigre.org (2018)
2. Cruickshank, A., Thorpe, G., Rose, I.: Evolution of embedded networks and localized markets in Australia. In: CIGRE 2018 Session Papers and Proceedings (C5-302), e-cigre.org (2018)
3. Mello, J.C.O., et al.: The new market paradigm of the Brazilian power system considering thermal base generation for supporting the renewable source expansion. In: CIGRE 2018 Session Papers and Proceedings (C5-301), e-cigre.org (2018)

CIGRE Technical Brochures

4. Doorman, G., et al.: Capacity mechanisms: needs, solutions and state of affairs. CIGRE TB 647 (WG C5.17), e-cigre.org (2017)
5. Levillain, C., et al.: Report on regulatory aspects of demand response. CIGRE TB 651 (WG C5.19), e-cigre.org (2016)
6. Game, D., et al.: Regulation and market design barriers preventing to capture all the value from fast and high-locations-freedom energy storage. CIGRE TB 752 (WG C5.25), e-cigre.org (2019)
7. Thorpe, G., et al.: Drivers for major changes to market design. CIGRE TB 709 (WG C5.20), e-cigre.org (2017)
8. Tacka, N., et al.: Impacts of environmental policy on power markets. CIGRE TB 710 (WG C5.21), e-cigre.org (2017)
9. Chuang, A., et al.: Costs of electric service, allocation methods, and residential rate trends. CIGRE TB 747 (WG C5.16), e-cigre.org (2018)
10. Ford, A., et al.: Risk management in evolving regulatory frameworks. CIGRE TB 667 (WG C5.15), e-cigre.org (2016)
11. Ford, A., et al.: Default management in electricity markets. CIGRE TB658 (WG C5.15), e-cigre.org (2016)
12. Hendrzak, C., et al.: Wholesale market price caps. CIGRE TB 753 (WG C5.23), e-cigre.org (2019)
13. Yu, Y., et al.: Global electricity network feasibility study. CIGRE TB 775 (WG C1.35), e-cigre.org (2019)

Other Papers

14. International Energy Agency: Competition in Electricity Markets. OECD/IEA (2001)
15. Patel, S.: 10 Takeaways from the IEA's Newest World Energy Outlook. Powermag (2019)
16. Smart Grid Smart City: Shaping Australia's Energy Future. AEFI Consulting Consortium, which included ARUP, Energeia, Frontier Economics and the Institute of Sustainable Futures (UTS) (2014)
17. Guthridge, M., Mohn, T., Vincent, M.: DERS, Prosumers and the Future of Network Businesses. Australian Energy Week (2019)
18. Nasi, M.: Testimony to the 21st Century Energy Policy Development Task Force Hearing. Indiana House Chamber, 31 Oct 2019

19. Navigant: Microgrids Overview; Market Drivers, Barriers, Business Models, Innovators, and Key Market Segment Forecasts. Navigant (2019). www.navigantresearch.com
20. Bonbright, J.C.: Principles of Public Utility Rates. Columbia University Press, New York (1961) (This book is consistently cited as the base reference for rate and pricing principles, even today)
21. Simshauser, P.: Network tariffs: resolving rate instability and hidden subsidies. A paper for the SAP Advisory Customer Council Heidelberg Germany, 16 Oct 2014. Available from AGL Applied Economics and Policy Research. www.agl.com.au
22. Farugui, A.: Ratemaking: Direct Testimony of Ahmad Faruqui on Behalf of Arizona Public Service Company (2016). files.brattle.com/files/13091_arizona_june_2016_ratemaking.pdf
23. Farugui, A.: A global perspective on time-varying rates. Camput Energy Regulation Course, Queens University Kingston Ohio (2015). www.camput.org
24. Hoch, L., et al.: Pricing and Integration of Distributed Energy Resources' Study (in press)
25. The GridWise Transactive Energy Framework is a Work of the GridWise Architecture Council (2015). www.gridwiseac.org
26. Shu, Y., et al.: Global Electricity Interconnection White Paper. IEC (2016). www.iec.ch
27. Ardelean, M., et al.: A China-EU electricity transmission link: assessment of potential connecting countries and routes. European Commission JRC Science for Policy Report (2017). https://ec.europa.eu/jrc
28. Hatziargyriou, N., et al.: Microgrids: An Overview of Ongoing Research, Development, and Demonstration Projects. Berkeley Lab—Environmental Energy Technologies Division (2007). http://eetd.lbl.gov/EA/EMP/emp-pubs.html
29. Burger, A.: Lessons from natural disasters spur development of new microgrids in Japan. Microgrid Knowledge (2017). https://microgridknowledge.com/
30. Ling, A.P.A., et al.: The Japanese smart grid initiatives, investments, and collaborations. Int. J. Adv. Comput. Sci. Appl. **3**(7) (2012)

Alex Cruickshank (Chairman SC C5, B.Sc., Dip.Ed., MBA) Alex has around 30 years of experience in energy markets within a range of organizations, including a vertically integrated utility (ETSA), a generator/retailer (AGL), a rule making body (NECA), and government (SA Treasury). Alex commenced consulting in energy markets and regulation in 2016 after leaving AGL, where he had various roles, including Head of Energy Market Regulation. Alex was involved in the initial design of the Australian National Electricity Market; including market design, process optimization, network development approaches, and access rules. He continued in the developmental role with NECA and oversaw all rules change applications and changes. Alex was involved in the market development from a private sector perspective and assisted in the expansion of AGL initially into generation but later into new technologies, holding senior roles in the Corporate Affairs division, including Head of Energy Regulation. In these roles, Alex was involved in developments in wholesale and retail markets and was often involved in working groups and task team examining specific rule changes. Alex and his colleagues are currently completing a study on the economic integration of distributed energy resources (DER) into the Australian market.

Yannick Phulpin (Secretary SC C5, M.Eng. (Elec.), Ph.D.) Yannick Phulpin graduated from both Supelec, France (2003), and TU Darmstadt, Germany (2004), in electrical engineering and received the Ph.D. from the Georgia Institute of Technology, USA (2009). Yannick worked as Assistant Professor with Centrale Supélec, France, Senior Researcher with INESC TEC, Portugal, and Researcher with EDF R&D, France. Since 2015, Yannick has worked as an expert in market design and market integration with the Direction of Optimization and Trading of EDF. He is the Vice-Chairman of the Eurelectric working group "Market Integration & Network Codes," and the French representative in the Eurelectric working group "Market Design & Investment Frameworks." He also contributes to the European Commission's expert group on electricity interconnection targets. He is the Secretary of CIGRE Study Committee C5 on electricity markets and regulation.

Active Distributed Systems and Distributed Energy Resources

Christine Schwaegerl, Geza Joos, and Nikos Hatziargyriou

Abbreviations

AC	Alternating current
ADMS	Active distribution management systems
ADS	Active distribution systems
BESS	Battery electric storage system
BMS	Battery management system
CCHP	Combined cooling, heat and power
CHP	Combined heat and power
CIM	Common information module
DC	Direct current
DER	Distributed energy resource
DERMS	Distributed energy resource management system
DG	Distributed (dispersed or distribution connected) generation
DSI	Demand side integration
DSO	Distribution system operator
EMF	Electromagnetic fields
EMS	Energy management system
EV	Electric vehicle
G2V	Grid-to-vehicle

On behalf of CIGRE Study Committee C6.

C. Schwaegerl (✉)
Augsburg University of Applied Science, Augsburg, Germany
e-mail: christine.schwaegerl@hs-augsburg.de

G. Joos
McGill University, Montreal, Canada

N. Hatziargyriou
Study Committee C6, National Technical University of Athens (NTUA), Athens, Greece

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_15

HV	High voltage
HVAC	Heating, ventilation, air-conditioning
ICT	Information and communications technologies
IoT	Internet of things
ISO	Independent system operator
LEC	Local energy communities
LV	Low voltage
LVDC	Low voltage direct current
MV	Medium voltage
MVDC	Medium voltage direct current
P2G	Power-to-gas
P2H	Power-to-heat
P2V	Power-to-vehicle
PMU	Phasor measurement unit
PV	Photovoltaic
RES	Renewable energy source
STATCOM	Static synchronous compensator
TSO	Transmission system operator
UPS	Uninterruptible power supply
V2G	Vehicle-to-grid
VPP	Virtual power plant
VSC	Voltage source converter

1 Introduction

1.1 Objectives

This chapter focuses on distributed energy resources (DER) and active distribution systems (ADS). More specifically, it addresses the impact of a high penetration of DER in distribution systems. It also addresses methods and approaches to deal with and exploit the potential of DER, at both the distribution and transmission levels, including in the development and operation of active distribution systems.

DER, connected to distribution systems, or when aggregated to transmission systems, includes:

- Renewable and conventional distributed generation units
- Energy storage systems, including battery and thermal energy storage
- Demand side integration.

Technical issues that limit the hosting capacity of distribution networks for fluctuating renewable generation like solar and wind include the thermal ratings of network components, voltage regulation, short-circuit levels and power quality considerations. Additional constraints may arise from islanding considerations and the possibility for reversal of power flows [1].

This chapter shows how a wide deployment of DER can help significantly reduce the impact of electric energy production, transmission and distribution on the environment and reduce dependence on fossil fuels. It demonstrates how DER technologies allow the deployment of generation based on renewable energy resources, primarily wind and solar. This wide deployment of DER enables the implementation of measures that facilitate the energy transition, including greater reliance on renewable energy resources for electric power production, enhanced flexibility of the grid, better operational and market procedures, energy efficiency improvements and electricity as the backbone for future multi-energy supply, including mobility, heat, etc.

This DER deployment will require an accelerated development of the **required new power conversion**, as well as storage technologies, and will lead to a greater control by consumers over their energy supply. As future electricity supply will be based on more non-synchronous generation, new primary and secondary control concepts are required.

1.2 Terminology

1.2.1 General Definitions

Distribution networks cover electricity infrastructure for delivering energy from the transmission system to end-users (customers) at medium voltage (MV) and low voltage (LV). Worldwide, there are different voltage levels up to which a network is to be considered as distribution; thus, in this chapter they are considered by function rather than by voltage level.

Active distribution systems are distribution networks with systems in place to actively control and manage distributed energy resources (DER). Distribution system operators (DSOs) have the possibility of managing electricity flows and voltages. In active distribution systems, DER will take some degree of responsibility for system support, which will depend on a suitable regulatory environment and connection agreement.

Elements and layers of the active distribution networks are shown in Fig. 1.

Demand side integration (*DSI*) is an umbrella term that covers all activities focused on advancing end-use efficiency and effective electricity utilization, including demand (side) response, demand (side) management and energy efficiency. Demand (side) response covers activities designed to encourage consumers to change their electricity usage patterns. This includes the timing and level of electricity usage and covers all load types and customer objectives. Demand (side) management relates

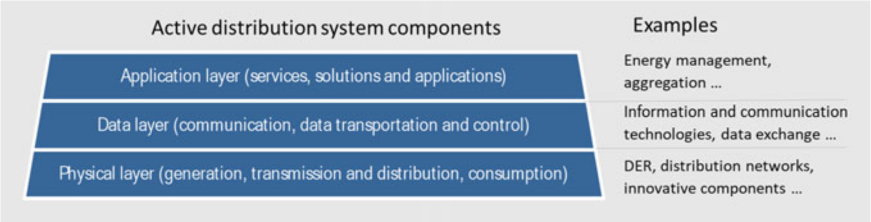


Fig. 1 Layers and elements of active distribution networks

to applications where the distribution system operator actually has direct control of the customer load. It is applicable for functions that enable the utility to manage the demand curve for emergency or asset management objectives [2].

1.2.2 Categories of DER

There has recently been an increased focus on distributed energy resources (DER) deployed in distribution systems. DER includes distributed generation (DG), both from conventional systems and renewable energy sources (RES), energy storage systems (ESS) and demand side integration (Fig. 2). DER is especially characterized by:

- Distribution connected **generation**—distributed generation (DG)
  (a) Local resources, including RES such as solar photovoltaic (PV) and wind with variable and intermittent power output, or other forms of RES and alternative fuels
  (b) Conventional fossil fuel-based—diesel engines, gas turbines, combined heat and power systems (CHP).

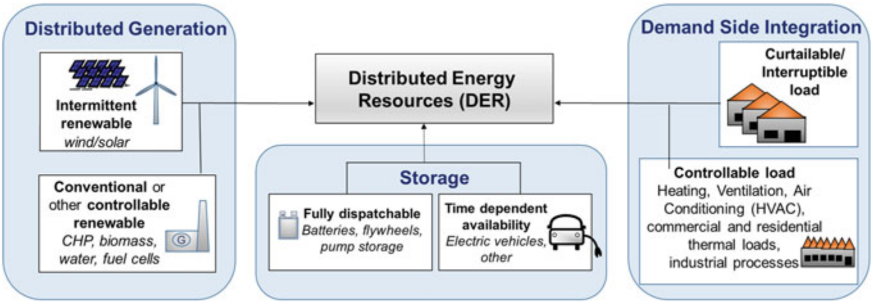


Fig. 2 Distributed energy resources—examples of types and features

- Electric energy **storage** systems—which can operate as a generator (discharging) or a load (charging) in a variety of possible application scenarios provided by different stakeholders, such as
    - (a) Firming production—balancing variability
    - (b) Leveraging (arbitrage)—storing/retrieving excess power
    - (c) Ancillary services provision, including participation in frequency regulation, reactive power regulation and voltage control, active power reservation, and black-start support
    - (d) Ramp rate control or grid code compliance.
- **Demand**—curtailable/interruptible and/or controllable loads
    - (a) Conventional controlled loads operating in a variety of applications, available for demand management
    - (b) New loads—electric vehicles, electric transportation battery chargers or power to X (heat, gas, and hydrogen) applications as a means to provide the required flexibility to balance variable renewable generation and to increase the share of renewable generation
    - (c) Aggregated loads allowing customer participation in the market.

1.3 Methodology

Figure 3 summarizes the topics covered in this chapter. It addresses the three building blocks of distributed energy resources (DER) deployment and active distribution systems (ADS) implementation, namely the

- pillars: distributed and renewable generation, applications of storage systems and demand side integration
- tools: enabling technologies including power conversion systems, solutions for deployment, planning and operation
- applications: distribution systems, microgrids, rural electrification, smart cities and homes, electric vehicles, multi-energy systems and DC systems.

In this chapter, the following methodology and approach are used and issues discussed:

- The state-of-the-art perspective—This is a description of the status of this field, including its technology, concepts, techniques, education, standardization and practices, with a focus of what is expected within the next five years.
- The requirements perspective—This provides a justified list of current or future needs not solved or poorly addressed by current practice and technology, including concepts, techniques, education, research, security, efficiency, regulation,

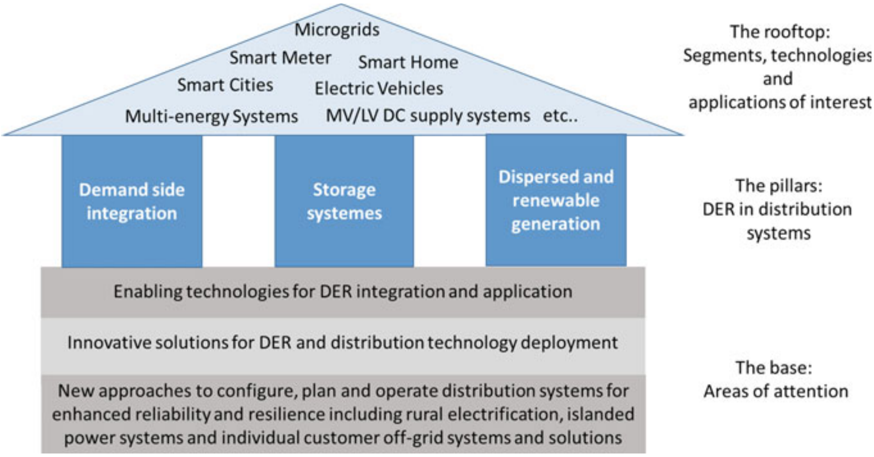


Fig. 3 Scope of DER and active distribution system technologies

standardization, policies, etc., as seen by stakeholders from different societal groups, including consumers, producers, utilities and operators, industry, economy, ecology, etc.

- The future perspective—This provides a justified list of topics, describing possible and long-range scenarios of evolution of technology, concepts, techniques, education, standardization, practices, etc., that need to be pursued or developed in this field, and how they will attain the above requirements.

Some topics, such as the organization of local energy markets, are important emerging topics in the context of a large deployment of DER, and these are dealt with in chapter "Electricity Markets and Regulation" of this book.

2 State of the Art

2.1 *Drivers in the Development of Active Electricity Distribution Systems*

There are multiple drivers in the development of electricity supply systems at the distribution level, which originate from various sources, some societal, some related to technological development and others to mature and emerging electricity markets. The main drivers are:

- the energy transition, including:
  - (a) the drive towards sustainability of electric energy supply, including the move away from fossil fuel dependence to renewable energy resources (solar, wind, biomass, water, other forms of energy);
  - (b) the drive towards wide electrification of various sectors, including ground transport, maritime, aviation, agriculture and heating and cooling, by displacement of fossil fuels by renewable energy sources. An example of electrification expansion is the push towards increased deployment of electric vehicles.
- deregulation of electric energy production and electricity supply, allowing access to markets for smaller DER owners and operators and the decentralization of the electric energy system;
- increased emphasis on electric energy supply reliability, security and resilience, exploiting the redundancy provided by multiple DER, including distributed generation from renewable energy sources, distributed energy storage, multi-energy systems (electricity and heat) and demand side participation.

More specifically, a variety of factors are driving the energy transition worldwide, with very different challenges, tasks, management, coordination, resource mix and market models:

- International and national policies that encourage lower carbon generation, the use of renewable energy sources (RES) and more efficient energy use (energy efficiency)
- Integration of RES and other distributed generation (DG) into distribution grids
- Increased customer participation, resulting in new needs, especially for distribution grids
- Progress in technology (technology push) including in the area of information and communications technology (ICT)
- Need for investment in end-of-life asset renewal, including distribution networks (addressing ageing assets)
- Necessity to handle grid congestion, including at the distribution level, using market and incentive-based approaches, among other techniques
- Evolution of market design and regulatory mechanisms to manage the grid transformation in an equitable, cost-effective manner
- Environmental compliance and sustainability of newly built and existing infrastructure
- Need to address the energy needs of a large number of people in the world with no access to electricity.

Suitable DER technologies, solutions and applications are the key tools that enable distribution systems to achieve high levels of reliability, efficiency and sustainability. This is achieved by providing local power generation, storage and demand side integration capabilities, including observability, controllability and efficiency, particularly with the use of sensing and information and communications technologies (ICT).

2.2 Technologies for DER Deployment

2.2.1 Distributed Energy Resources (DER)

Mechanisms for the Deployment of DER

Options for deploying DER include individual units in distribution systems or aggregations of units with a common connection to an electricity network, such as wind parks and solar farms. Aggregation, in power ranges above 100 MW, typically requires connection to the transmission system (Fig. 4). Aggregation can be also in the form of microgrids or virtual power plants (VPPs), in low and medium voltage networks. While microgrids have their DER connected at the same location, the location of DER in VPPs needs not to be in the same geographic area nor connected to the same substation. However, DER in VPPs should be aggregated into one regulatory area of an independent system operator (ISO) or transmission system operator (TSO). At the consumer level, aggregation can be in the form of local energy communities (LEC) or industrial parks.

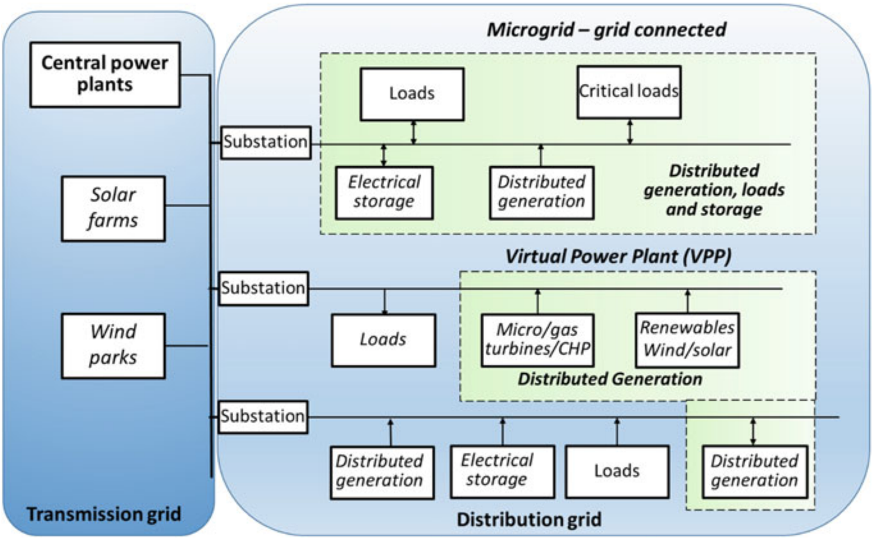


Fig. 4 DER deployment—distribution and transmission systems

The increased penetration of DER requires that utilities reconsider the planning and operation of distribution systems. One response is to make these systems more controllable and responsive (active distribution systems) and to enhance the role of the distribution system operator (DSO) and its distribution management system (DMS). These developments also enable consumer involvement and response to the state of the distribution network, including responsiveness to price signals. They also directly affect distribution system reliability and resilience.

Finally, as DER displaces part of central generation, transmission system operators (TSOs) have to consider their controllable behaviour for planning and operation purposes in close cooperation with DSOs and owners or DER [3].

Challenges in Integrating DER—Inverter-Based DER

In addition to the need for integrating in a rational manner an increasing number of DER and managing the resulting need for increased flexibility, system operators are facing a number of new issues and challenges related to the nature of the resources and technologies used in DER systems:

- Variability and intermittency of renewable energy-based generation—The output power of these generators is dependent on the primary resource. For many types of renewable energy sources, particularly wind and solar energy, this gives rise to variability and intermittency of the output power. This variability requires balancing by other resources within the power system. RES-based generators typically operate at the maximum possible power output, limited by the resource constraint, in order to maximize economic return. However, alternative operating modes are possible, such as curtailment to leave a power margin for ancillary service provision.
- Power electronic interfaces—These interfaces have performance characteristics unlike those of rotating synchronous generators, namely they can respond rapidly to real and reactive power changes (Fig. 5). On the other hand, they lack inertial response due to decoupling of rotating machines, if any. Built-in inertial response characteristics in power electronic interfaces are possible however, in the form of synthetic inertia.
- Use of electricity storage systems—Battery energy storage systems are an effective and direct means of managing the variability of renewable energy resources, and they offer many features that are not available in conventional generators and systems. They allow renewable generation to be dispatchable, with controllability similar to conventional generators.
- Active loads—This includes load management and demand response, enabled by electronic controllers and advanced sensing, information and communications technologies, that can be used to enhance the flexibility of the electricity system.
- New electric loads/generators—These include battery chargers for electric vehicles (EVs), including larger vehicles such as buses and trucks. Plugged-in EVs

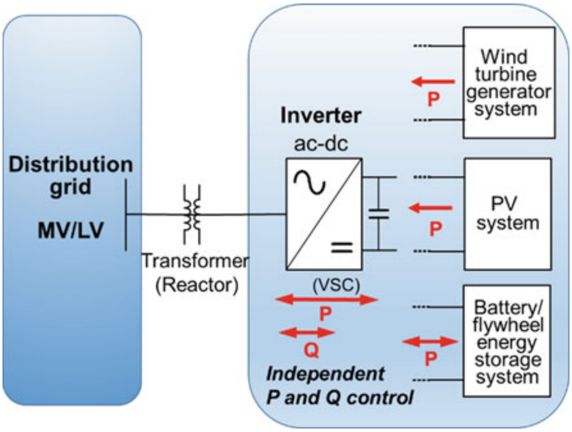


Fig. 5 Static (power electronic) inverter-based DER grid interfaces

can be used as either loads or generators, depending on the state of charge of the on-board battery, providing flexibility services.

- Converter-interfaced DER can provide four-quadrant operation (Fig. 6), with both real (P) and reactive (Q) power being injected or absorbed. This can provide any required combination of P and Q, within the rating of the converter.

Enabling Technologies in Support of DER Deployment

Recent technology developments in the areas of power, control, data management, communications and advanced computer-enabled technologies allow for intelligent applications supporting the change to a more reliable, affordable and sustainable electricity supply and a possible disruption of existing business models.

Enabling technologies include:

- Power electronic interfaces for electrical power generators, loads and power system compensators, and, more specifically for DER, power electronic interfaces for load flow control and voltage support.
- Sensor, information and communications technologies (ICT), including advanced control of DER.
- Digitalization of most aspects of the control, communications and marketing of electric power, including
  (a) advanced control system, integrating artificial intelligence and machine learning in the operation of distribution networks (e.g. forecasting and dispatching of DER);
  (b) advanced and automated energy transactions, including transactive energy based on concept such as blockchain transactions;

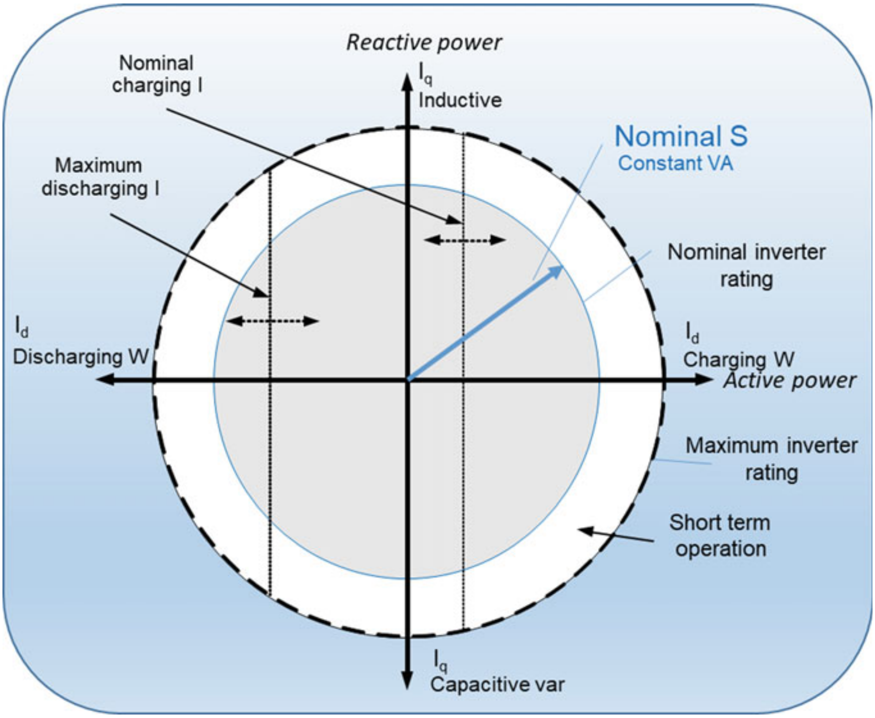


Fig. 6 Inverter-based four-quadrant interface

(c) deployment of Internet of things (IoT) approaches for generators, loads and electricity system assets.

Serious concerns regarding the digitalization and the large-scale deployment of ICT and IoT are possible cyber security vulnerabilities.

2.2.2 Electric Energy Storage Systems

Role of Battery Energy Storage

Electric energy storage systems, especially in the form of battery energy storage systems (BESS), are increasingly entering electricity distribution networks to improve operational efficiency, postpone or eliminate the need for large capital expenditures to upgrade networks or to generate service revenue. In its simplest architecture, a BESS consists of (Fig. 7):

- Grid-connected power conversion equipment, typically four-quadrant power electronic converters;
- Batteries, connected into the DC side of the converter;

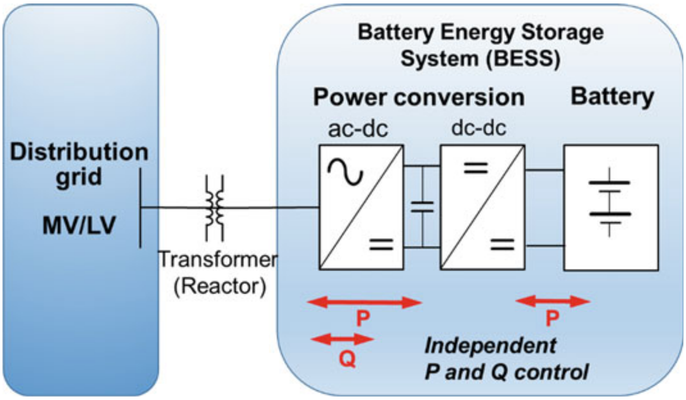


Fig. 7 Battery energy storage system (BESS) topology and structure

- Battery management system (BMS) for control, monitoring and communications, often with several layers;
- Interconnection and support systems, including equipment such as transformers, switchgear, cabling, thermal management and protective devices.

The location of BESS depends upon the application it is servicing, but also on the size of the system (stored energy) and the desired voltage level (MV, LV). It can be located at the substation, along the distribution feeder, associated with a renewable energy resource or close to the load.

Interfacing BESS

BESS can exist as centralized or decentralized installations in the electricity network (Fig. 8). These diverse arrangements of BESS in distribution grids need proper coordination and control structures in order to exploit the storage potential in a systematic and effective manner. In active distribution systems, depending on their ownership, they can contribute to different grid services:

- BESS can be interfaced with a distribution management system (DMS) and operated by DSOs for voltage control, demand side integration and local power balancing.
- BESS can be integrated into secondary substations/feeders and located close to local generation units, for optimizing the active and reactive power control.
- BESS can also be integrated into consumers' premises to provide local generation, backup and black-start power, demand side participation, etc.

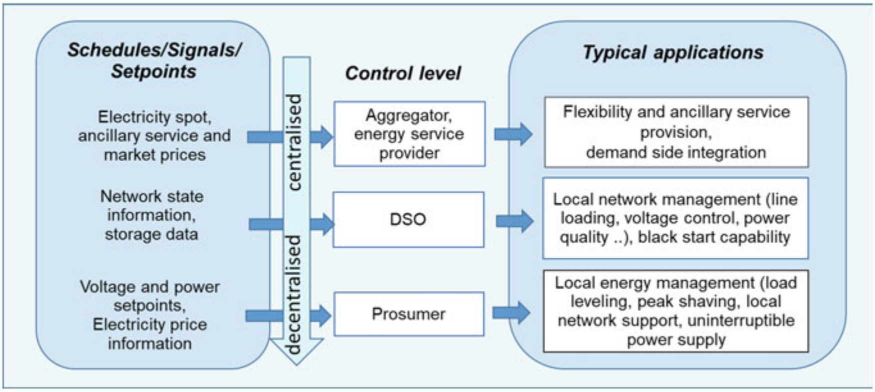


Fig. 8 Framework for the operation of BESS in distribution grids

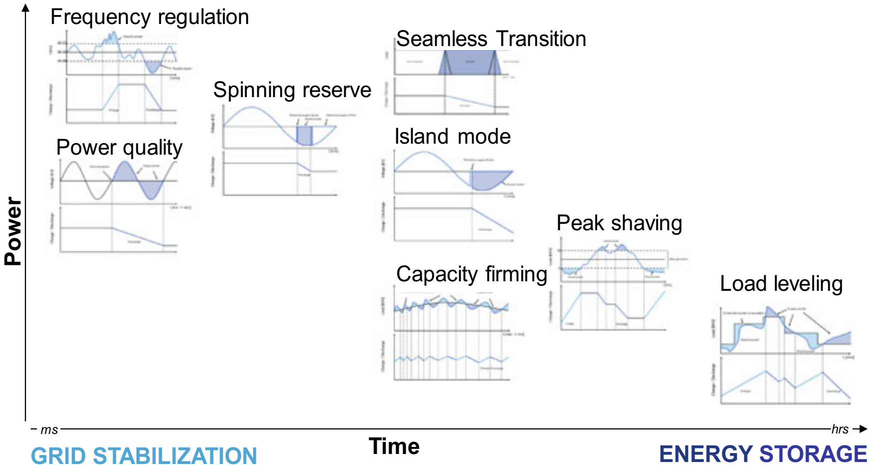


Fig. 9 Battery energy storage system (BESS)—features and grid services [4]

Applications

BESS has a very fast dynamic response compared with other energy storage devices and, as a result, they can cover a wide range of applications from short-term power quality support to long-term energy management. They can provide a number of benefits to distribution network operation, Fig. 9.

BESS creates a number of prospects for energy and capacity trading in electricity markets. BESS forms a key enabling technology in managing the intermittency of renewable energy generation and increasing its capacity factor and value in electricity wholesale markets. It can substitute conventional generation reserves and firm capacity to address the uncertainties of renewable generators through regulation and balancing markets. During congestion in control areas, BESS could also help to reduce the variance between the system and spot price of electricity.

BESS connected to the distribution system can have impacts both at the local distribution level and at the transmission level. General features and benefits of BESS can be categorized as follows, with the monetary value depending on the manner in which distribution and transmission systems are operated within the relevant market and regulatory frameworks:

- **Load levelling and peak shaving**—direct benefits are related to averaging out feeder loading, which can be used to defer investment in infrastructure upgrades for heavily loaded distribution feeders. With sufficient installed numbers of BESSs, it may also be possible to defer transmission capacity increases as well. BESSs can also reduce demand charges, if applicable in the regulatory context.
- **Ancillary services**—direct benefits come in the form of voltage regulation (through reactive power injection/absorption), frequency regulation and support (through real power injection), power system oscillation damping (power system stabilizer functions typical of synchronous generator excitation systems, with the added functionality of fast real and reactive power injection), power quality (voltage distortion and harmonic mitigation) and spinning reserve.
- **Balancing renewable energy/ramp rate control**—BESS can balance and firm-up renewable energy outputs and enable them to comply with local grid codes. It can mitigate power variations from wind and solar. Benefits can be considered across a range of timescales and purposes such as

    (i) short-term balancing (power variation smoothing),
    (ii) multi-hour storage, allowing renewable resources to be dispatchable,
    (iii) capacity firming, which allows committed levels to be maintained and
    (iv) providing short-term overload capacity.

- **Energy arbitrage**—this feature can be exploited where electricity market conditions exist which provide opportunities to purchase electricity at a lower cost and sell at a higher price, including in a time-of-use market. Benefits arise across several timescales from medium term (less than one hour) to longer term (multi-hour or day).
- **Resiliency**—this allows blackout ride-through by serving loads during the failure of the distribution system. Benefits can be considered across a range of purposes such as eliminating supply interruption and providing backup power, in particular to critical loads (providing uninterruptible power supply (UPS) functionality), supporting microgrids in the transition from grid-connected to islanded mode, and enabling islanded operation. BESS can also provide black-start capabilities.

2.2.3 Demand Side Integration

Contributions to the operation of distribution systems can be made by customers through the deployment of distributed energy resources (DER) on their premises, supported by modern control and communication systems. Customer empowerment approaches include the provision of information and tools for managing their consumption, normally encouraged by financial incentives. Load curtailment, shifting and levelling are typical demand side functions. Demand side integration (DSI) is one of the tools available to implement active distribution systems, Fig. 10.

Further work is required to make full use of demand side integration. This includes understanding the interests, expectations and requirements of the DSO; the potential role of the consumer in a more active distribution system; and the enhanced control of distribution loads. In addition, appropriate sensing, communication and control infrastructure is required to interface with the customer's equipment.

There are several current and planned approaches to DSI around the world to empower customers and a number of case studies and examples of deployments. However, additional guidelines and demonstrated solutions are needed.

The purpose of DSI programs is to modify the usage patterns of electrical loads of different customer types, usually domestic appliances or commercial or industrial facilities [2]. This is mainly to:

- optimize energy production costs
- optimize energy utilization costs
- improve the reliability of the system
- match utilization to environmental factors or
- improve the hosting capacity of the grid.

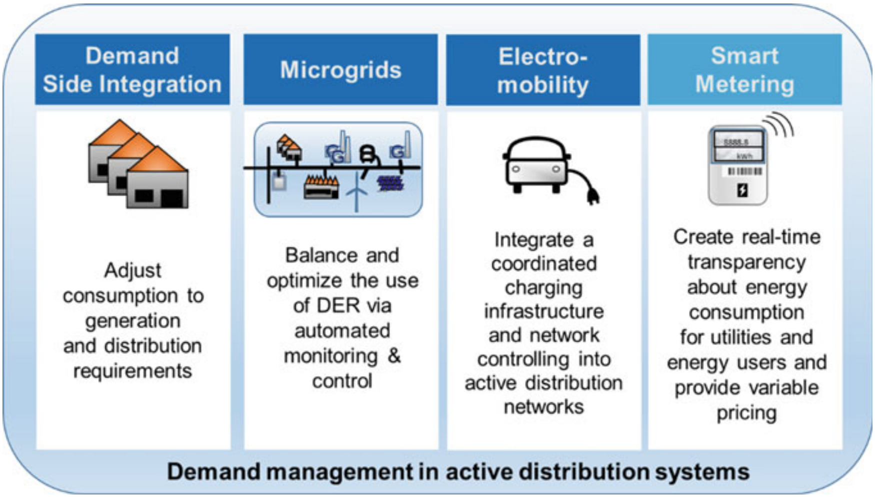


Fig. 10 Active distribution systems—demand side integration

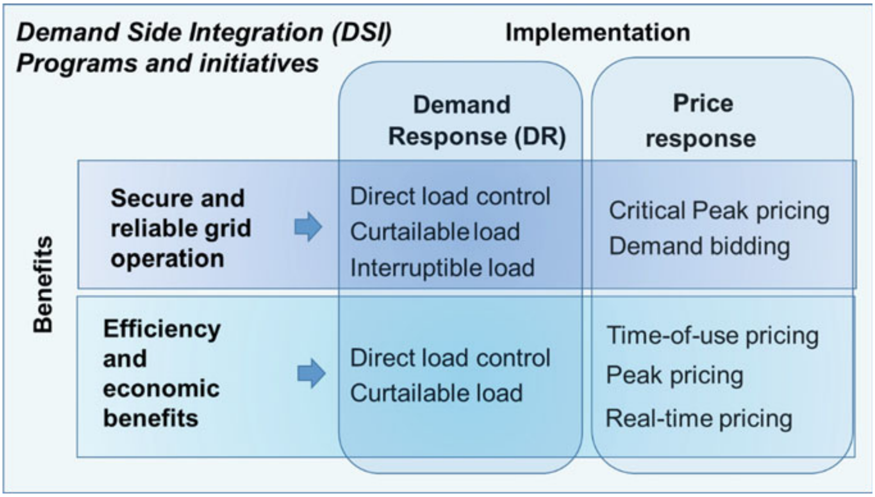


Fig. 11 Benefits and implementation of demand management

When properly designed, DSI programs also contribute to defer investment in new infrastructure. In such cases, the network operator often initiates the DSI program. Nevertheless, DSI can also be triggered by electricity markets.

Different approaches exist to manage the load, either by direct control (switch off, dispatch) or by indirect control (consumer response to price signals). Figure 11 summarizes the benefits and realization of different demand management programs.

The shorter the reaction time required, the more often, direct control is applied, especially in emergencies.

2.3 Standardization and DER Interconnection Rules

Grid codes, planning standards and economic evaluations still need to develop further to fully capture the benefits of DER and to ensure that DER is treated in an equitable manner in comparison to other forms of generation. This is particularly important for BESS, as recognition of the multiple services able to be provided by a BESS would enhance the business case for their installation.

Standards cover a number of aspects of DER deployment, including

(a) DER interconnection requirements—individual DER requirements, such as voltage and frequency ride-through, voltage variations, ramp rate control, power quality requirements and protection settings, as in IEEE Std 1547-2018 or CEI 0-21 [5], ENTSO-E and CENELEC, utility grid codes, as applicable. Figure 12 presents typical frequency and voltage ride-through requirements;
(b) aggregated DER management—IEEE 2030 standards series:

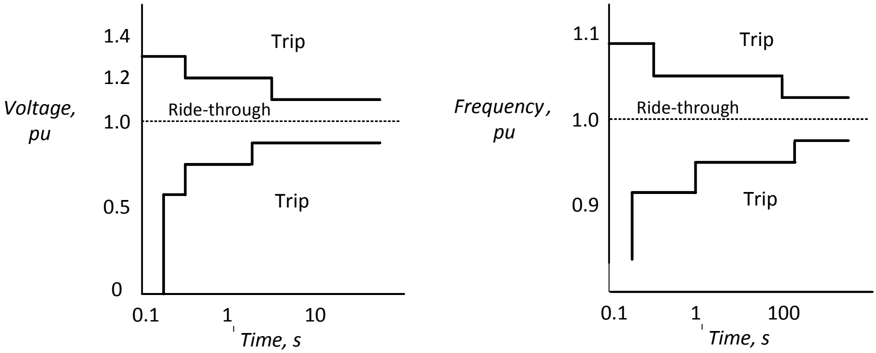


Fig. 12 Grid codes—typical DER voltage and frequency ride-through requirements

(1) IEEE Std 2030.7-2017—IEEE Standard for the Specification of Microgrid Controllers;
(2) IEEE P2030.11—Distributed Energy Resources Management Systems (DERMS) Functional Specification—under development;

(c) smart grid interoperability standards—IEEE 2030 standards series:

(1) IEEE Std 2030-2011—IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads;
(2) IEEE Std 2030.2-2015—IEEE Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure;
(3) IEEE Std 2030.3-2016—IEEE Standard Test Procedures for Electric Energy Storage Equipment and Systems for Electric Power Systems Applications;

(d) IEC 61850 standards and related developments:

(1) IEC 61850—Communication networks and systems for power system automation. This collection of international standards describes devices in electrical substations and information exchanges between intelligent electronic devices (IED), Fig. 13;
(2) IEC 61850-7-420—Communication networks and systems for power system automation—basic communication structure—distributed energy resources logical nodes. This standard gives object models for DER, including BESSs.

International electro commission (IEC) efforts in standardizing information exchanges lead to developing a common information module (CIM). The proposed reference architecture based on IEC 60850 series is applicable to information exchange and modelling of DER and of active distribution systems and also ties into cyber security.

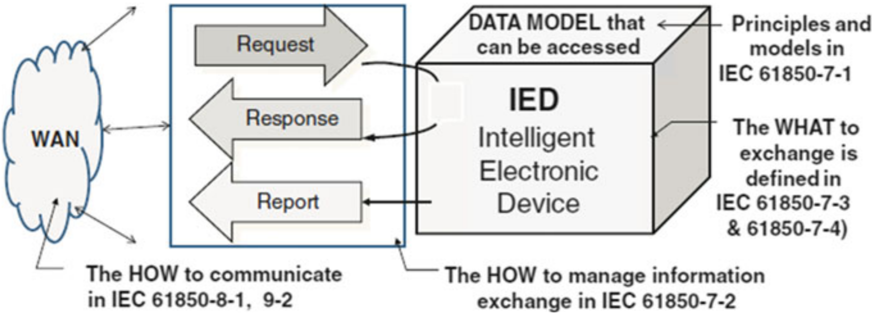


Fig. 13 Information exchange between intelligent electronic device (IED) and the grid

3 New Requirements

3.1 Societal Requirements

3.1.1 Stakeholders

The stakeholders in the deployment of DER and active distribution systems include:

- customers (end-users, prosumers);
- owners and operators of DER (individual or aggregated, wind and solar farm owners and operators, etc.);
- distribution system operators (DSOs) and transmission system operators (TSOs) that can benefit from the services provided by individual or aggregated DER under their control or under the control of independent aggregators or DER management system operators;
- regulators.

Citizens are at the centre of the energy transition. The ability to install their own local generation sources thus gives them the opportunity to become prosumers and allows them to shape their own energy profile.

DSOs are key enablers for the success of the ongoing energy transition and thus play a crucial role in the relevant developments. They must act as neutral market facilitators and guarantee distribution system stability, power quality, technical efficiency and cost-effectiveness in the future evolution of energy networks towards a smarter grid concept.

The developments in the distribution network also affect the overall planning and operation of the system, and thus, TSOs are also interested.

Researchers and academia, equipment manufacturers, ICT developers and providers, etc., are obviously very important for these developments.

Finally, regulators and policy-makers are the main stakeholders that facilitate, if not enable, these developments.

The European Technology and Innovation Platform for Smart Networks for Energy Transition (ETIP-SNET) is the key EU initiative consolidating the views of all the above energy stakeholders [6].

The largest challenge faced with the adoption of new technologies is the provision of abundant energy forms, at affordable rates and with the required quality and reliability to its customer base. This customer base includes the developing parts of the world with low electrification access (i.e. less than 50% of the country population electrified), to the highly developed and technologically advanced economies, where customers demand ever-increasing reliability, environmental protection and energy efficiency. Customers are demanding a higher level of integration and as prosumers have now also become players in the market place. System operators and electricity markets need to increasingly manage bidirectional energy flows with variable resource requirements. Utilities and distributors are faced with the "death spiral" where customers are disconnecting from the grid, while expecting to maintain the "security" associated with a grid-connected point of supply, even when disconnected.

TSO, DSO, energy retailers, aggregators, private and industrial customers will be a part of the new active distribution systems. Policy-makers will be also part, since new regulations have to facilitate possibilities for demand response.

3.1.2 Environmental Protection

Most DERs are based on RES, including biomass and waste, as well as solar and wind. Their optimal integration has direct positive effects on the environment. The increase in efficiency of operation reduces energy use offering additional positive advantages.

The deployment of DER based on renewable energy sources and the complementary technology, energy storage, will have a direct and beneficial impact on the environment. It will allow decarbonization of electric energy production and more generally, through increased use of electricity as an alternative energy source to fossil fuels; it will lead to gradual decarbonization of human activities, in commercial, industrial and transportation sectors.

The deployment of DER depends on economic, ecological and technical considerations, as shown in Fig. 14. In addition, the regulatory and legal framework affects all aspects. For example, regulation can contribute to the limitation of pollution by imposing emission costs that quantify the drawbacks of conventional fuel-based generation greenhouse gas (GHG) emissions. Similarly, the regulatory framework establishing the price of electricity directly determines the economic criteria.

3.1.3 Economic Considerations

The construction and operation of active distribution networks have a direct positive effect on network costs, reliability and security. Figure 14 illustrates some of the issues. It affects the cost of energy, lowering operational costs and thus has a positive

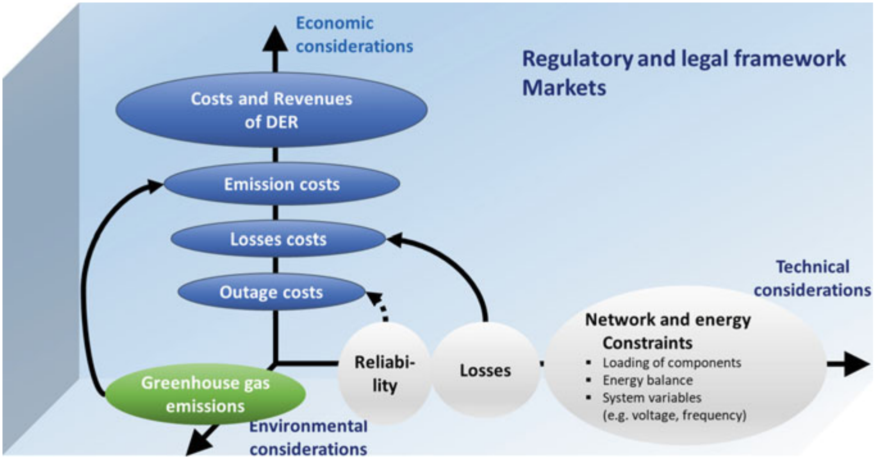


Fig. 14 Active distribution network impact considerations

effect on overall economy. Prosumers are able to lower their bills by educated use of their resources. The operation of local markets can further reduce operational costs.

Challenges abound, as emerging economies have the opportunity to leapfrog technology adoptions (similar to the cell phone industry) by integrating DER and microgrid technologies, without the need for constructing expensive generation and grid infrastructures. Technology needs to be affordable to cater for the needs of emerging economies, to ensure that access to electricity is accelerated in such countries. The opposite extreme is found in developed countries where increasing reliability, sustainability of resources (e.g. shift from coal to renewable energy sources) and affordability of energy drives the quest for more efficient electricity supplies.

Price elastic consumption will be important for development, i.e. time-of-use tariffs, spot market prices, a market for providing spinning reserve, etc.

The new possibilities provided by recent and expected developments include:

- Smart cities—DER deployment and management and interaction with other energy sectors
- Smart homes—impact on distribution and transmission grids
- Transport systems—electric vehicles and trucks, trains, urban transportation systems
- Rural electrification and off-grid distribution systems—microgrid deployment opportunities.

3.1.4 Education Needs

Current university educational curricula include courses about RES, distributed energy resources and active distribution networks. There is a huge need to inform citizens about the opportunities offered by the new DER technologies for their benefit and for the environment. There is high need for further education at the utility level for practicing engineers.

New technology requirements have led to steep learning curves, particularly in developing countries where current grids and networks compete with the introduction of microgrids, BESS and DER applications. Knowledge transfer, tools and systems adoption and application guidelines are all "put together on the fly", as customers and distributors roll out new technologies.

At universities with master's courses in energy systems/power systems, project work and thesis research can be seen addressing active distribution systems and DERs. Ph.D. research projects are focusing in this area, too. However, there are not many courses directly related to the topic. However, there is work ongoing within the EU to start up multidisciplinary studies and courses related to this area.

At this time, the energy portion of the topic of distributed energy resources and active distribution systems is covered in a number of courses given in the areas of power systems (transmission and distribution) and power conversion (rotating machines and power electronic converters). Other topics, such as control and communications, are covered in general courses in the respective areas.

3.2 Grid Requirements

3.2.1 Security, Reliability and Resilience

Driven mainly by the requirements of the electricity supply system of the future, and by new developments in hardware, software and ICT, distribution systems are expected to change substantially in the long term. One main impetus will come from the need to cope with the increasingly complex group of stakeholders involved in a more decentralized electricity supply system.

This will motivate changes in the architecture of future systems, with impacts in the engineering lifecycle and its methods.

3.2.2 Flexibility

The need to balance supply and demand in a system significant penetration of intermittent generation requires a high degree of flexibility in the system. This flexibility will be provided by generation, both conventional and distributed, and by other resources available in the system. These will include energy storage systems, and conventional (e.g. heating and cooling) and new (e.g. electric vehicle) loads with greater controllability (Fig. 15).

Flexibility describes the ability of a power system to cope with variability and uncertainty in both generation and demand (Fig. 16), while maintaining a satisfactory

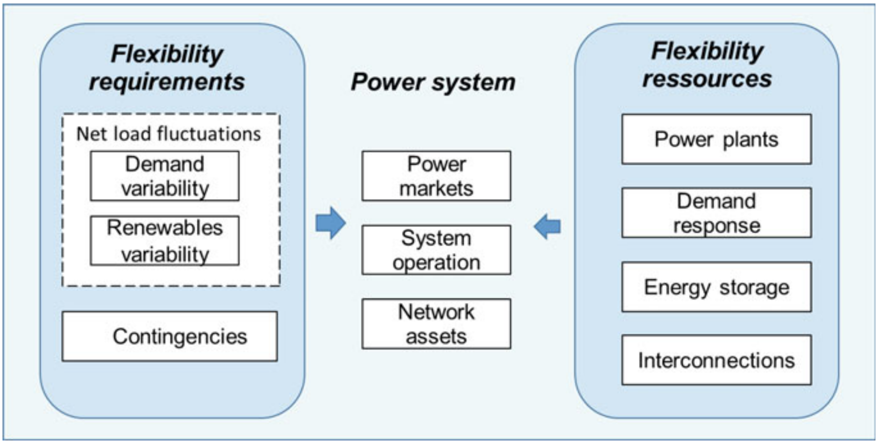


Fig. 15 Flexibility—needs and resources

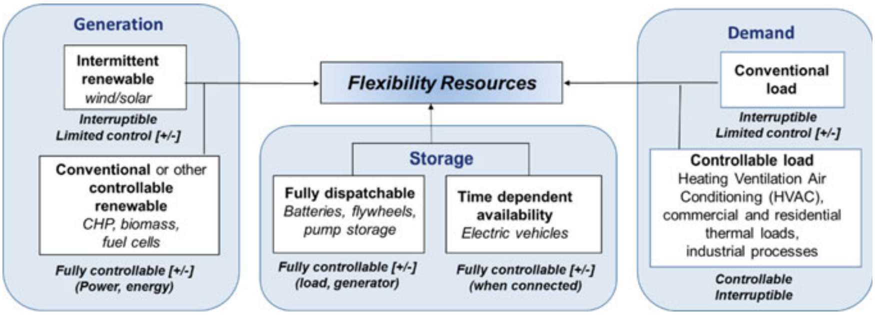


Fig. 16 DER providing flexibility

level of reliability at a reasonable cost, over different time horizons. Multi-energy systems can also provide increased levels of flexibility.

3.2.3 Efficiency

In developed countries, the impact on load growth scenarios has been profound in recent years, as customers and manufacturers have been encouraged to adopt energy efficiency measures. The move from incandescent to LED lighting, improved manufacturing systems, power factor correction techniques, etc., have all combined to improve the overall energy efficiency of customer electrical installations. Increased automation, real-time data availability, etc., will no doubt further increase such measures in the future.

Energy efficiency should always be addressed and, to get a better total energy balance, it is important to consider multi-energy systems to get the best out of their interaction. This includes waste heat, excess wind power production, the electrification of heating systems and of the transportation sector.

3.2.4 Regulation and Policies

Regulation and market policies in many countries have drastically changed from monopolistic approaches to market-based approaches allowing the participation of DER for providing energy and flexibility services. Still a lot more needs to be done to facilitate these developments and ensure a level playing field for all RES at the distribution level.

Tools for the participation in electricity markets of new loads such as electric vehicle or electric transportation system battery charging stations need to be developed. Tools for interaction with, for instance, district heating using heat pumps and electrical boilers should be further investigated.

4 New and Emerging Technologies and Applications

4.1 Multi-energy Systems

Multi-energy systems are integrated schemes from different energy vectors, sectors and networks such as electricity, gas, heating, cooling and transport. These systems are key to generating new types of energy flexibility as well as techno-economic and environmental opportunities for reliable operation and least-cost planning of future smart electricity grids.

Benefits of multi-energy systems, Fig. 17, include:

- Better energy efficiency of the total energy system;
- Possibilities to use more renewable energy, for instance from excess power from wind or PV generation;
- Making use of new forms of storage facilities (heating/cooling/gas and also electricity, e.g. usage of vehicle-to-grid (V2G) concept);
- Possibilities to counteract fluctuations from RES;
- Possibilities to use waste power from industry.

To allow for multi-energy system interactions in distribution grids, it is necessary to study the configurations, impacts and prospects of multi-energy systems that enable enhanced solutions for intelligent electricity systems, energy storages and demand side management in the electricity grids with an increasing share of DER.

There are opportunities and impacts of multi-energy systems in future electric power systems; thus technologies and systems that integrate multiple sources

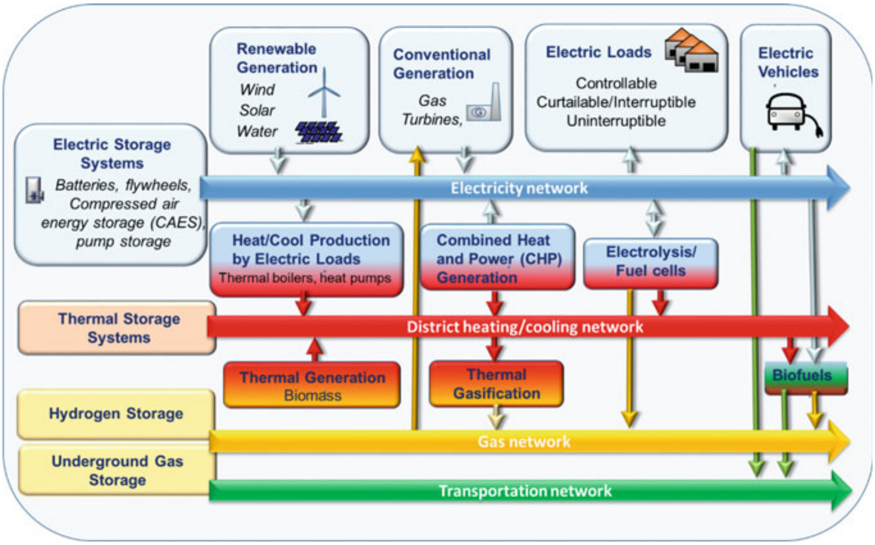


Fig. 17 Application of multi-energy systems

of energy need to be considered. These include power-to-gas (P2G), including electrolyzers, fuels cells, hydrogen storage, injection into gas networks; combined heat and power (CHP); combined cooling, heat and power (CCHP); power-to-heat (P2H), including electric boilers, heat pumps, thermal storage; power-to-vehicle (P2V) including vehicle-to-grid (V2G) services; and compressed air and pumped hydro-storages.

4.2 Electro-mobility

4.2.1 Electric Transportation Systems

The impact of electrical mobility on the grid might create local constraints, as the LV and MV infrastructure has to cater for increased needs for charging of vehicles. Grid reinforcements may become necessary, especially when the charging time coincides with load peaks or it can create new peaks in the case of dual tariffs. This uncontrolled charging will unavoidably lead to increasing capital expenditures, overloading can be avoided however by applying smart charging techniques that distribute wisely the charging load in a period of time. This intelligence can smoothen the load curve, achieving a much better use of the network infrastructure. The vehicle-to-grid (V2G) impact is so far largely untested, and such characteristics will become more practical to adopt when the number of EVs in the market has substantially increased. Currently, high EV costs are limiting the acceleration of the adoption of EVs for private, public transport and commercial purposes.

4.2.2 Electric Vehicle Charging Systems as DER

Supported by national policies, the number of electric vehicles is increasing worldwide. Main aspects of EVs with impact on future electricity systems include:

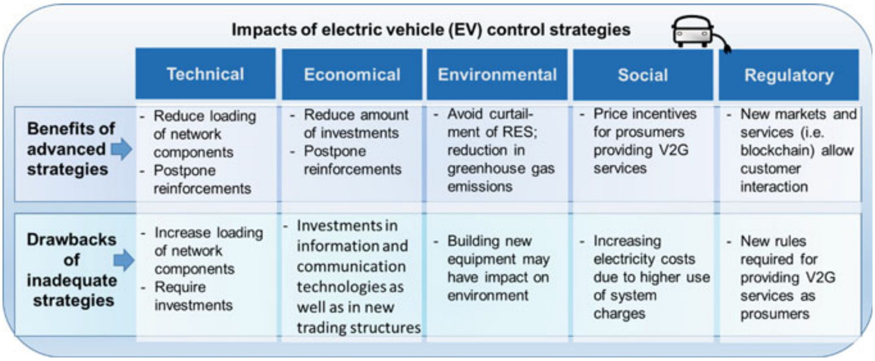
- EV charging technology and deployment: smart chargers using smart converters, fast and slow chargers, connection deep within the distribution system (slow chargers) or on dedicated feeders (fast chargers)
- EVs as a storage technology that can be deployed in distribution systems, with the ability to provide power to the network in addition to electric vehicle charging. This allows new approaches to enhance distribution system reliability and resilience
- EVs as flexible resources. EVs can be a component of consumer integration and empowerment, allowing demand response and demand side integration
- EVs as a component of smart cities: integrated EV technologies, power, control and information and communications technology deployment for flexibility.

The battery on-board an EV can provide flexibility to the DSO when the EV is connected to the charger, similar to a stationary BESS. The state of charge of the EV battery and the available energy depends upon the past and planned use of the EV, as well as the energy stored in the battery during the charging process at the time of use of the system, as a DER. In the charging process, the EV battery becomes a fully flexible load, potentially allowing the DSO to control the charging rate. When fully charged, the EV battery can become a fully controllable BESS. When multiple EV chargers are considered, EV charging can be controlled and coordinated to meet the distribution grid requirements and constraints. In addition, when fast chargers incorporate stationary batteries for fast EV battery charging, demand charges can be reduced and the stationary battery acts as a BESS, even in the absence of a connection to an EV.

There are various configurations of EV charging stations, and these configurations are evolving as more experience is gained. The benefits and impacts of the various configurations on the distribution grid, and their potential to enable enhanced solutions for intelligent electricity distribution systems, need to be considered.

The following issues need to be addressed:

(a) impact of EV charging (and discharging) on the distribution grid and the hosting capacity of distribution networks for EV chargers;
(b) charging requirements, charger locations and charging patterns for slow and fast charging for different types of EVs: cars, buses and trucks;



Impacts of electric vehicle (EV) control strategies

	Technical	Economical	Environmental	Social	Regulatory
Benefits of advanced strategies	- Reduce loading of network components - Postpone reinforcements	- Reduce amount of investments - Postpone reinforcements	- Avoid curtailment of RES; reduction in greenhouse gas emissions	- Price incentives for prosumers providing V2G services	- New markets and services (i.e. blockchain) allow customer interaction
Drawbacks of inadequate strategies	- Increase loading of network components - Require investments	- Investments in information and communication technologies as well as in new trading structures	- Building new equipment may have impact on environment	- Increasing electricity costs due to higher use of system charges	- New rules required for providing V2G services as prosumers

Fig. 18 EV charging station—impact of control strategies

(c) technology readiness and expected developments, charger types (slow and fast charging), charger technology, enabling bidirectional capabilities (vehicle-to-grid and vehicle-to-building); different semi-fast and fast chargers with integrated storage (battery storage, other technologies), installation in residential, commercial and utility settings; coupling chargers with renewable energy resources, standardization (existing and planned);

(d) managing EV charging, including single EV charging, multiple charger control and coordination, demand management and response to meet grid constraints; managing fast charging and the impact on the planning and operation of distribution systems;

(e) EV charger ancillary service provision to DSOs and TSOs and the associated regulatory issues, business and ownership models, role of aggregators, technological, socio-economic, financial aspects and business cases for EV charger deployment.

Figure 18 illustrates the potential of appropriate EV charger control strategies that will become increasingly important with increasing market penetration level of EVs.

4.3 Microgrids

4.3.1 Context and Definition

Microgrids comprise low or medium voltage distribution systems with distributed energy resources (DER), including distributed generation (DG), storage devices and controllable loads. A microgrid can typically operate *grid-connected*, whereby it can freely exchange electricity with the upstream distribution network. On the other hand, (e.g., in case of failures in the upstream network) a microgrid can also operate autonomously as an *islanded* network, in which case it would solely rely upon its own

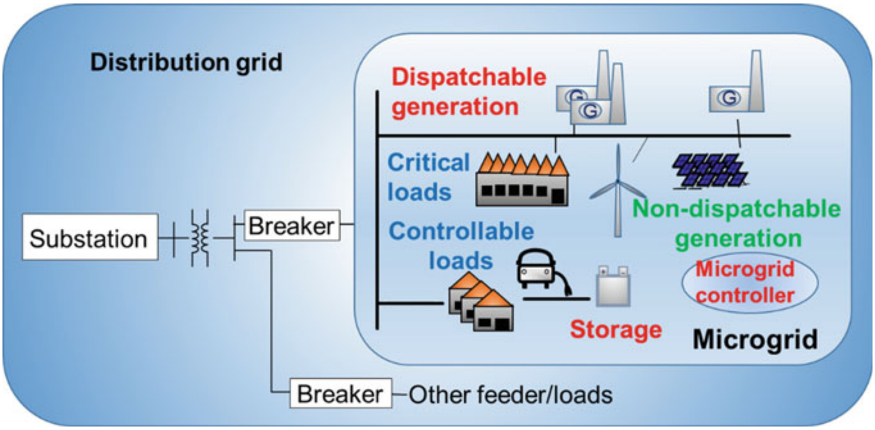


Fig. 19 Microgrid—DER assets and management

resources to maintain demand/supply balance with an adequate level of reliability and power quality [7].

A number of benefits from microgrid adoption may arise for customers and utilities, particularly owing to the possibility of operating normally uncontrolled DER units in a coordinated way.

The size of microgrids varies in different applications, from building-level up to a complete distribution network. Mostly, microgrids comprise a portion of distribution systems. There are no specific requirements for operating them as grid-connected systems, other than an interconnection agreement with the DSO, Fig. 19.

In Europe, at the end of 2019, very few microgrids exist, even in pilot mode. In the current regulatory structure, DSOs are not allowed to operate microgrids, or own and use DER for network benefits. A new boost in microgrids is expected via the development of local energy communities (LEC), which are based on microgrid structures. In other countries, including Australia and the USA, there are examples of utility-owned microgrids for resilience and increasing reliability, e.g. lowering outage times during maintenance, etc.

The market for microgrids for greenfield electrification is massive, with increased electrification of developing countries in Africa, Asia and South America. Natural resources often abound, and the use of local resources will enable residential, industrial and mining supplies to be developed. As these supplies are developed, decisions will need to be made on whether to adopt AC or DC technology for this new infrastructure.

It is expected that AC will continue to predominate in areas where such infrastructure is well established. However, DC grids might be adopted on ships, oil platforms and other more isolated places. DC home in case of DER generating DC current allows for higher efficiency.

Microgrids will be established in only rural areas with benefits. If you have an existing grid infrastructure, you should take advantage of this, being able to use energy also from distant renewable power production units like large offshore wind farms and big solar power plants.

4.3.2 Microgrid Controller

A microgrid controller, Fig. 20, is a basic component of microgrids. It coordinates, in an optimized manner, the integration and dispatch of local DER and loads. It:

- allows seamless disconnection and reconnection to the grid;
- sets the power exchanges (real and reactive) with the grid;
- enables the provision of ancillary services to the grid;
- enables market participation of DER within the microgrid.

Implementation is realized either as a centralized controller sending commands to elements or as a decentralized control system with local controllers (agent-based) playing the main coordination role. Sensing, monitoring, data management and information and communications technologies are required.

4.4 Virtual Power Plants (VPPs)

VPPs aggregate generators in different locations and of different types, for example wind turbine generators (in a wind farm), solar power generators and conventional power plants, typically combined heat and power (CHP) to achieve behaviour similar

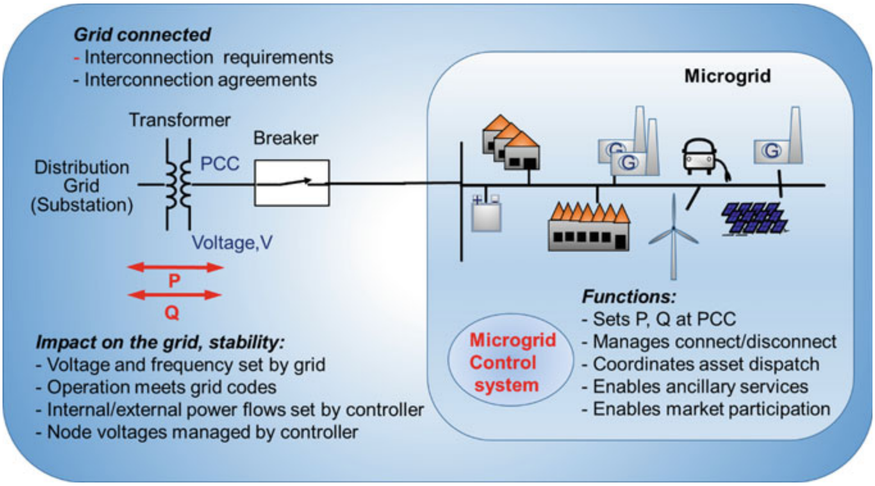


Fig. 20 Microgrid control functions

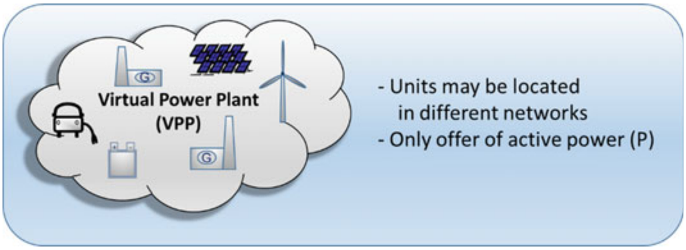


Fig. 21 Virtual power plants

to a conventional power plant (Fig. 21). In addition, sufficient size enables participation in different markets (frequency regulation, power exchange market, bilateral supply contracts, etc.).

The aggregated generation profile equates only to a theoretical balance as the location of the generation units may be in different networks with different operational requirements. Supported by information and communications technologies, corresponding signals for monitoring and control of all units are sent. Thus, VPP only offers schedules for active power provision.

4.5 Rural Electrification, Islanded and Off-Grid Systems

Rural electrification is the main field of efficient distribution network development, enabled through the deployment of DER, supported by modern control and communication systems, for both grid-connected and off-grid electric distribution systems. Key to the deployment of these systems are sources of a secure electric energy supply, provided by transmission, distribution and LV grids, local generation resources (small hydro, diesel generators), renewable energy resources (solar, wind, small hydro), alternative energy resources (bioenergy, including biogas and biomass), hybrid generation systems, types and role of energy storage.

Specific considerations are the sustainability of the energy supply, enabled through the use of renewable energy resources (wind, solar and small hydro), emissions and greenhouse gas (GHG) reduction, environmental protection and impact, footprint, power quality, reliability and availability of the energy supply, and energy security (short term and long term). Other issues that need to be addressed are ownership, maintenance and operation of DER, including generation, integration, interconnection requirements, grid codes and standards as well as rural electrical loads. Applications are found in agricultural, industrial, mining and commercial settings. Demand response, energy efficiency, metering for billing, monitoring and control should be based on the latest technologies. These systems can be operated in either grid-connected or in off-grid modes, with islanded possibilities in the case of weak grids, with low reliability.

Current practices and approaches in generation and distribution deployment and rural electric distribution system architecture need to be analysed and reviewed in the light of intelligent grid technologies. Techno-economic challenges and present and future solutions need to be considered, as well as political, institutional and societal issues.

Off-grid systems and remote grids can be designed using the principle of rural electrification, but need to be autonomous electric systems.

4.6 Local Energy Communities

Local energy communities (LEC) are promoted as an excellent means to facilitate active customer engagement, increased penetration of RES, higher energy efficiency and means to combat energy poverty. They aggregate different DERs to share energy and capacity among LEC stakeholders, and they are based on the participation of LEC in local energy markets directly or through energy aggregators.

Among the issues to consider are:

(a) the relationship and the data exchange between stakeholders within an LEC, and between the LEC and the local DSO;
(b) the mechanisms for the participation of LEC stakeholders and the LEC itself in electricity markets;
(c) the role of the regulator and local legislations in the business cases defining the internal organization of the LEC;
(d) the mechanisms for consumers entering and leaving a LEC;
(e) options for an LEC in being locally responsible for the balance between generation and demand.

4.7 DC Distribution Systems

Increased interest is shown recently for DC distribution systems, both at LV and MV levels. The following sections focus on MV DC grids.

4.7.1 Motivation of MVDC Grids

Medium voltage direct current (MVDC) is a promising technology for upgrading and modernizing power distribution networks and achieving increased reliability, flexibility and efficiency. MVDC can effectively be used as an alternative to medium voltage AC (MVAC) distribution systems. Studies show that the power capacity of a MVDC circuit is up to 1.63 times that of the corresponding MVAC circuit having similar installation ratings and conductor cross section.

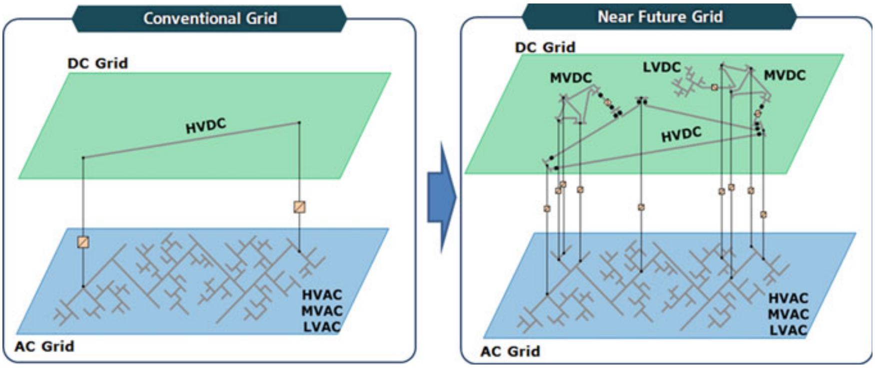


Fig. 22 Conventional grid (left) and future grid with parallel DC structure (right) [8]

In areas where electric grids are undergoing fast expansion, MVDC is becoming more economical and versatile for moving large blocks of power over a long distance.

The future power system will involve coexistence of the regional AC transmission and distribution networks with DC grids (Fig. 22). An active smart DC power distribution network should enable the bidirectional control of power flow with high reliability and efficiency.

In addition, the MVDC grid can be used for rural electrification. Rural communities with small populations widely spread geographically may result in electrical power plants that have high capital costs and low efficiency. Currently, diesel plants are the best solutions to provide power to such locations. However, the cost of fuel and transportation are high for many rural communities. The development of MVDC will be an economical means of transporting electrical energy from low-to-high cost locations, this reducing the overall energy costs in rural communities.

4.7.2 Current Limitations of MVDC

Despite all the benefits of MVDC, the development of such systems comes with its own challenges:

- DC circuit breakers are required to clear faults, but MVDC circuit breakers are still under early development;
- DC/DC converters are required to connect two DC systems at different voltage levels; these are still under development and not commercially available.

4.7.3 Structure of MVDC Systems

The structure of MVDC grids is either a point-to-point structure based on current source converters (CSC) or a multi-terminal structure based on voltage source converters (VSC).

A radial MVDC system is a structure in which the main bus connects the existing AC grid through a single path (Fig. 23). Conventional AC loads are supplied by converting the MVDC voltage to LVDC, and then converting DC to AC or by converting the MVDC directly to MVAC and then stepping the voltage down using a transformer to supply the AC load. This configuration is relatively simple, minimizing distribution losses and making it easy to select and utilize different voltage levels. However, loads and generation at all nodes are lost in the event of a single failure. A ring or loop network structure overcomes the disadvantages of the radial configuration, with high-speed DC switches placed at both ends of each DC bus for the isolation of failure points.

In a mesh configured MVDC distribution, Fig. 23, also known as a multi-terminal network, two or more AC grids are connected to the MVDC grid, thus increasing its reliability. Similar architectures have been utilized in high voltage direct current (HVDC) systems for offshore wind farms. Modular multilevel converter technology with voltage source converters (VSC-MMC) technology is currently the most suitable approach for MVDC.

In the past, research on MVDC attracted more attention, but the experience of the pilot projects in China shows LVDC is more efficient and practicable in near future, indicating MVDC part should include a pure LVDC supply system.

4.8 Smart Metres

Smart metres are considered as a basic step towards empowering customers to become active players and improving energy efficiency. In Europe, it is planned to complete their deployment by 2020–2023, with the target penetration ratio of 100%. Similar

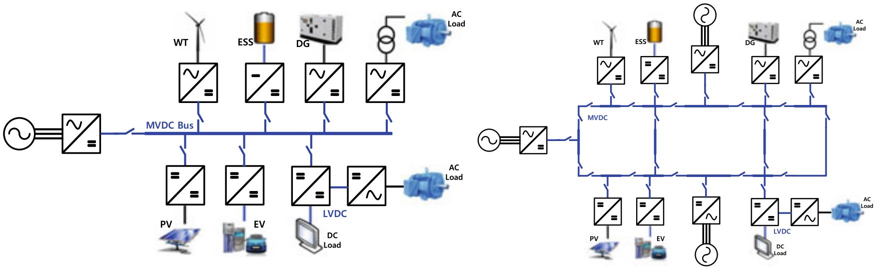


Fig. 23 Radial (left) and meshed (right) configuration of MVDC systems [8]

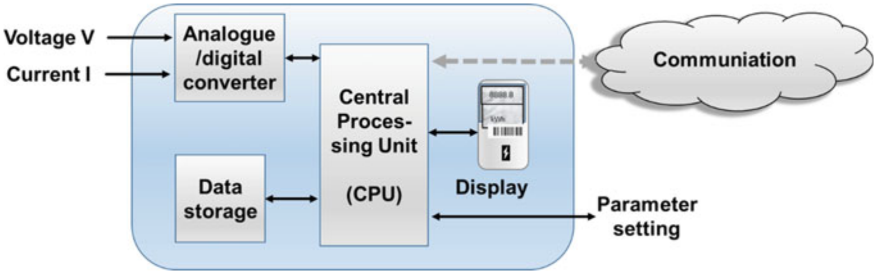


Fig. 24 Typical smart metre system

rollouts are also foreseen in many other countries. Besides customer side empowerment, there are various purposes for implementing smart metres. DSOs are motivated to utilize them for reducing labour costs for metre reading for billing purposes, for reducing non-technical losses and as dispersed sensors at the MV/LV level for optimizing operations and maintenance. In the future, implementing demand side integration and time-based tariffs will also be facilitated [9].

Typical metering infrastructure consists of electronic metres, concentrators for collecting data from tens to several hundreds of smart metres, and central systems (HES/MDMS) for storing and managing metered data, Fig. 24.

Suitable communications media need to be available. The media used will depend on the environment and prevailing availability of technology.

Measurement data vary among countries, with available resolution of the measurement intervals mainly 15 or 30 min. The transmission intervals have a wider range and vary from hourly to monthly, depending on the medium that is chosen for communication. Overall, this indicates that smart metre data measured every 15 or 30 min will be the input of use cases, and that the output from them cannot be any faster or any more frequent than the transmission intervals. It is necessary to consider both measurement intervals and transmission intervals when designing systems for utilizing smart metre data.

4.9 Information and Communications Technologies

4.9.1 Data Collection and Management—Internet of Things

DSOs have access to a huge amount of data available through smart metres and sensors installed in smart devices in the network or from phasor measurement units (PMUs). There is a great need to manage millions of daily real-time signals through satellite, power line communication systems, radio, fibre-optic lines and other communication technologies. The digital transformation of energy will gradually transform DSOs into data-centric companies. Data management will continue being one of the key features of smart grid design, together with infrastructure for digitalization and automation. Data affect all functions of the distribution network, e.g. DER enabled by big data-driven local balancing of supply and demand, data-driven asset strategies including preventive and condition-based maintenance and predictive outage, automated controls to improve network safety and efficiency, customer analysis, providing field workforce with mobile access to maps, data, real-time expertise [10]. Internet of things (IoT) technologies can enhance further all the above capabilities for distribution network planning and operation.

The management and accuracy of data, and a network that is not geared towards the rapid adoption of the IoT are a stumbling block for greater autonomy and a move towards distribution automation, network visibility and network control in the developing world. Telecommunication and tele-control requirements, together with advanced active distribution management systems (ADMS) are required to translate the interface from the metre to the control room, into a more reliable and robust system. It is also noted that this is often not translated into reality as utilities and distributors stick with the traditional systems.

Data collection and forecasts will be an important aspect of making the system flexible, so these aspects have to be considered.

4.9.2 Physical and Cyber Security Issues

As the industry relies more on interconnectivity, the potential for cyber attacks to cause severe disruption to operations, loss of data and financial losses is a key concern for energy executives. For this reason, there is intense ongoing activity at national and international levels for ensuring cyber security.

Electricity networks are critical infrastructure systems. Smart grid technologies require remote control and supervision of electric networks. These technologies are vulnerable to security threats such as:

- External attacks
- Internal attacks
- Natural disasters
- Equipment failures
- Data manipulation
- Loss of data.

Confidentiality, availability, integrity and non-repudiation standards for information security are being developed. Advanced encryption methods and the objectives of the standard IEC 62351 “power systems management and associated information exchange—data and communications security” can be applied.

Communication is governed by the standard series IEC 61850.

As the data proliferation increases, and data is moved to the cloud, the risk associated with cyber security increases. Improved firewall controls will be required to ensure that customer and distributor owned information is not abused. This needs to be addressed since many sensitive data are collected by smart metres.

In developing countries, the uses of renewable energy sources, e.g. PV panels and batteries, are the primary sources of energy for communication and lighting. The physical safeguarding of assets in remote areas thus remains a challenge and will require some intervention to minimize the impact of such abuse.

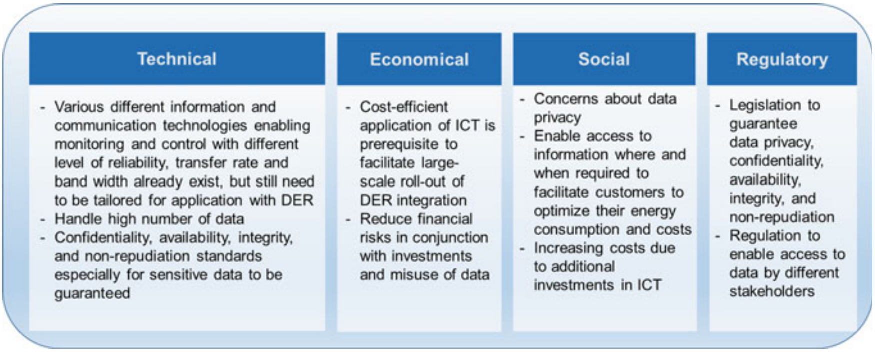
4.9.3 Impacts of ICT Application

Figure 25 illustrates the technical, economic, social and regulatory issues of ICT technology used for integrating DER.

4.10 Other Equipment and System Requirements

Active distribution systems also draw on expertise from other areas such as:

- MV and LV substations
- MV and LV switching equipment
- Distribution transformers
- Power electronic equipment technology, including MVDC and LVDC
- Transmission and distribution protection
- Telecommunication systems for transmission and distribution.



Technical	Economical	Social	Regulatory
- Various different information and communication technologies enabling monitoring and control with different level of reliability, transfer rate and band width already exist, but still need to be tailored for application with DER - Handle high number of data - Confidentiality, availability, integrity, and non-repudiation standards especially for sensitive data to be guaranteed	- Cost-efficient application of ICT is prerequisite to facilitate large-scale roll-out of DER integration - Reduce financial risks in conjunction with investments and misuse of data	- Concerns about data privacy - Enable access to information where and when required to facilitate customers to optimize their energy consumption and costs - Increasing costs due to additional investments in ICT	- Legislation to guarantee data privacy, confidentiality, availability, integrity, and non-repudiation - Regulation to enable access to data by different stakeholders

Fig. 25 ICT issues for DER integration

5 New Methods and Tools

5.1 *DER Impact Assessment Tools*

5.1.1 DER Models for Different Timescales

The purpose of DER assessment tools is to identify the impact of a large deployment of DER at the distribution level and repercussions on the transmission grid, to investigate different methods of aggregating DER and to determine the benefits of aggregating DER at the distribution and transmission levels.

Simulation tools allow analysis of the impact of DER installed at the distribution level on the transmission grid, considering static and dynamic aspects. Planning and operation tools at the distribution and at the transmission levels consider the impact of a wide deployment of DER on reliability and resilience, and the economic aspects of the generation of power and increased reliability and resilience (Fig. 26).

Considerable efforts are still needed to present, analyse, assess and describe the needs for the development of benchmark DER models that can be used for a range of distribution systems studies in planning and operations over a range of different timescales. Distribution planning and operation for including non-wires alternatives need to be considered as part of distribution investment decisions and DER impacts on distribution network operations considering the integration of DER within customer systems, communities and for the support of the bulk power system (TSO/DSO interface requirements).

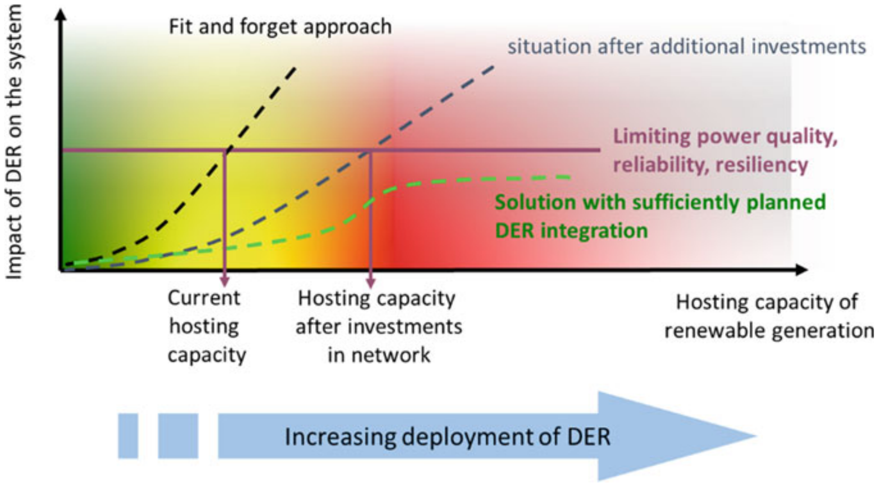


Fig. 26 Objectives of network planning

Benchmark DER models based on the type of study and the type of DER involved—for example smart inverters, energy storage and controllers, electric vehicle charging management, microgrid controllers, customer energy management systems and smart loads—need to be developed. Expected impacts of emerging techniques and systems—probabilistic methods, aggregation, transactive systems—on the adequacy of the DER benchmark models and their integration in the distribution network assessment and planning tools need to be studied.

5.1.2 Planning Tools for a High Penetration of DER

Active operation of distribution networks needs to be considered by planning tools. New planning and operation tools are required at distribution and transmission levels to:

(a) identify the impact of a large deployment of DER at the distribution level and repercussions on the transmission grid;
(b) analyse the impact of individual and aggregated DER on the distribution and the transmission systems;
(c) analyse the impact of DER installed at the distribution level on the transmission grid, considering static and dynamic aspects;
(d) investigation of different methods of aggregating DER;
(e) consider the impact on reliability and resilience, and the economic aspects associated with the generation of power and increased reliability and resilience.

5.2 Tools for Distribution System Operation Incorporating DER

5.2.1 Flexibility Provision from DER

The concept of flexibility allows innovative solutions for DER and distribution technology deployment.

Reliable operation of future distribution networks will depend on the role and potential of distributed energy resources (DER) in providing ancillary services, particularly flexibility, and participating in balancing markets and whole system operation.

There are different drivers and new requirements for flexibility at different stages of power system planning and operation. These drivers also vary with the different voltage levels within the power system, from the bulk system to a local network. With intermittent renewable-based DER, there is the potential for DER and multi-energy coupling to provide flexibility over different timescales and in different forms.

DER can contribute to operational and planning flexibility in transmission and distribution networks in current and future power systems. It can provide multiple services to TSOs or DSOs, depending on their requirements. It can be facilitated by new actors (aggregators) and new grid architectures (interconnections, microgrids, virtual power plants and energy hubs).

Electricity supply systems of the future will increasingly consist of a mix of large conventional centralized generation and transmission systems, and of electricity supply systems consisting of a large number of distributed energy resources (DER). The DER will be connected to the distribution systems or aggregated to power levels suitable to be connected to the transmission system (typically 100 MW or more connected to systems 120 kV or higher).

System services allow for the secure and reliable operation of transmission and distribution networks. There are a number of different specifications of these services worldwide but in principle system services cover:

- Primary frequency regulation, secondary frequency power: (a) voltage regulation, primary and secondary—reactive power; (b) power/energy reserve, primary and secondary
- Dynamic services: (a) power ramping, ramp duration; (b) other services—inertial response, stabilization.

These services can be provided to either the distribution system (distribution system operator, DSO) or the transmission system (transmission system operator, TSO), as relevant.

Examples of grid services provided by VPPs include:

- Frequency regulation
- Operational reserves
- Energy arbitrage
- Peak demand management.

DMS and DERMS provide all VPP services plus:

- Voltage management
- Optimal power flow
- Locational capacity relief.

5.2.2 DER Management Systems

In order to provide these services, DER management systems (DERMS) are needed (Fig. 27). If DERMS provides services to both the DSO and TSO, it becomes the interface between DSO and TSO for interactions at the level of services provision, Fig. 28.

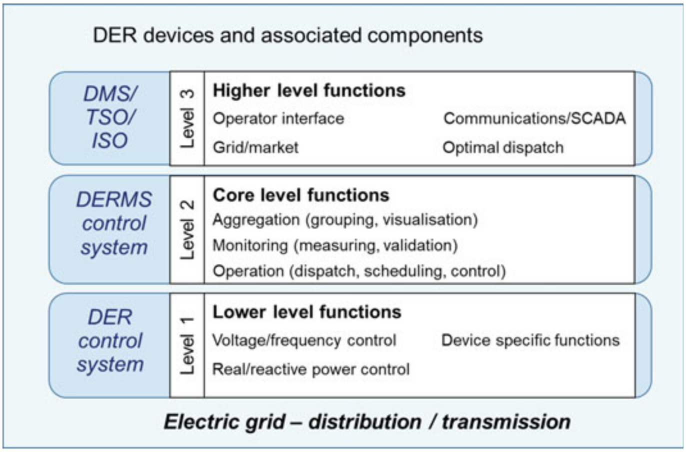


Fig. 27 DER management system (DERMS) functions

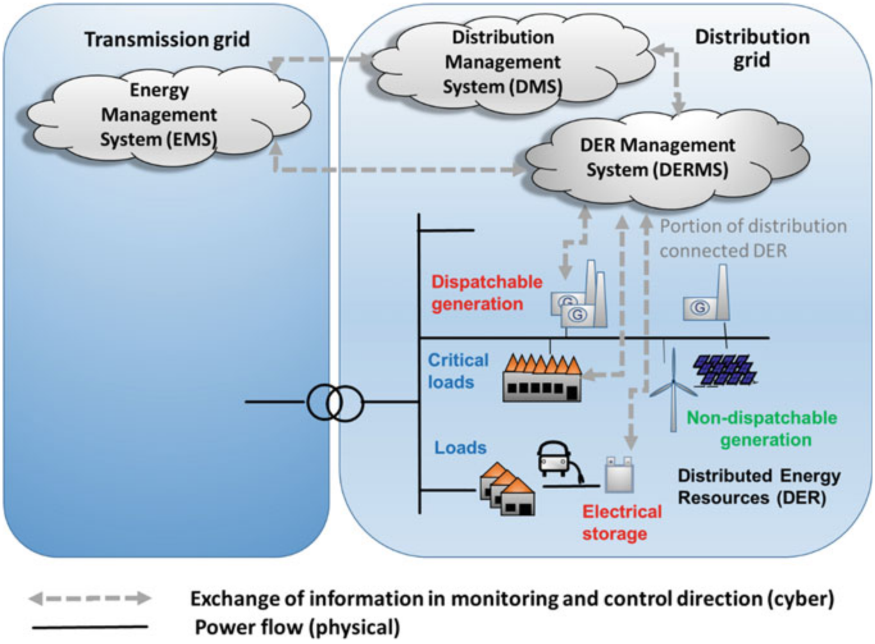


Fig. 28 DERMS DSO-TSO interaction

5.2.3 DER Aggregation Platforms

DER aggregation platforms are being developed for the provision of flexibility services—they involve technical, economic and regulatory aspects of DER aggregation and methods for integrating aggregated resources into network planning and operation. Economically attractive DER aggregation approaches are classified according to contracted customers and offered services, as well as aggregator interaction with other major stakeholders, such as participation in ancillary services markets, including frequency regulation, capacity and energy markets, bilateral agreements with distribution network operators, including voltage support, congestion management, black start and restoration and services to end-users and customers, including backup power.

Aggregation technologies including distributed energy resource management system (DERMS), virtual power plant (VPP) and microgrids, considering among others the role of ICT and forecasting, trading and scheduling optimization and analyse the technological improvements that will allow DER aggregation move to the next level of controllability and flexibility, Fig. 29.

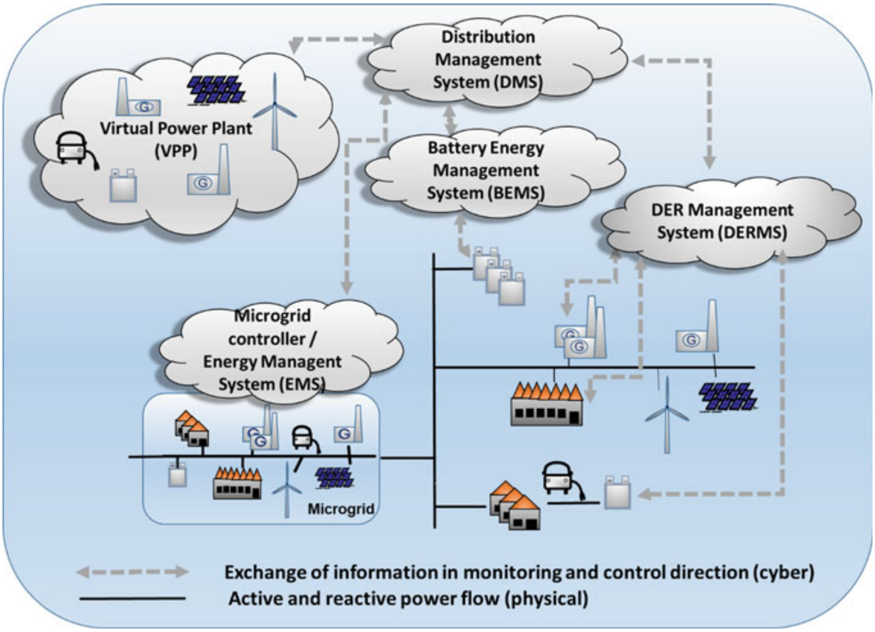


Fig. 29 Aggregation technologies

6 Research and Innovation

6.1 Innovation

6.1.1 Evolution of Technology, Concepts, Techniques

Far-reaching changes within the power industry, especially at the distribution level, are already underway. Customers are becoming prosumers and are integrating within the existing grid, while also trading in markets. Innovative technologies are required that will enable this transition and will engage every element of the value chain, i.e. distribution networks, DER, DSOs and enabling technologies. New distribution structures and models are being developed, like virtual power plants for DER market participation and microgrids for resilience. New technologies, such as seamless charging of batteries and fuel cells need to be developed.

6.1.2 New ICT Tools

Improved data analytics and wide application of artificial intelligence and machine learning will enable the efficient operation of future distribution networks. Automation will be widely adopted in distribution system operations and work management; human operators will however always be required to safeguard security. IT and OT tools will increasingly converge, while requiring high-speed and mass data crunching capability. Peer-to-peer technologies, blockchain for the operation of local markets, Internet of Things (IoT) for capturing data including social media sources and drones for network inspection are expected to be widely applied.

6.2 Organization and Managerial Aspects

6.2.1 Organizational Aspects

Next to technologies, distribution companies need to revisit organizational and management aspects. The future business will have to be far more agile and adept at adapting to changing requirements. As the future is also increasingly uncertain, strategic planning within the organization has to also provide a more scenario-based and probabilistic outcome.

6.2.2 Project Management Requirements

In the planning phase:

- to demonstrate the benefits which will result from the project,
- to guarantee that sustainable development principles and issues are being incorporated,
- to take into account public views, consultation and needs already in the system planning and design and options (e.g. the choice of alternatives).

In the construction and operation phases:

- to demonstrate the compliance with environmental standards,
- to obtain support for the necessary actions (e.g. maintenance).

6.3 Research Opportunities

6.3.1 Research and Development Needs

Research is very important for the successful achievement of the sustainability goals set worldwide and will become a main priority in the future. Research is needed in several fields, and there are a lot of ongoing research, development and demonstration (RD&D) activities regarding the integration of distributed renewable generation in distribution grids, demand response, BESS and other forms of storage and multi-energy-systems. Hierarchical control structures have been set up for the control, taking different timeframes and pricing methods into account. Validation of innovative research via large-scale demonstrations is an area, however, that needs further attention. This is important to manage risks and to test the integration of new electricity production technologies, consumption and other new technologies, as well as energy conversion technologies with the adequate level of digitalization.

The needs must be geared towards finding cheaper and more sustainable DER technologies, while improving the expected life and operation of the assets. It is also necessary to ensure that existing distribution assets are further optimized, through improved maintenance regimes, alternative technology adoptions, e.g. non-wire alternatives, efficiency improvements, etc. Modern asset management could make efforts on this through the utilization of big data, machine learning and AI technology with the emphasis on integration of tangible and intangible assets, physical assets and empirical knowledge, preventing knowledge fault, lack of talents and establishing knowledge base.

In the short term, PV and wind technologies in conjunction with BESS are required to provide greater energy and load factor efficiencies.

6.3.2 Active Distribution Networks

Networks allowing bidirectional power and data flows at distribution levels and up to transmission networks require research in the following areas:

- Increased DER intelligence—The massive penetration of smaller DER units requires coordination and control between units and the distribution network; one approach is the development of DER management systems (DERMS); coordination of DER can be achieved through either centralized or decentralized control
- Coordination and interaction with transmission systems and electricity markets; this requires coordination between transmission system operators (TSO) and distribution system operators (DSO) in the management of DER
- Monitoring and metering—The massive penetration of smaller DER particularly controllable loads and new loads requires advanced metering, including data collection for billing and market participation as well as state estimation of the system
- Increased deployment of electric energy storage systems—impact on existing and future grids
- Market rules and the regulatory framework need to be adapted to allow market efficiency, fairness and stranded asset use cost recovery; it must also allow market participation of new entities such as microgrids and virtual power plants.

6.3.3 Power Electronic Conversion

Research on integration of power electronic-based generation with AC systems must focus on the impact of power electronics interfaces on power quality, system control and system security. Given the very different dynamic response and performance of these systems compared to conventional generation and AC systems, new approaches need to be developed to ensure a smooth and reliable operation of the hybrid system, particularly under faults and contingencies.

6.4 Education and Training

The system complexity of active distribution networks requires highly skilled people from various disciplines. New methods of learning and teaching must be scheduled and applied at all levels of higher education, both undergraduate and postgraduate, including interdisciplinary and experimental approaches, research-based training or through digital media, interaction with industrial stakeholders, etc. Education does not stop at the university, but it also includes continuous education for professionals through higher education courses providing the latest available knowledge. Continuous education and training for operators, aggregators, market participants, prosumers of any size and energy systems engineers with high-end ICT knowledge are needed, supported by training and simulation tools [1].

Digitalization and the associated high-level of automation imply new jobs with different qualifications to perform the operation and the maintenance of digitalized energy systems. In the future, across the energy sector, all workers will need ICT skills to use and operate digital technologies.

7 Future Developments

7.1 Scenarios

7.1.1 General Context

The future deployment of DER and ADS on a wide scale depends on priorities set by people and their governments in relation to energy production and uses and the move away from fossil fuels. These are key to increasing generation from renewable energy resources, and increasing electrification in industrial, commercial, residential and transportation systems. This increasing use of electricity as a source of energy will spur a number of innovative technologies in power conversion and control and communications and information technologies facilitating DER deployment.

7.1.2 DER and Active Distribution Systems Deployment

From the perspective of active distribution system deployment, it is expected that the following developments will take place:

- **Within the next 5 years**:
  - (a) Wider DER deployment, as a complement of central power plants;
  - (b) DER aggregation to provide power, energy and ancillary services to the DSO and TSO;
  - (c) Integration and coordination of multi-energy systems for levelling out power generation fluctuations from RES and more effective use of total generated energy;
  - (d) Integration of new loads into the distribution system, such as electric vehicle charging systems, larger heat pumps, electric boilers and electrolysers;
  - (e) Wider deployment of electric energy storage systems, mainly batteries;
  - (f) Wider use of demand response and demand management to better match load to available generation and establishing load priorities;
  - (g) Development of tools for dispatch, integration and operation of DER covering multiple timescales, from the short-term integration and impacts (seconds

and minutes) to the longer term dispatch (hours, days), and extending the operation concepts and tools to long-term distribution system planning;

- **Within the next 5–15 years**—DER will have an increasing impact on the operation of electric power systems, both at the transmission and distribution levels. In displacing large central power generation, DER will be increasingly integrated into the energy management systems of the distribution and transmission systems and will be required to support grid operations. A number of technologies currently at the research and demonstration stage will be state of the art within this time frame.
- **Within the next 10–20 years**—Depending on how the DER technology, applications and electricity markets evolve, in terms of

  (a) the cost of DER equipment and systems,
  (b) how the cost electricity produced by DER compares with the cost electricity from conventional (and legacy) electrical power plants,
  (c) whether installed and legacy distribution and transmission grids will be sufficient to meet the demand,

  future topics will include the planning and operation of distribution system with an increasingly higher share of DER, renewable energy resources and/or alternative energy resources, or a mix of energy resources, using multi-energy systems. In parallel, assuming that the interest in customer empowerment expands, new technologies and structures will be investigated to allow for the deployment of electricity markets at the distribution levels. These markets will require new tools for the design and operation of distribution systems. The impact of a large deployment of DER on the transmission system and the support it can provide in terms of ancillary services will be key to the further expansion DER.

7.2 Issues and Consequences of a High DER Penetration

The challenges of a greater DER penetration into conventional distribution transmission systems include:

- Integration of variable and intermittent RES-based generation and the need for balancing variability and matching generation and load by using storage and load management;
- Steady-state and contingency operation of a power system in the presence of a mix of inverter-based generation and synchronous machine-based generation, with very different dynamic performance characteristics in terms of real and reactive power control and speed of response;
- Consequences of the loss of inertial response from synchronous machine-based power plants;

- Protection integration and coordination of the power systems with a mix of generation as described above, and the added issue of bidirectional power flow in electricity grids;
- Inverter/converter integration challenges, primarily with power quality and generation of higher frequency harmonics;
- Equipment life cycle and safety issues; most notably the performance and behaviour of electrochemical batteries;

8 Conclusions

8.1 General Future Directions

The coming years will be marked by innovations in many aspects of DER deployment, in the areas of power, control and communication technology, and electricity systems and market policies and regulations.

Reliability and resilience of regional and local power systems rely on:

- Integrated energy systems, with the electricity systems as the backbone, designed and operated to prevent or minimize the effects of contingencies, with local/regional black-start capabilities activated within a few minutes.
- Risk (weather and other hazards) assessment and mitigation measures, considered in system planning and operation.
- Seamless (strongly automated) operation through fully interoperable and networked sub-systems allowing the coupling of all energy carriers in an optimal, integrated way.
- Peer-to-peer transactions integrated with centrally and locally controlled electricity networks, supported by automated local grids together with network operator actions.

Specific issues include:

- Integrating increasing amounts of DER into existing distribution systems, and the design of new systems integrating larger shares of renewable resource-based DER;
- Managing existing distribution systems in an increasingly constrained financial environment, thus requiring innovative ideas in order to survive as an industry;
- Creating affordable alternatives to conventional grid solutions for the developing world via the adoption of microgrid and nanogrid technologies;
- Taking cognizance of the disruptive influences of new technology requirements, particularly in transportation systems, such as electric vehicle (EV) charging systems and their potential grid-to-vehicle (G2V) and vehicle-to-grid (V2G) capabilities.

8.2 Societal and Technical Priorities

The general higher level priorities in the area of advanced distribution systems integrating an increasing share of DER, including renewable energy-based DER, include:

- improving affordability and accessibility to electricity across all jurisdictions, notably in developing countries;
- establishing a framework for sustainable and affordable electricity supply systems and markets, particularly in areas where per capita income is low, while ensuring that the distributor obtains a reasonable return on investment;
- improving DER technologies to increase reliability and life expectancy and to reduce manufacturing, installation and maintenance costs;
- simplifying DER deployment, integration and operation at the distribution system level and facilitating the provision of ancillary services in support of the bulk electricity system.

Acknowledgements The authors would like to acknowledge the contributions received from CIGRE Study Committee C6 members Alex Baitch, Birgitte Bak-Jensen, Ray Brown, Britta Buchholz, Kurt Dedekind, Zhao Ma and Yasuo Matsuura (in alphabetical order).

References

1. CIGRE: Technical Brochure TB 586—Capacity of Distribution Feeders for Hosting DER, Results of WG C6.27 (2014). ISBN: 978-2-85873-282-1
2. CIGRE: Technical Brochure TB 475—Demand Side Integration (2011)
3. CIGRE: Technical Brochure TB 733—System Operation Emphasizing DSO/TSO Interaction and Coordination, Results of JWG C2/C6.36 (2018)
4. CIGRE: Technical Brochure TB 721—Impact of Battery Energy Storage, Results of WG C6.30 (2018)
5. CEI Comitato Elettrotecnico Italiano: Reference Technical Rules for the Connection of Active and Passive Users to the LV Electrical Utilities, Milano (2019)
6. ETIP SNET—Vision 2015, Integration Smart Networks for the Energy Transition: Serving Society and Protecting the Environment
7. CIGRE: Technical Brochure TB 635—Microgrids 1 Engineering, Economics, & Experience (2015)
8. CIGRE: Technical Brochure TB XX—MVDC Grid Feasibility Study, Results from WG C6.31 (2019)
9. CIGRE: Technical Brochure TB 782—Utilization of Data from Smart Meter System (2019)
10. CIGRE: Technical Brochure TB 726—Asset Management for Distribution Networks with High Penetration of Distributed Energy Resources (2018)

Professor Dr.-Ing. Christine Schwaegerl received her Diploma in Electrical Engineering from the University of Erlangen, Germany, in 1996, and her Ph.D. from Dresden Technical University, Germany, in 2000. In 2000, she joined Siemens AG as a consultant with Siemens Power Technologies International, being responsible for several national and European research and development activities on power transmission and distribution networks. Since 2011, she has held the role of full professor at Augsburg University of Applied Sciences. She currently is also chair of CIGRE SC C6 Active Distribution Systems and Distributed Energy Resources.

Professor Geza Joos (M.Eng., Ph.D., McGill University, Canada) is a Professor of Electrical and Computer Engineering at McGill University, Canada, since 2001, where he holds the NSERC/Hydro-Quebec Industrial Research Chair on the Integration of Renewable Energies and Distributed Generation into the Electric Distribution Grid since 2009, and the Canada Research Chair in Powering Information Technologies since 2004. His research activities are in the application of high-power electronics to electric power systems and power conversion, including distributed generation and renewable energy (wind energy). He held positions in industry (ABB Canada), and academia (Concordia University, École de technologie supérieure, Canada). His professional activities include consulting work in power electronics applications and power system operation. He is active in CIGRE, where he is Secretary of Study Committee C6, Active Distribution Systems and Distributed Energy Resources since 2017, and in the Institute of Electrical and Electronics Engineers (IEEE) Power and Energy Society, where is involved in standards activities since 2011, mostly related to microgrids controllers and DER management systems. He is a Fellow IEEE, Fellow CIGRE and Fellow of the Canadian Academy of Engineering and the Engineering Institute of Canada.

Nikos Hatziargyriou is a Professor in Power Systems at the Electrical and Computer Engineering School of the National Technical University of Athens (NTUA). He is Director of the Power Systems Division and founder of the “SmartRue” research unit at the Electric Energy Systems Laboratory. From April 2015 to September 2019, he was Chairman and until June 2018, CEO of the Hellenic Distribution Network Operator (HEDNO). From February 2007 until September 2012, he was executive Vice-Chair and Deputy CEO of the Public Power Corporation (PPC), responsible for the Transmission and Distribution Divisions. He was chair and currently Vice-Chair of the EU Technology and Innovation Platform on Smart Networks for Energy Transition (ETIP-SNET) and former chair of the European Technology Platform on SmartGrids. He is honorary member of CIGRE and past Chair of CIGRE SC C6 “Distribution Systems and Distributed Generation”. He is a Life Fellow Member of IEEE, past Chair of the Power System Dynamic Performance Committee (PSDPC) and currently Editor in Chief of the IEEE Transactions on Power Systems. He has participated in more than 60 RD&D projects funded by the EU Commission, electric utilities and manufacturers for both fundamental research and practical applications. He is author of the book “Microgrids: Architectures and Control” and of more than 250 journal publications and 500 conference proceedings papers. He is included in 2016, 2017 and 2019 Thomson Reuters lists of the top 1% most cited researchers.

Materials and Emerging Test Techniques

Ralf Pietsch

Abstract One main topic discussed by SC D1 is the understanding and improvement of insulation materials such as solids, liquids and gases and their combinations. The main driving forces for the power equipment is the demand for more compact power equipment, the use of power electronics as they will cover more areas and applications, and the use of vacuum circuit breakers because higher voltages will reach market maturity. Consequently, the electric fields within the insulation systems will increase and thus pose higher stress on these materials. This might in addition accelerate the aging processes. Another topic, which will influence the design and testing of power equipment in the future, is the increase of various diagnostic sensors, the improvement of their sensitivity, and compactness and their immunity against strong electric and magnetic fields. Physical integration of sensors will be a more common practice within power equipment, such as fiber optics in cables (temperature and tension control) and in transformers (temperature distribution, hot spots). These main topics and directions of the future WGs in SC D1, which will support the challenges of the electricity supply of the future, will be discussed in the following chapter.

Keywords Test voltages · Voltage shapes · Gaseous insulation systems · Liquid insulation systems · Solid insulation systems · High temperature superconducting materials · Dielectric tests · Diagnostic tools · Partial discharge · PD · DC · AC · LI · SI · VLF · GIS · UHF PD method · Risk assessment in GIS · HTS systems · Moisture measurements in oil · DGA interpretation · Corrosion · Nano materials · Field calculations

---

On behalf of CIGRE Study Committee D1.

R. Pietsch (✉)
HIGHVOLT Prüftechnik Dresden GmbH, Dresden, Germany
e-mail: R.Pietsch@highvolt.com

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_16

1 Introduction

1.1 Development of Test Voltages and Insulation Material

To understand how SC D1 can support and deliver solutions for the future electricity supply systems [1, 2], one has to know how testing and especially rated system voltages and test voltages have evolved with the least 50–100 years. Figure 1 shows the development of the highest transmission voltages starting in 1900. As one can see, the voltage levels raised on the average every 20 years, up to 1200 kV in 2019 [3].

Figures 2 and 3 show the testing voltages for AC, LI, SI, and DC as they are defined in the corresponding standards. Lightning impulse test system levels, for example, can reach 4000 kV. There are only slight differences of typical test levels between AC and DC power equipment.

Figure 4 shows the development of insulation materials, starting at 1950. Natural air and oil-paper insulation and ceramics were the main insulation media at that time. In the middle of the 1960s, SF_6 insulated substations were introduced. Polymeric insulation materials like PE for cables and FRP for insulators and bushing come into operation. They replace more and more the ceramics, and oil-paper insulations where possible and technically feasible.

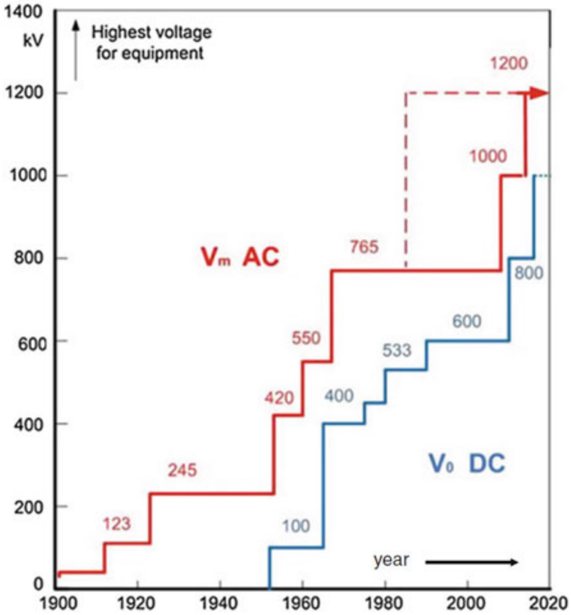


Fig. 1 History of HVAC and HVDC transmission systems [3]

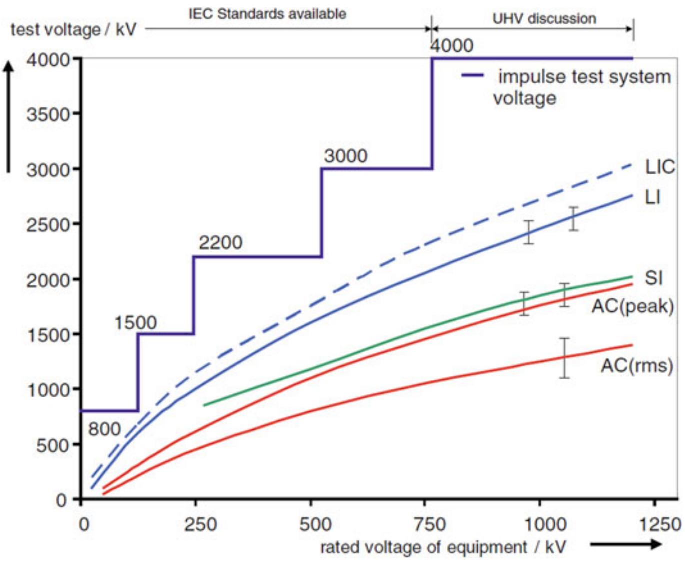
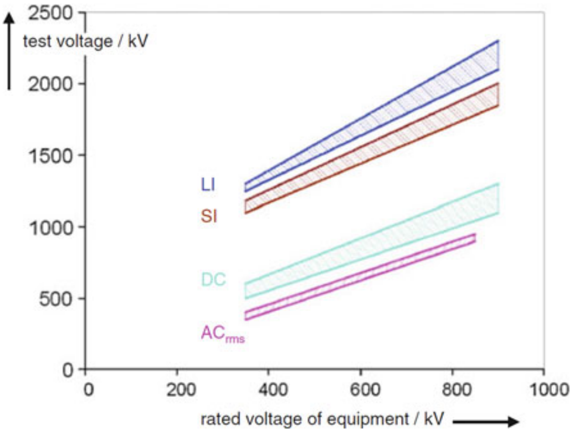


Fig. 2 Highest withstand test voltages for high-voltage AC equipment and the selection of impulse voltage test levels [3]

Fig. 3 Highest withstand test voltages for high-voltage DC equipment and selection of impulse voltage test levels [3]



As the rated voltages of the systems will not increase significantly, the transmission voltage for AC is up to 1200 kV and for DC 800 kV, 1000 kV are planned. Studies and prototypes up to 1100 kV or even 1200 kV are underway [4]. Higher voltages than those mentioned are not to be expected.

Therefore, significantly higher test voltages are not expected for the next decades. The main driving forces are, therefore, the demand for more compact power equipment, the use of power electronics as they will cover more areas and applications,

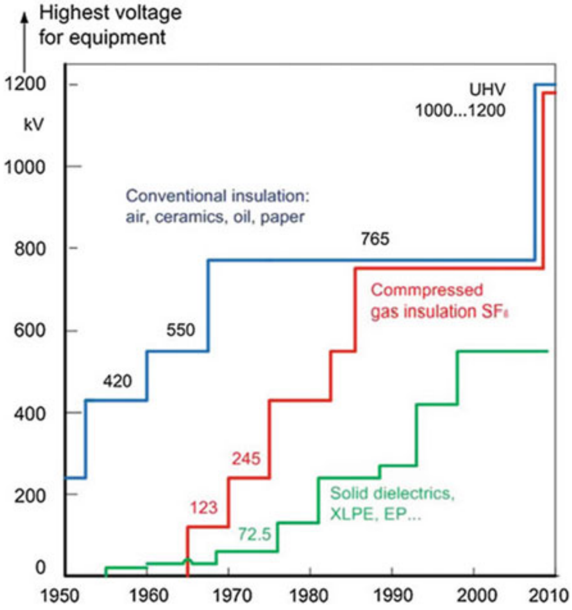


Fig. 4 History of the application of insulating materials [3]

and the use of vacuum circuit breakers for higher voltages will reach market maturity, see also chapter A3 and B1 and B3. Consequently, the electric fields within the insulation systems will increase and thus pose higher stress on these materials. This might in addition accelerate the aging processes.

The breakdown behavior and the aging process of insulation materials (gases, liquids, or solids) depend also strongly on the transient phenomena, such as lightning impulses, so-called very fast transients in GIS and the transients produced by the power electronics used in HVDC equipment.

Because the electrical field as function of time is the main ruling factor for insulation materials, we will have a closer look at such transient behavior or voltage shapes. Figure 5 gives an overview of typical operating voltages and transient voltages, which might stress the power equipment, and thus, the various insulation materials and insulation systems are used.

1.2 Test Voltages and Test Frequencies

The test levels and test procedures change during the development and operation of a power equipment.

In Fig. 6, a typical life cycle of power equipment is shown, e.g., for power transformer or a GIS [3].

The typical sequence starts with research and development test, followed by type testing. If the equipment reaches production level, then each product has to perform

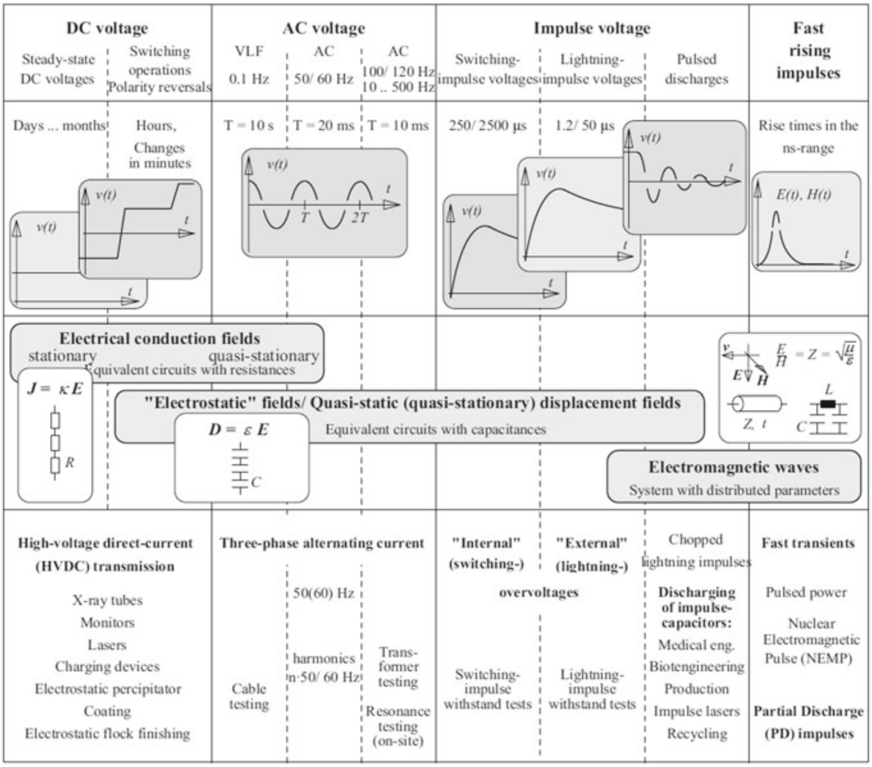


Fig. 5 Overview of important technical voltage stresses in high-voltage engineering: typical time curves (top), kinds of fields and equivalent circuits (middle), and typical applications (bottom) [5]

a routine test and commissioning test on site. During operation and maintenance, further and additional tests can be performed. If possible, all measurement, test results, and technical information should be collected and recorded during the life cycle of the equipment to facilitate a better diagnostic and residual lifetime prognosis.

If interested in further details, one will find them, for example, in [3, 6–8].

1.3 Voltage Stresses Due to Power Electronics

As earlier mentioned, with the increased usage of power electronics and higher system voltages, insulation systems have to handle and withstand; thus “new” voltages stresses. Figure 7 shows as an example a bunch of possible voltage amplitudes and wave shapes, which are typical at the terminals of a machine, fed by three-level converter. Further details are given in TB 703 [9].

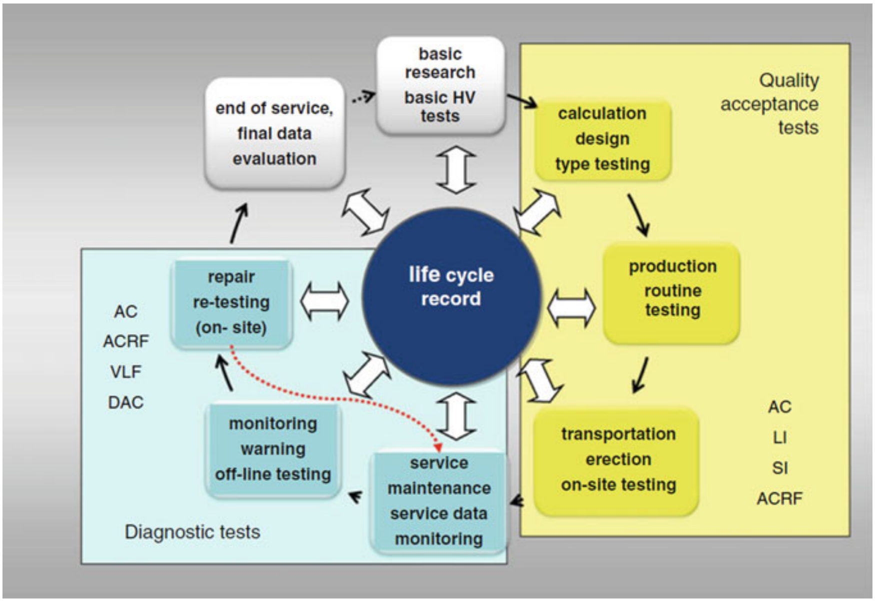


Fig. 6 Tests and measurements in the life cycle of HV insulation [3], AC—Alternating voltage, LI—Lightning impulse voltage, SI—Switching impulse voltage, ACRF—Resonant test system with variable frequency, VLF—Very low AC frequency, 0.1 Hz, DAC—Damped AC voltage

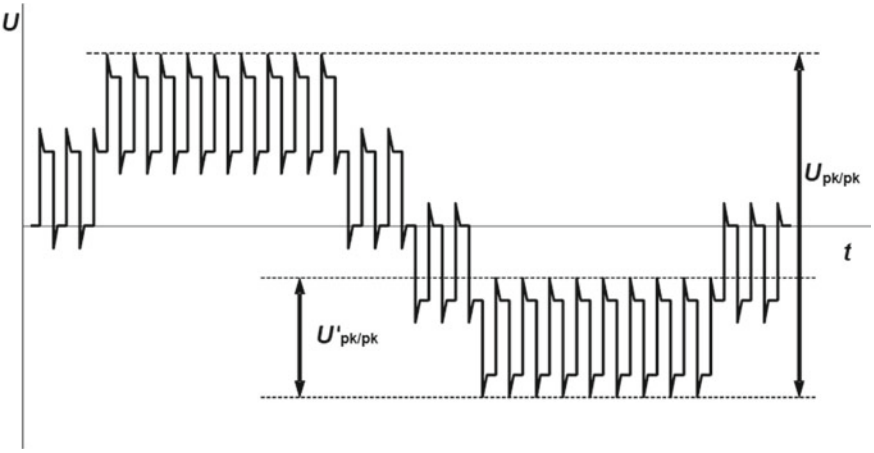


Fig. 7 Phase to phase voltage at the terminals of a machine, fed by a 3-level converter [9]

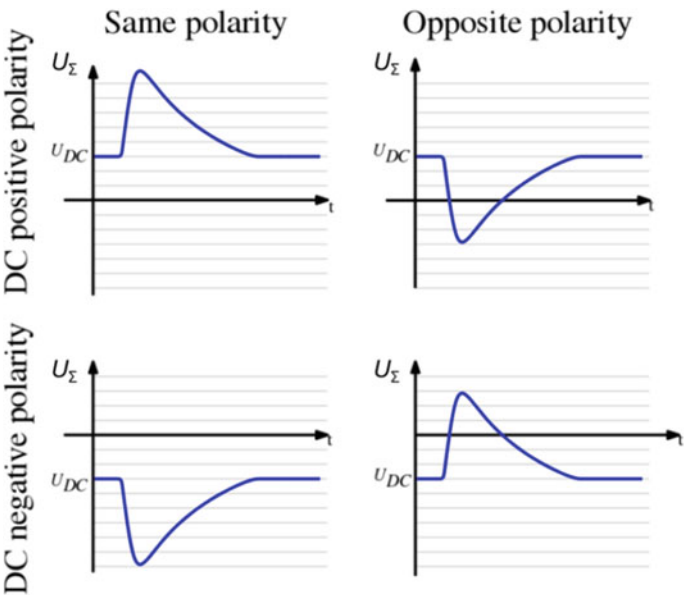


Fig. 8 Four quadrants of superposition DC and impulse voltage, WG D1.B3.57

Another typical voltage stress can be found in DC applications. For DC cables and DC GIS, superimposed voltages have to be performed as type test, see IEC 62895 [10], WG D1.B3.57: "Dielectric Testing of gas-insulated HVDC Systems" and [11, 12] (Fig. 8).

These very different voltage shapes and frequency stress the insulation material, and automatically, the following question arises: What are the indicators that the insulation system is working properly at a given test or test sequence and under operation in the power grid. Which diagnostic parameters and tools are available, physically and technically? This will be briefly discussed in the next chapter.

2 Diagnostics

Another trend, which will influence the design and testing of power equipment in the future, is the increase of various diagnostic sensors, the improvement of their sensitivity, and compactness and their immunity against strong electric and magnetic fields. Physical integration of sensors will be a more common practice within power equipment, such as fiber optics in cables (temperature and tension control) and in transformers (temperature distribution, hot spots).

Sensors for diagnostic applications are nowadays very compact and faster to develop. One possible drawback still exists: Interpretation is more complex, and the lifetime of such electronic products is normally shorter than the operational lifetime of a transformer, cable, or GIS.

Nevertheless, sensor technology will improve and being integrated in transformers to analyze multiple gases [13], or to measure humidity in oil [14]. Other parameters such as decomposition products in gas-insulated systems will also be measured and analyzed online. In additional analyzing, software tools and algorithm will improve the interpretation and status definition of the power apparatus.

Additional parameters that might influence the dielectric properties and thus withstand voltages of power supply equipment should be mentioned here, as these factors influencing the aging of these material and insulation systems too:

- Mechanical stresses, vibrations, wind forces, earthquakes
- Heat and cold, large daily temperature cycles
- Environmental influences: Rain, snow, dust, pollution, temperature, air density, humidity
- Dielectric stresses which defines the relevant and suitable test voltages AC, DC LI, LIC (chopped LI), SI, VFT, superimposed voltages, mixed voltage stresses (DC + LI).

Remark

Due to the increasing high-voltage levels (electrical fields) and the high capacity of the test objects, the production of the needed test voltages and test currents is technically extremely challenging and in some cases not possible due to physical reasons.

SC D1 deals mainly with testing procedures and material properties plus diagnostics (PD, DGA, tan delta) to verify the quality and performance of these materials and systems, the influences on the environment (e.g., SF_6), influence of pollution (bushing, FRP and silicones insulations, suspension insulators), and influence of rain and atmospheric corrections (altitude, moisture, and temperature).

3 Typical Insulation Media and Materials

Now, we are coming to the question which insulation media in the power systems and apparatus is applied. The right insulation material depends strongly on the voltage stress under operation: DC or AC. Why?

To simplify the answer, there are two main factors which influence the electrical field within the insulation.

Under AC stress, the electrical field is mainly controlled by the permittivity (dielectric constant ε_r) and can be calculated correctly and easily my means of available field calculation software. Furthermore, the electrical field does not change under temperature variations.

Under DC stress, the electrical field is under steady-state conditions controlled by the resistivity of the material and strongly depend on the temperature distribution with the insulation material. This is the major difference compared to the AC field. We will come back to this important aspect later again.

Figure 9 shows as an example the difference of the calculated AC and DC field distribution of a conical spacer inside a GIS as function of temperature T. This paper was published by WG D1.63 as "Interim Report of WG D1.63: Progress on Partial discharge detection under DC voltage stress," at the CIGRE Joint Colloquium on Study Committee A2, B2, and D1 in New Delhi, 2019 [15].

Let us focus again on the different insulation materials. One can generally structure them in three classes: solids, liquids, and gases and their combinations. Depending on the application, one can also subdivide them into indoor or outdoor applications. Consequently, the working groups of SC D1 are structured according to those three insulation groups.

Gases

- Natural air, typical for OHL, bushings, MV equipment
- SF_6, nitrogen, CO_2, gas mixtures used in GIS and GIS
- "new" gases: gas mixtures of CO_2 and or O_2 with fluoronitrile and fluoroketone.

Liquids

- Mineral oil, silicon liquids, ester liquids are used in all kinds of transformers (MV, HV, and power transformers) in combination with solid insulation (paper) [3, 5].

Solid dielectrics for indoor and outdoor applications

- Paper (as oil-paper insulation), PE, ceramics, epoxy resin in different variations, silicone coated insulators, composite insulators (FRP), …

Remark
This list mentions the main insulation materials and applications.

Therefore, some more details about a few of these three insulation material groups in different insulation systems are given in the following paragraphs.

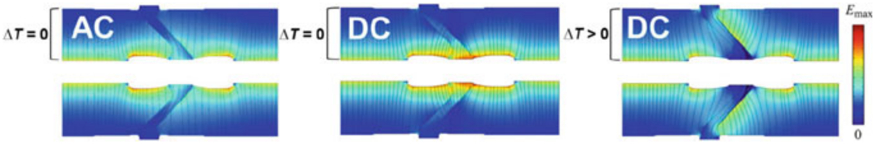


Fig. 9 Electric field distribution of a conical insulator at AC voltage (left), DC voltage (middle, $\Delta T = 0$), and DC voltage with a temperature gradient between conductor and enclosure (right, $\Delta T > 0$) [15]

3.1 Gaseous Insulation Systems

In addition to the traditional gases such as air, nitrogen or vacuum (which actually is not a gas) and SF_6, there is a trend to create gas mixtures, which combine excellent dielectric properties with low cost and improved environmental aspects.

- Vacuum interrupters are designed for circuit breakers and load switches in SF_6 switchgear.
- SF_6 is commonly used for the insulation in GIS and GIL. Its disadvantages are rather a high liquefaction temperature, its strong contribution to the greenhouse effect, and its relatively high cost. Therefore, the search for an alternative gas to SF_6 is of considerable interest. SF_6/N_2 mixtures were studied intensively as a suitable substitute from the ecology and economic considerations. In terms of environmental compatibility, it is uncritical as it is a naturally occurring in the atmosphere. Unfortunately, pure N_2 as insulation medium would require unrealistic and uneconomic equipment designs for the desired insulation levels. Adding some SF_6 to N_2, the gas mixture produces a good insulation capability that can be applied in GIS or GIL. The breakdown behavior of the gas mixture depends on the concentration of SF_6 (5–20%) in N_2 and on the pressure [2]. SF_6 is used still, but due to its high global warming potential, this is unacceptable.

3.1.1 Replacement of SF_6

Various TBs have handled this important topic to reduce or even avoid the use of SF_6, as it is the gas with the highest global warming potential, GWP.

The authors of TB 730 [16] wrote: “Gases such as dry air, N_2, CO_2 and N_2/SF_6 gas mixtures are chosen and studied according to the terms of reference. A number of investigations have been done for these gases and the data are now available. Dry air, N_2 and CO_2 have lower dielectric performance, but they are environmentally friendly, easy to handle and suitable for alternative dielectric (routine) tests in a factory, and have a potential to be widely applied to gas-insulated systems. These gases do not require special gas treatment procedures, as it is necessary for SF_6. National or international regulations concerning the application and the treatment of flour-containing gases do not take effect for such gases as dry air, N_2 or CO_2. Gas mixtures of N_2/SF_6 are also included in the study, since it has already been used to gas-insulated systems for GIL for more than ten years, and is effective to reduce the GWP of the systems.” [17]

“Researches on the new alternative gases like Fluoronitrile and Fluoroketone started a few years ago but not so many practical data are available at the moment.” For example, these gases are studied and discussed in WG D1.67.

Figure 10 shows the topics, which were investigated in TB 730, finished in June, 2018 [16].

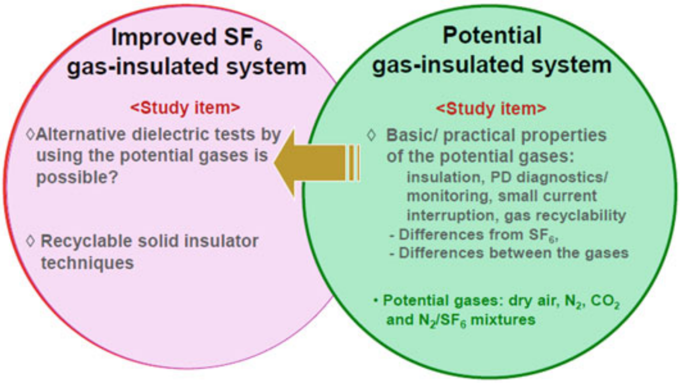


Fig. 10 Main study items of this Technical Brochure to realize improved SF_6 and potential gas-insulated, TB 730 [16]

Figure 11 gives an overview of dielectric properties of gases as a potential replacement for SF_6. Shown is the dielectric strength (normalized by SF_6) versus boiling temperature. This figure does not include the "new" gases fluoronitrile and fluoroketone.

Some of the gases shown in Fig. 12 have a higher dielectric strength than SF_6 but also a higher boiling point. This makes them unsuitable for the applications in GIS or GIL. Some of them are also toxic under normal conditions. Figure 13

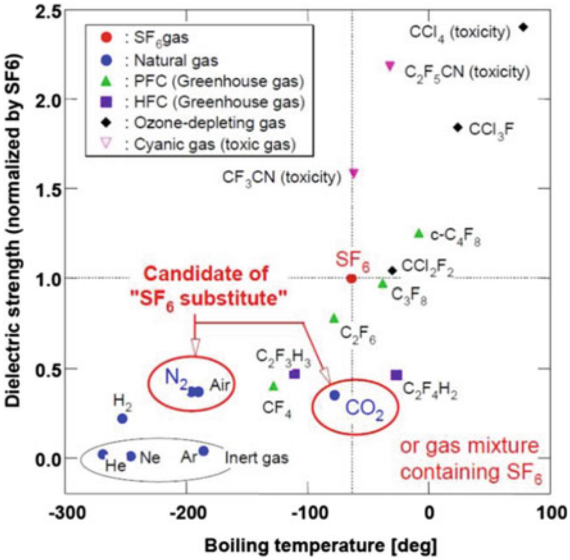


Fig. 11 Dielectric strength versus boiling temperature of gases, TB 730 [16]

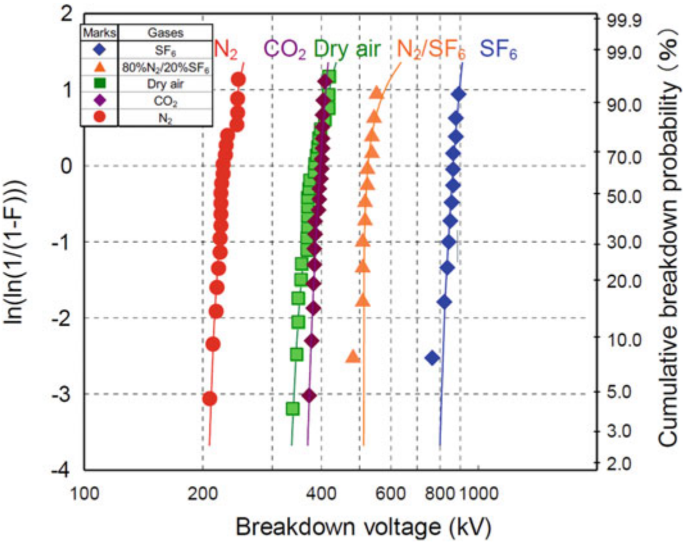


Fig. 12 Weibull plots of AC breakdown voltages of various test electrodes in dry air, N_2, CO_2, 80%N_2/20%SF_6 mixture, and SF_6 at 0.7 MPa, TB 730 [16]

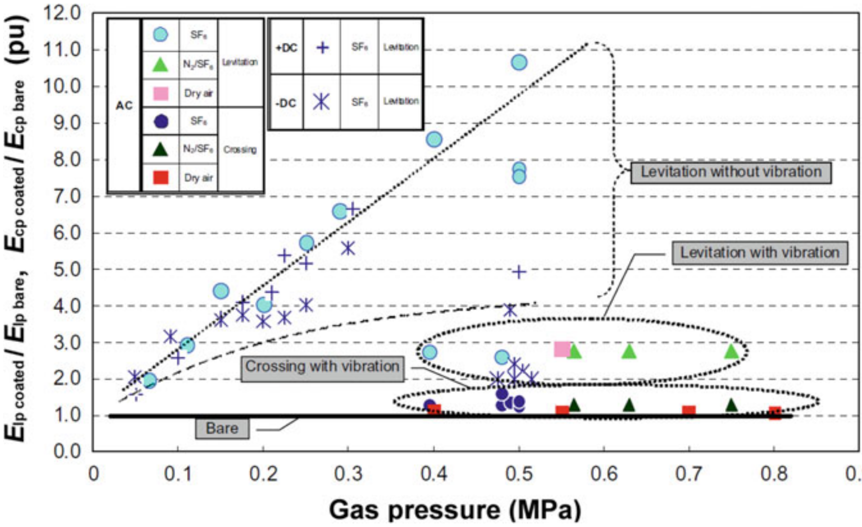


Fig. 13 "Effects of dielectric coating on enclosure inner surface compared with bare enclosure as a function of gas pressure. *E*lp coated, *E*cp coated and *E*lp bare, *E*cp bare indicate particle levitation and crossing electric field strength on enclosure inner surface for dielectric coated and bare enclosure, respectively;" further explanations are given in TB 730 [16]

shows the influence on the breakdown voltage of free moving particles. An additional parameter to increase the breakdown voltage in the presence of this defect type is coated electrodes.

Insulating gases have to fulfill two main functions in a GIS, namely the dielectric insulation and the arc interruption capability. SF_6/N_2 gas mixtures are inferior to pure SF_6, so this gas mixture cannot be used for this purpose. Gas mixtures without SF_6, such as CO_2/O_2/fluoroketone gas mixtures or Heptafluoroisobutyronitrile gas (C_4F_7N) mixed with the background gas of CO_2 seem to be promising candidates.

3.2 *Liquid Insulation Systems*

Here, we like to let the authors of the mentioned TB 224 [2] speak again, as since 2003, nothing significantly has changed, and their statement is valid:

> Although solid and gaseous insulation have become increasingly important during the last decades the use of mixed insulation (solid/liquid) is still essential for some applications, e.g., transformers. Transformers are one of the key components of electric power distribution and transmission systems and their reliability is of paramount importance. … Even today, the most frequently used insulation systems in these devices are still the traditionally used liquid immersed paper and pressboard insulation. Due to cost constraints a combination of cellulose paper and mineral oil has been the most common choice of materials, although for special applications different combinations of insulating liquids and of porous solid insulation immersed materials are in use. [2], Chap. 7.2.

Within the last years, one can observe the strong trend that usage of ester liquids is steadily increasing. This will also be the case for the nearest future.

Why? The explanation is well given in [2] again:

> When searching for a PCB (polychlorinated biphenyl) substitutes, ecological considerations were paramount in the search for a non-combustible and non-toxic liquid dielectric having good cooling properties. Ester liquids consisting of organic esters were proposed for distribution transformers. The method of obtaining such a liquid consists of synthesis. … The fire resistance of this liquid is much higher than that of mineral oils. Ester liquids are somewhat in an intermediate position however, between PCBs and mineral oil based on flash ignition and self-ignition temperature. Ester liquid belongs to the HFP (high fire point) liquids also known as “less inflammable” liquids. By definition a HFP liquid must have a minimum fire point of 300 °C. Ester liquids are non-toxic, well digested by micro organisms and posses a low vapour pressure at operating temperatures of power transformers. In a fire they generate no dioxins or toxic products and possess a good ability for biodegradability. … Ester liquids possess good ecological properties, this feature together with the ability to dry the solid insulation (impregnated paper) are considered as positive. However, the viscosity, which is the principal parameter for heat calculations, is higher than that of transformer oil; slightly larger cooling channels are generally required. Esters are also prone to the possibilities of hydrolytic detachment through moisture content.
>
> For many years ester liquids have been used in distribution transformers, because these liquids comprise several additional advantages. They have a lower inflammability and a high hygroscopicity. High hygroscopicity is usually seen as a disadvantage but may be a benefit when a solid insulation is in contact with the insulating liquid where water, assimilated at the solid insulation, can be extracted. Further, ester liquids and mineral oil possess an almost

> similar density. They are completely mixable at any ratio. Almost all electrical and dielectric properties of ester liquids are similar to mineral oils despite the relative permittivity ε_r, which is higher (3.3) than those of mineral oils (2.2). This is however, an additional benefit if the ester liquid is used for impregnating cellulose as the relative permittivity is closer to that of cellulose, (about 6), thus resulting in a more uniform electrical field distribution within the combined insulation. [2], Chap. 7.2.

3.3 Solid Insulation Systems

Again, the arguments written in TB 224 are still valid today and applicable for the future too:

> In the last 30 years two synthetic solid insulation materials have been widely used in components of electrical power systems. These are polyethylene used mainly as cable insulation and cast resin materials used in high voltage and low voltage systems. These materials are distinguished, as they are easy to handle, have excellent electrical and dielectric properties and have good resistance against chemical stresses. Whereas the operating temperature of Polyethylene (PE) is limited to about 90 °C cast resin materials can withstand thermal stresses up to 300 °C. Furthermore, cast resin materials have excellent mechanical properties. For this reason, this solid insulating material is widely used in electrical applications for switchgear, bushings, rotating machines and transformers. By variation of the moulding material components the properties of the insulating material can be adapted to the application requirements.
>
> An important influence on the electrical behaviour of a filled cast resin insulated system is that internal mechanical stresses are frozen in the solid material during the manufacturing process. This results from different coefficients of thermal expansion of the resin system and associated encapsulated materials, e.g., the windings in dry type transformers. The interface between the matrix and the enclosed metal and the interface between the matrix and filler are critical points where cracks may occur. These defects can lead to partial discharges (PD) and finally to an electrical breakdown of the insulating system. Polyethylene is used mainly as cable insulating system. Nowadays PE-insulated cables are in operation up to a voltage of 500 kV. PE has very good electrical properties. Critical features of PE are PD and water. Improved technologies now allow the manufacture of cables with significantly improved PD characteristics. [2], Chap. 7.1.

For some of these solid insulations, a significant improvement was achieved for various insulation materials. For example, special polyethylene was developed which can now also been used for DC applications, as the space charge phenomenon is better controlled and suppressed by developing and producing special PE. This material is used mainly for extruded DC cables.

3.4 Comparison Between Liquids Insulation and Solid Insulation Systems

For a rough orientation about the suitability of an insulation material or system for a special application, a comparison between liquids and solid insulation, and solid/liquid insulation systems is given. As one can recognize, not only dielectric properties are of importance.

This list gives in addition a brief indication for an outlook of insulation materials and systems, which might be improved to cope with the tasks of future power systems.

Advantages of liquids (list is not complete):

- Better heat transfer
- Good convection and self-healing
- Possibility of reconditioning, in some applications replacement of the liquid insulation is possible, but has to be studied further
- Less susceptible to PD.

Disadvantages of liquids (list is not complete):

- Fire hazard and possibility of explosion
- Environmental hazards resulting from leakage
- Different permittivity between solid and liquid insulation can cause field distortion at the interface
- Water deteriorates the breakdown strength and can cause failure in the liquid at low temperature
- Cellulose as solid insulation does not allow higher operating temperature.

Advantages of solids (list is not complete):

- Better, easier handling
- Less environmental impact
- Higher operating temperature is possible with resin systems
- Less danger of fire hazard
- Mechanical stressing is possible.

Disadvantages of solids (list is not complete):

- Heat transfer ability is lower
- Sensitive to PD activities
- Sensitive to varying mechanical stress
- Sensitive to temperature changes.

As a first resume, it was shown in the last sections, that one important task of SC D1 is to investigate new materials, their properties, and parameters. The future tasks should concentrate on some of the following demands:

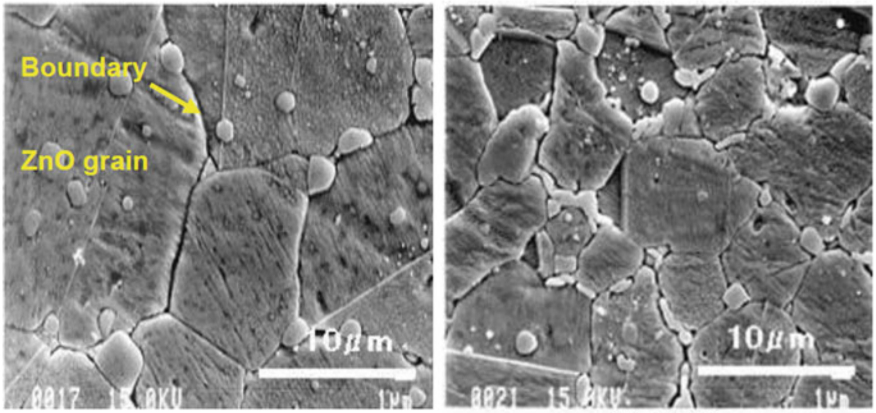
- Investigating materials with higher temperature withstand capability

- Searching for insulation systems with better PD performance and high fields withstand capability
- Researching of materials with a better electrical performance which allows higher operating electrical fields
- Finding materials with a high surface resistivity (mainly for AC applications)
- Searching for insulation systems with better performance for the different HVDC and pure DC applications
- Investigating materials with a better transferability to allow the design of more compact power equipment.

Which insulation material and insulation system is mostly suited depends strongly on the application; therefore, their application in a transformer (distribution or power transformer), a GIS, or GIL, within a support insulator, a bushing, in cable and joints, or in motor generator can be very different [5].

4 Protection as a Supplement

As an additional component for a better performance of the insulation materials, it is the application of surge arresters, which is partly a topic of SC D1 too. This additional measure helps to protect or keep the stresses of the insulation within a given limit [3, 5]. One has to consider that the application of surge arresters is an important part to allow a secure operation of the power components during transient surges within the network. Therefore, a more compact design of such surge arrester in the future will increase the field strength. As an example of the microstructure of such metal oxide surge arrester, Fig. 14 shows the comparison of the microstructure between



(a) 2 kV/cm

(b) 4 kV/cm

Fig. 14 Microstructures of MO resistors with the field strength of 2 kV/cm and 4 kV, TB 696 [18]

MO resistors operating at 2 kV/cm or 4 kV/cm. The MO resistor of 4 kV/cm has a smaller grain size of ZnO than that of 2 kV/cm [18].

As mentioned earlier, application and behavior under AC are quite well understood and technically on mature level. For DC application, there are still improvements possible and further investigations and research needed.

5 New Materials and Insulation Systems/New Technologies and Testing Procedures

The last sections have shown briefly the status of the work on insulation materials and systems performed by SC D1. To understand the following arguments, one has to recognize that power equipment is investment goods. They have to operate for more than 20 years and up to 40 years or even longer. Therefore, aging processes under the mentioned and various stresses must be well understood!

Consequently, the development and industrial application of new insulation media or systems needs time. One has to understand the physical and chemical basics. Breakdown behavior and aging characteristics of gases, liquids, or solids have to be investigated for new applications, before they can be technically introduced and applied in transformers, cable systems, or GIS. These steps need comprehensive R&D investigations, R&D tests, and type tests, which might take at least 5–10 years. Additionally, the acceptance of the producers and utilities (the market) will finally decide their application. The so-called technology readiness level describes this too.

The status of those activities and their results about new materials and technologies will now be briefly highlighted by some examples. They will underline their potential influences on the power systems of the future.

5.1 Nano-Materials

The technical brochures TB 661 [19] and TB 451 [20] and WG D1.69 give an comprehensive overview of this material and its possible applications. For the definition, what nano-materials are, we like to cite the definition given in TB 451 [20]:

"What is the modern meaning of nanotechnology? It is a general term covering a widerange of many fields ranging over such as electronics, photonics, mechanics, micro-machines, and biomaterials. We may recognize that it is not as yet a science that is theoretically arranged, nor an engineering that is systematically structured, such as physics and electrical engineering (Iijima 1991). It deals with characteristics in nanometer size and/or mesoscopic regions on materials and functional devices. It should be stressed that macroscopic performances must appear as collective behaviors of individual performances at the nanometric level. Therefore, it is a key issue

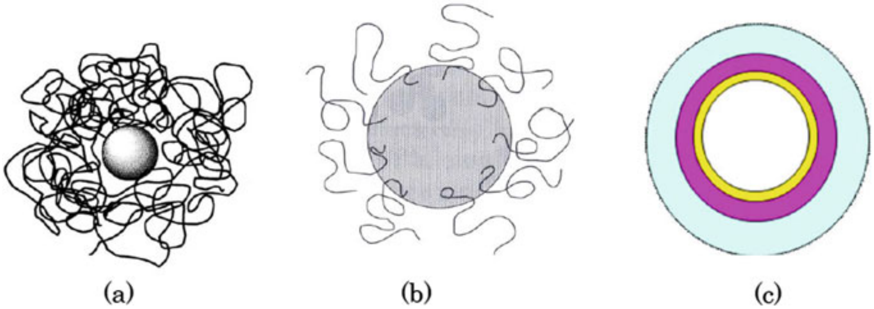


Fig. 15 States of interfaces between nanofillers and polymers, from TB 451 [20]

for us to control mesoscopic characteristics. Then, it is expected that such a nanotechnology will bring about enormous innovation in various fields such as structural materials, resources and energy, communication and electronics, biotechnology, environmental safety, medicine, and health"….Polymer nanocomposites are a composite of organic polymers and inorganic nano fillers. Since they have enormous total areas of interfaces around the nano fillers that contact the polymer matrices, it is widely recognized that they are significantly affected in their performances by the properties of such interfaces. Figure 15 shows three representative models for interfacial states (Tanaka 2005). Sub-figures (a) and (b) show two kinds of directed polymer chains; (a) random or parallel direction to the surface of a nano particle, and (b) more or less perpendicular to the surface of a nano particle. The sub-figure (b) represents a spherulite in part. Interfaces are expanded in radial direction outside the surface of a nano particle, and have their thickness that is usually called an interaction zone. Such interfaces are different in their performances from both nano particles and polymer matrices," TB 451 [20].

Example of nanomaterial applications are cable systems, stator bus insulation, GIS, and transformers. They are in use today, but more complex insulation systems are under research and investigation. The experience shows that from research to a broad industrial application, it might take several decades, see also [2]. Their main task is to reduce losses, to decrease the dimension, and to allow tailor-made applications. WD D1.73 continues this work (Fig. 16).

5.2 Insulations for High-Temperature Superconducting (HTS) Materials

Insulations for HTS applications is another interesting topic, as this can significantly reduce losses and physical size of power system components. This material can conduct currents without losses at about 77 K, and therefore, they are called high-temperature superconducting materials. Possible applications are:

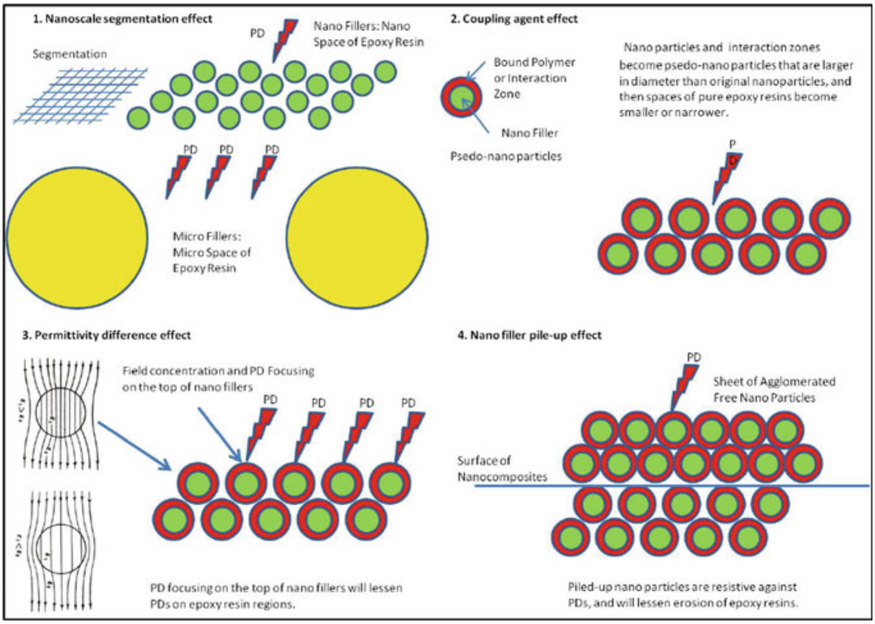


Fig. 16 Various factors create more PD-resistant properties of polymers with the aid of nanofillers [19]

- Rotating machines
- Cables
- Fault current limiter
- Energy storage (SMES).

Further details are found in TB 644 [2, 21]. Additionally, WD D1.69, "Guidelines for test techniques of High-Temperature Superconducting (HTS) systems," continues this work.

The actual status of this technology is shown in the next section by some examples of development and field tests for HTSC cables.

At the time when this chapter was written, several dozen experimental superconducting cable lines have been installed to study the possibility of electricity transmission using the superconductivity effect. They all have in common that their lengths do not exceed more than one kilometer [22, 23]. Figure 17 shows as an example the design of a HTSC DC cable [22].

According to the authors of [22], "*…long-distance cable transmissions are possible only with the use of DC lines, since any, including superconducting, AC cable lines have a length limitation, due to the occurrence of charging currents, which lead to a decrease in power at the far end of the line. … As a result, the length of AC cable lines does not exceed several tens of kilometers*."

In Russia, the following HTSC cable is under construction. This DC cable will connect the two substations, "Tsentralnaya" 330 kV substation and "RP-9" 220 kV

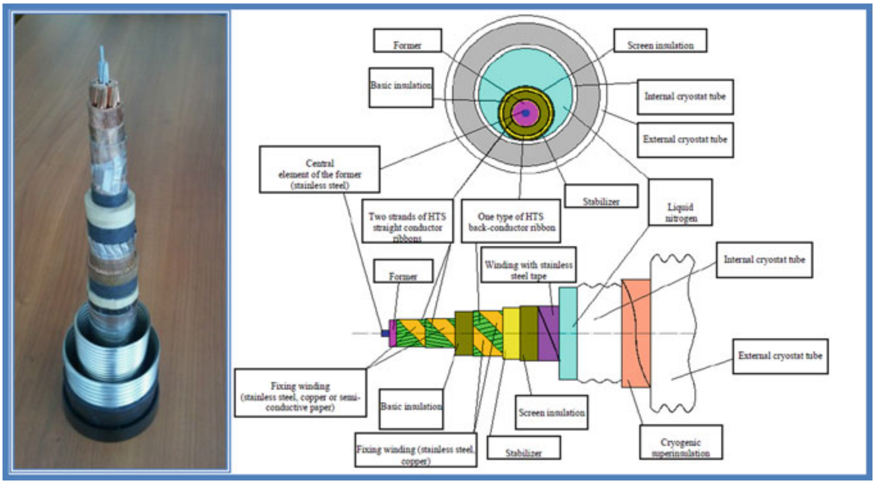


Fig. 17 Superconducting cable design [22]

substation, in the St. Petersburg power grid. The length of the cable is 2.5 km, and the loop of pumping with liquid nitrogen is 5.0 km [22, 23]. The concept of this HTSC link is shown in Fig. 18, and its main features are given in Table 1.

In addition, also AC cables (three phases) and prototypes are developed and installed too or will be finished soon (2019). Figure 19 shows as an example a three-phase HTSC AC cable installed in Korea [24].

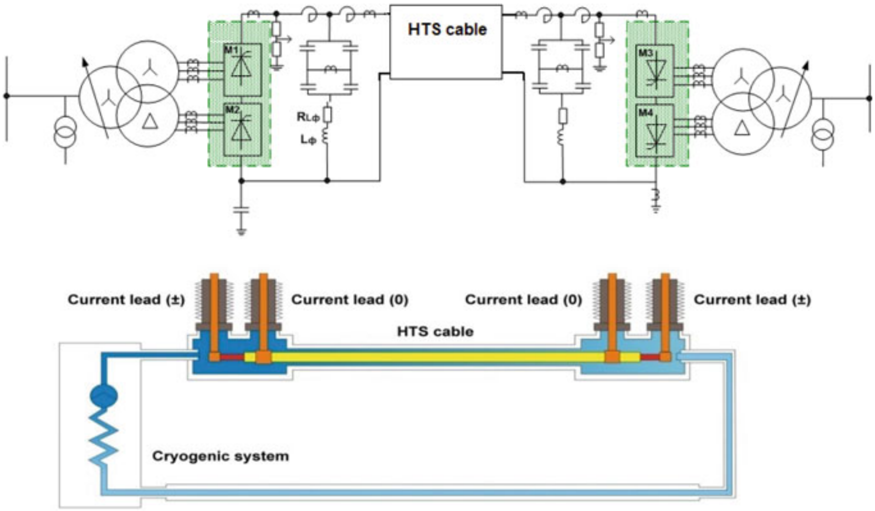


Fig. 18 Electrical scheme of superconducting line (top) and possible schemes of cooling with the placement of cryogenic station from one end of the line (bottom) [22]

Table 1 Characteristics of the high-temperature superconducting line [22]

Transmitted power	50 MW	Type of converters	12-pulse
Rated voltage	20 kV	Possibility of reverse	Provided
Rated current	2500 A	Cooling capacity of cryogenic plant	12 kW @ 70 k
Working temperature	66–80 K	Pressure of liquid nitrogen	up to 1.4 MPa
Length of cable	2500 m	Flow rate of liquid nitrogen	0.1 ÷ 0.6 kg/s

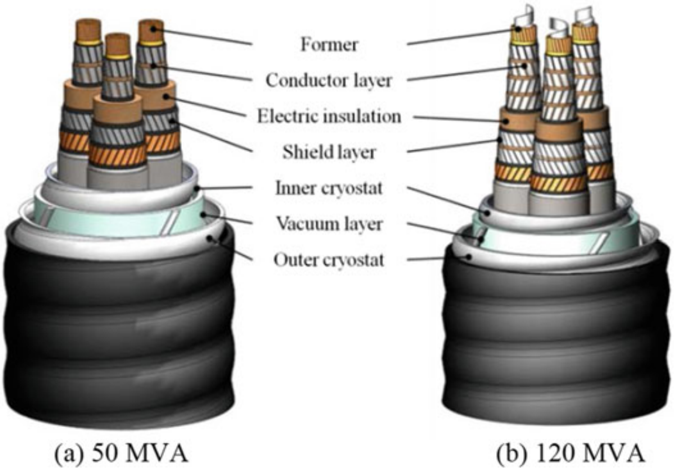


Fig. 19 Structure of the AC 23 kV “triad type” HTS cable, described in [24]

Nevertheless, one can assume that the number of applications will be still limited for special fields. If these projects will show their effectiveness and technical readiness under real operation conditions, one can expect that in the long-term run more superconducting cable links will be installed.

5.3 Use and Improvement of Simulation Tools—Some Examples

At his point, we like to discuss briefly the influence and application of improved simulation software used generally in SC D1 and the other SCs. This is an important aspect to allow further improvement of the insulation system and diagnostics of the future power systems.

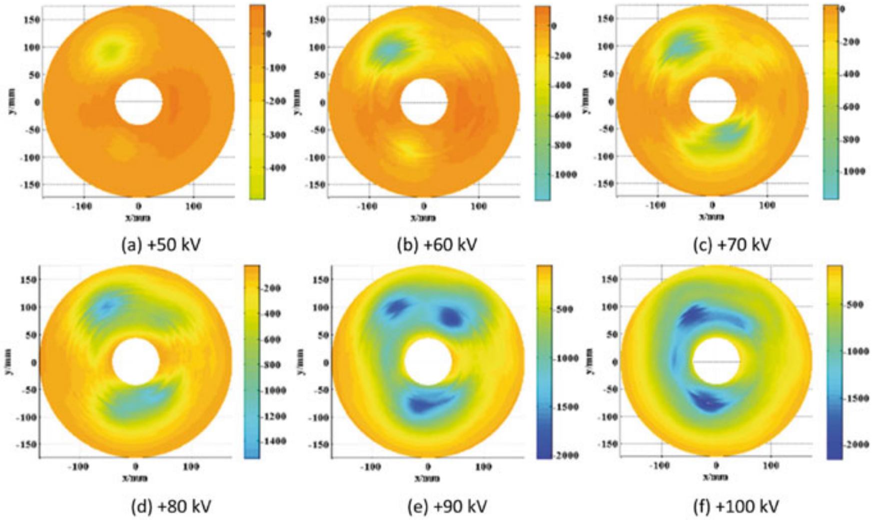
It is important to stress again within this context that the main dielectric design parameter is the electrical field, as this governs all electrical effects such as breakdown behavior and partial discharge activities. Another fact must be highlighted, which is often forgotten: Statistical processes rule all breakdown behavior and aging processes.

Due to these boundary conditions, the development of hardware for power components needs experiences and cannot only be simulated. The reason is that the parameters, which govern the dielectric performance, are not always known or physically understood. For example, the dielectric properties and field strength are controlled on a microscopic scale and at insulation interfaces (paper-oil, gas–solid, metal-gas,…). For example, the field calculation of a polymer insulator surface in air under high humidity, DC stress, with surface and space charges, is very complex and difficult to describe by theory only. Beside this limitation, they are very important tools and support significantly the understanding and simulation of insulations systems. One brief example is shown here.

5.3.1 Field Calculation

Simulation tools will be constantly improved, and more flexible and several physics can be handled simultaneously, like thermal properties, DC conductivity as function of temperature and field strength in 3D, and under time variations. Due to the complexity of the calculations, the results of these simulations are not easy to verify, and thus, measurements will be still needed in the future too. The following example demonstrates the possibilities of such tools (Fig. 20).

This example shows the measurement of surface charges, which are compared with simulations. Details are given in [25].



(a) +50 kV
(b) +60 kV
(c) +70 kV
(d) +80 kV
(e) +90 kV
(f) +100 kV

Fig. 20 Surface potential distribution under positive DC voltage application in 0.5 MPa SF_6, [25]

6 Active Working Groups of SC D1 and Possible Future Tasks

This was a brief overview about new materials and technologies for the future challenges around this topic. Where else can SC D1 contribute? Which topics in SC D1 can support other SCs for their future challenges?

A forecast into the future work and tasks might be more reliable, if one looks at the topics, which were handled within the different WGs of SC D1 in the last 10 years. As one can see, at least two main new working fields appeared; “Diagnostics” and “DC,” Fig. 21. As mentioned, the actual major trends within SC D1 are reflected by the actual topics of the 24 WGs, which are listed in the four groups: Gases, liquids, solids, and testing and diagnostics. In doing so, one can also recognize the future trends and which topic should be investigated by former new and follow-up WGs in SC D1. Clearly, DC applications will increase further. Why is this further work and research needed?

Breakdown behavior, diagnostics, and aging are in detail different under AC or DC field stress. Field distribution inside the power equipment, field amplitudes, and transient influences are different. In addition, due to power electronics, new kind of electric stresses have to be considered. This has also consequence on the way of testing and testing procedures. The main active working groups within SC D1 and their potentials to support and solve the challenges of the future power system are as follow. Some of them were already mentioned and discussed shortly.

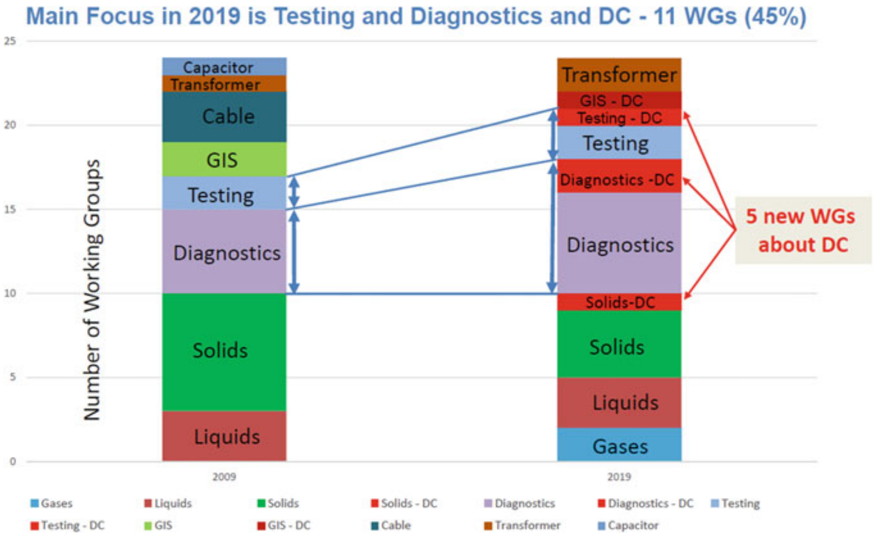


Fig. 21 Development of WG topics from 2009 to 2019 of SC D1

6.1 Gases

- Dielectric testing of gas-insulated HVDC systems (**JWG D1/B3.57)**
  - DC new test strategies, transient voltage stresses => input for new standard
- Requirements for PDM systems for gas-insulated system (**WG D1.66**)
  - PD monitoring system, noise rejection, data representation, reporting, and defect localization
- Dielectric performance of non-SF_6 gases and gas mixtures for gas-insulated systems (**WG D1.67**)
  - Methods for finding new insulating gases, definition of tests, and test procedures.

6.2 Liquids

- New frontiers of DGA interpretation for power transformers and their accessories (JWG D1/A2.47)
  - Improved diagnostics for different fault types, effects of mixtures, and online gas sensors
- Mechanical properties of insulating materials and insulated conductors for oil-insulated power transformers (**WG D1.65**)
  - Review of functional performance of materials and test methods, and suggestion for revision of standards
- Field experience with transformer solid insulating aging markers (**JWG A2/D1.46**)
  - Evaluation of online gas monitors and procedures for verifying their accuracy
- Functional properties of modern insulating liquids for transformers and similar electrical equipment (**WG D1.70**)
  - Overview of functional requirements, procedures for determination inhibitor content, review of test methods and existing standards, and input for possible revision of standards.

6.3 Solids

- Harmonized test for the measurement of residual inflammable gases in insulating materials by gas chromate (**JWG D1/B1.49**)
    - Diagnostics/testing—input for standard revision
- Field grading in electrical Insulation systems (**WG D1.56)**
    - Establishing of field grading materials, field simulation techniques, and applications
- Evaluation of dynamic hydrophobicity of polymeric insulating materials under AC and DC voltage stress (**WG D1.58**)
    - RRT tests, reproducibility—development of test methods as input for IEC standards
- Methods for dielectric characterization of polymeric insulating materials for outdoor applications (**WG D1.59**)
    - Evaluation of various materials at different temperatures and frequencies, def. of test specifications, and RRT tests
- Surface degradation of polymeric insulating materials for outdoor applications (**WG D1.62**)
    - Influence of degradation and aging behavior
- Electrical insulation systems at cryogenic temperatures (**WG D1.64)**
    - Summary of principles and test issues about discharges in insulation materials at cryogenic temperatures
- Nanostructured dielectrics: Multifunctionality at the service of the electric power industry (**WG D1.73**)
    - Review about recent nanodielectrics, choice of multifunctional parameters, definition of test sample design, and selecting and performing test

6.4 Dielectric Tests and Diagnostic Tools

As mentioned in the introduction of this chapter, different tests have to be performed during the development of power equipment and their components. It is worth to mention that those tests do not cover only dielectric tests. There is a bunch of tests, such as research and development tests, type tests, pre-qualification tests, factory tests, commissioning tests, on-site tests, and diagnostics. The majority of them are descripted in the corresponding standards, such as for bushings, cables, power transformers, and GIS.

In combination with all the tests, criteria have to be defined, how to check and prove, if a test was successful. The observation of “no breakdown” is not sufficient and will not guarantee, that the tested component is in proper condition. Therefore, in the last decades, additional **diagnostic tools** were developed and continuously improved. Additional guidelines for the application and interpretation of measured parameters such as PD measurements with UHF sensors [26], PD analysis in power transformers [27], and DGA [13, 28] of power transformers are typical examples. In addition, techniques like frequency response analysis, FRA, fault location in cables, and PD monitoring of GIS by the UHF method will be continually improved within the next years. Furthermore, as consequence of the fast development of new and compact sensor techniques, new parameters of the insulation might be accessible to evaluate the status of an insulation system.

New IEC standards will define testing voltages (such as wave shape, frequency, harmonics, and tolerances) and are currently partly under revision [29].

Further, WGs cover these diagnostic topics

- Principles and methods to measure the AC and DC resistance of conductors of cables and overhead lines (**WG D1.54**)
  - Review of state-of-the-art measurement and test equipment, development of test procedures, evaluating of influencing factors, and determination of reliability
- Traceable measurement techniques for very fast transients (**WG D1.60**)
  - Review of existing maintenance practice, questionnaire, and new methods and developments for condition-based maintenance
- Optical corona detection and measurement (**WG D1.61**)
  - Test procedures for a RRT, evaluation of UV cameras available on the market
- Test of material resistance against surface arcing under DC (**WG D1.72**)
  - Definition of test arrangement and test procedure, RRT
- PD measurement on insulation systems stressed from HV power electronics (**WG D1.74**)
  - Survey of possibilities to measure PD in power apparatus, extraction of PD features (waveform and bandwidth), investigation of voltage endurance for insulation systems
- Atmospheric and altitude correction factors for air gaps and clean insulators (**WG D1.50**)

- Checking and evaluation of existing correction factors and collection of new data, defining and performing a round-robin-test (RTT), and guidance for standard revisions

According to these arguments, some example of diagnostics and their capabilities will be discussed.

6.4.1 Atmospheric and Altitude Correction Factors for Air Gaps and Clean Insulators

WG D1.50 is collecting data about atmospheric and altitude correction factors, as one has found that there are different factors in different IEC standards, which is not acceptable, especially under the demand of reducing equipment size and safety clearances. Figure 22 shows results collected by WG D1.50 about the influence of humidity on insulators [30].

With the increasing use of HVDC systems and DC lines, correction factor under DC stress were also investigated. Figure 23 shows the influence of humidity for a gap range of 100–700 mm and as function of altitude range (500–1900 m). These investigations are needed as it was realized that a correction according to IEC 60060 appears to be invalid for DC. Therefore, the results of WG D1.50 are needed for the revision of IEC 60060-1 [29].

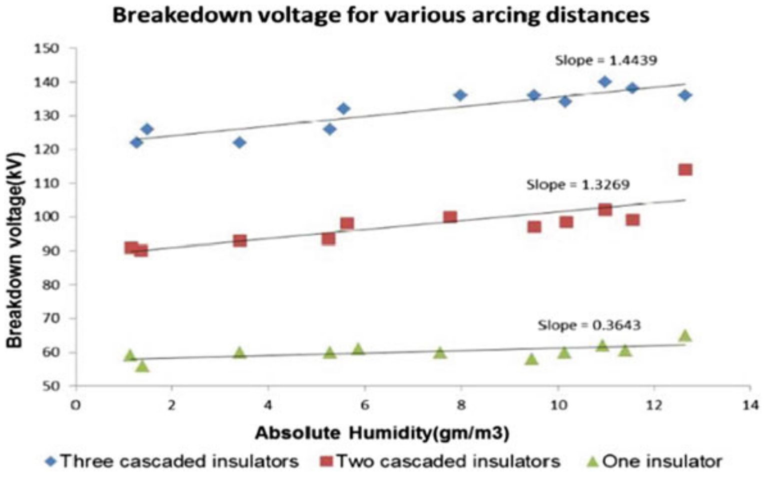


Fig. 22 BD voltage as a function of absolute humidity and arching distances [30]

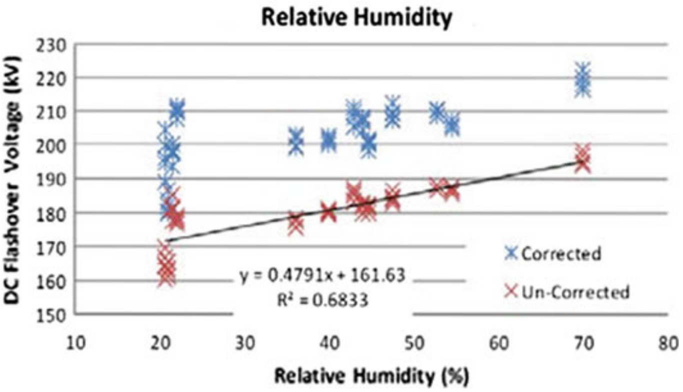


Fig. 23 BD voltage versus relative humidity [30]

6.4.2 Partial Discharge Detection Under DC Voltage Stress

Partial discharge detection under DC voltage stress is the task of WG D1.63 [15]. Experiences have shown that the PD activity and their measurement under DC stress are very different from those under AC stress. The IEC standard 60270 [31] does not cover DC measurements correctly. This was the reason to find this WG. Their result will serve as input for the revision or as amendment for this standard.

The main two tasks of WG D1.63 are to describe the understanding of the differences of PD behavior between AC and DC. The physical process and the influencing factors of operating conditions (as e.g., polarization, temperature, etc.) on different insulation systems under DC stress and respective effects on PD phenomena are investigated. Figure 24 shows an example of the PD repetition rate of a void inside a cable joint under DC stress, and Fig. 25 shows the simulated electric field stress in an oil-paper insulation.

6.4.3 Diagnostics for GIS by Means of the UHF Technology

For about 20 years, the ultra-high frequency (UHF) method for PD detection in GIS was introduced. Since then, there was a need to verify the sensitivity of these diagnostic measurements. WG D1.25 collected the experiences gained over a period of about 15 years of this sensitivity check, TB 654 [32].

The described procedure ensures that defects causing an apparent charge of 5 pC are detected on site. The comparison between different diagnostic methods was performed, and the level of partial discharge activity associated with different types of the defects was established. It was found that there is no direct correlation between the PD level detected by any diagnostic methods and the flashover voltage of the defects.

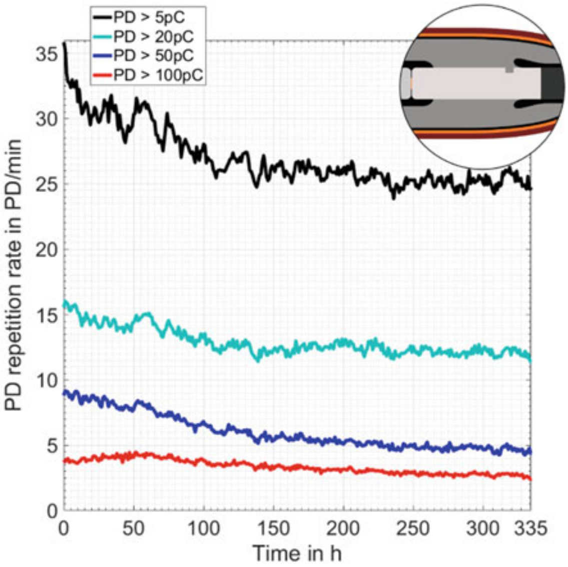


Fig. 24 PD repetition rate of a void type defect inside a cable joint at 180 kV and elevated temperature [15]

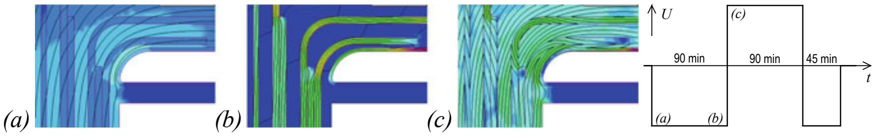


Fig. 25 Electric field stresses and equipotential lines in an oil-board barrier system during polarity reversal test: **a** displacement field after switching on, **b** close to steady-state DC field after 90 min, and **c** superposition of steady-state and displacement fields after polarity reversal [15]

In most types of GIS, the UHF energy is concentrated between 100 MHz and 2 GHz. The sensor's frequency response depends on its size, shape, and the connection method used. Most sensors are themselves resonant structures at UHF frequencies, and this can be used to advantage. Typical sensors are shown in Fig. 26.

Figure 27 shows the damping of the PD signal along the GIS busbar: "…an example of the frequency dependent attenuation characteristics along the busbar of a single-phase encapsulated 220 kV GIS is shown. The busbar of this type of GIS and this configuration shows quite low signal damping. The pulse generator signal used for carrying out the on-site sensitivity verification can even be identified at the sensor 14 bays further away (at 495 MHz). It can be seen that the signal-to-noise ratio is higher for the frequencies below 1 GHz compared to the frequencies above 1 GHz. Furthermore, with increasing distance from the artificial pulse signal injection point, the frequency content tends to concentrate on specific resonance frequencies with decreasing bandwidth."

Fig. 26 Examples of sensors, TB 654 [32]

6.4.4 Risk Assessment on Defects in GIS Based on PD Diagnostics

For the operation of the assets, in general, and for the future, a risk analysis is of importance. This is in general not easy to achieve, as very often the status of the equipment (transformer, GIS) is not completely known. In addition, the possible weak points or defects are unknown. Therefore, WG D1.03 studied the combination of diagnostics with a risk assessment for a GIS, equipped with a UHF PD measurement technique. The results were published in TB 525 [33]. The approach in form of a flowchart presents Fig. 28.

This reports shows further that depending on the type of defect, different aspects for each of the impact parameter have to be considered. Table 2 shows the technical impact parameters and the related aspects for different defects detected by PD measurements. Some of these aspects can be defined by the PD measurement; others are related to the service condition like, e.g., occurrence of temporary AC overvoltages [33].

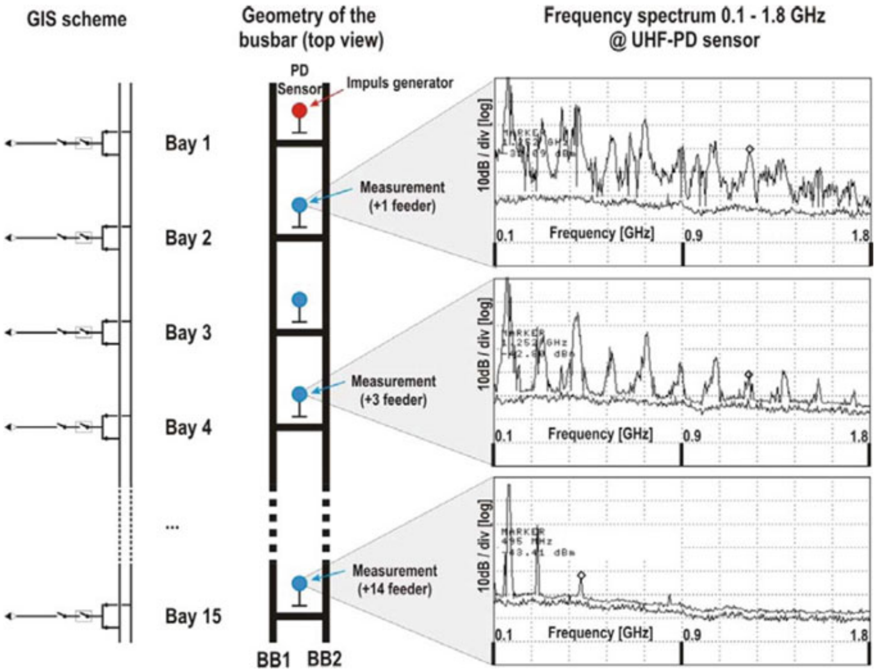


Fig. 27 UHF signal attenuation characteristics along 220 kV GIS busbar, TB 654 [32]

6.4.5 Diagnostics for Liquid Insulation Systems

TB 738 summarizes the influence of water and oxygen on cellulose aging in mineral oil [34]. The Arrhenius plots of aging of (a) kraft paper and (b) thermally upgraded paper, taken out of this brochure, are shown in Fig. 29.

This papers shows, “that the temperature dependence for oxidation of kraft paper is less than hydrolysis, and more in line with the ageing of thermally upgraded paper. One can also see that increased water content in thermally upgraded kraft paper is not as harmful as for pure kraft paper, while presence of oxygen seems to be more or less equally harmful for both papers. This gives a clear indication that hydrolysis is suppressed by the upgrading, while oxidation is not and that for upgraded paper oxidation seem to be a more prominent mechanism.” [17]. This example shoes the relevance to the methods offered for on-site oil reconditioning or reclamation. The drying of the cellulose is a possible bonus effect from processes mainly focused on degassing, reconditioning and reclamation the oil itself. For all these methods, the cellulose and pressboard are dried via the oil transported through the processing apparatus. The ability of the methods to get water and ageing by-products out of the winding will depend on, and increase with, the temperature of the insulation system in the transformer during the processing. To remove water requires time: the temperature dependence of the solubility and diffusion of water is basically known.”

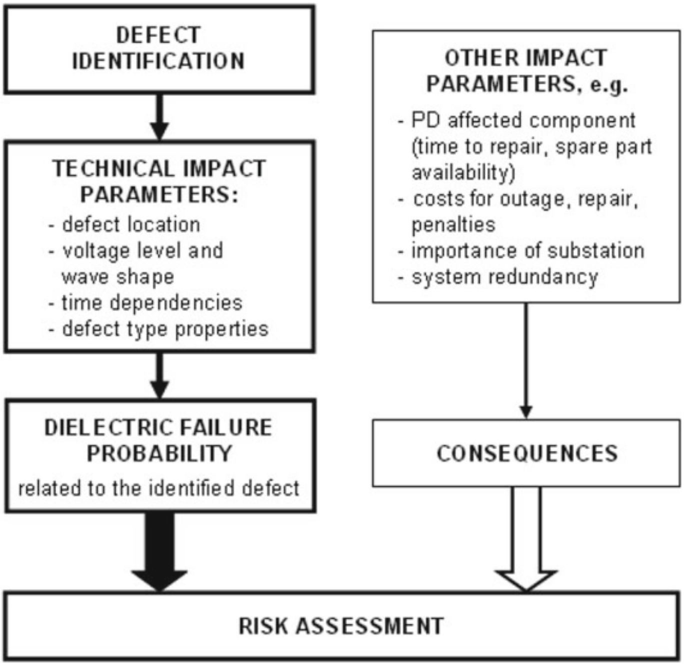


Fig. 28 Flowchart of the proposed risk assessment procedure [33]

6.4.6 Significance of Moisture Measurements in Oil Together with the Application and Suitability of New Sensor Techniques

On this basis, it is obvious that the measurement and knowledge of the water content in oil are important for the status analyses of a transformer. How these moisture measurements are done and the available technologies were investigated and collected by WG and recently published as TB 741 [35].

Figure 30 shows the direct dependency between breakdown voltage and relative saturation of insulating liquid. The combination of this graph with a graph describing moisture concentration in % in paper and % relative humidity would give the dependence of % moisture in paper from the breakdown voltage in oil under equilibrium conditions, see Fig. 31 [35].

This diagram shows that at lower temperatures the breakdown voltage in oil does not significantly change with the water content of the solid insulation. The sampling temperature is necessary for a correct evaluation of the water content and for estimation of the breakdown voltage as well.

TB 741 presents also the capacitive polymer sensors. “They are widely used in monitoring of moisture in HV equipment, as well as in automated equipment for oil processing and refurbishment (reclaiming). The use of capacitive sensor instruments is a mature technology and has been used since 1970’s in various applications to

Table 2 Aspects of technical impact parameter for different PD defects [33]

Type of defect	Technical impact parameters			
	Defect type properties	Defect location	Time dependencies	Voltage level and wave shape
Mobile particle	– Particle dimension and mass – Jump height	– Vicinity to spacer – vibration initiating movement – Local field strength – Particle trap – Dielectric coating	– Trend of magnitude – Activity – Time of flight	– AC voltage level – DC stress – Superimposed stress
Floating element	– Movement (fixing design) – Number/cycle	– Vicinity to spacer	– Trend of magnitude – Activity – Phase angle	– AC voltage level
Particle on insulation	– Tip shape – Length	– Local field strength	– Activity	– LI – VFT
Protrusion	– Tip shape – Length	– On HV electrode	[b]	– LI – VFT
Void	– Size[a] – Number[a] – Shape[a]	– Local field strength	– Trend of magnitude – Intermittent activity – Phase angle stabilisation – Inception/extinction voltage	– AC voltage level – Inception by transient voltage

[a] No information is currently available from PD measurement

[b] No influence to the calculation procedure for probability

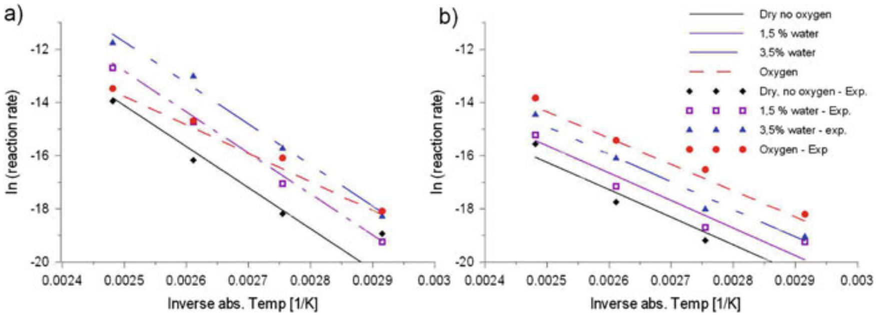


Fig. 29 Arrhenius plots of aging of **a** kraft paper and **b** thermally upgraded paper, TB 738 [34]

Fig. 30 Dependency between breakdown voltage and water content in insulating liquid, TB 741 [35]

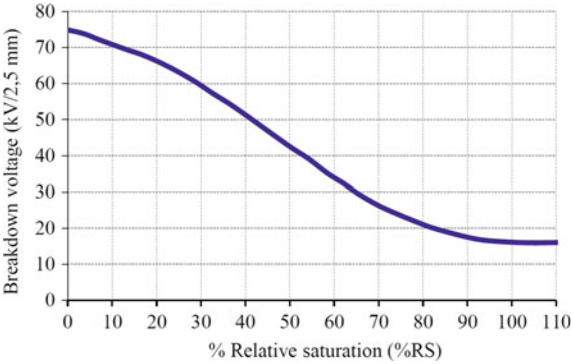
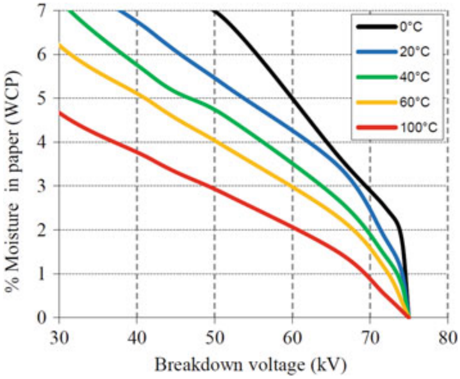


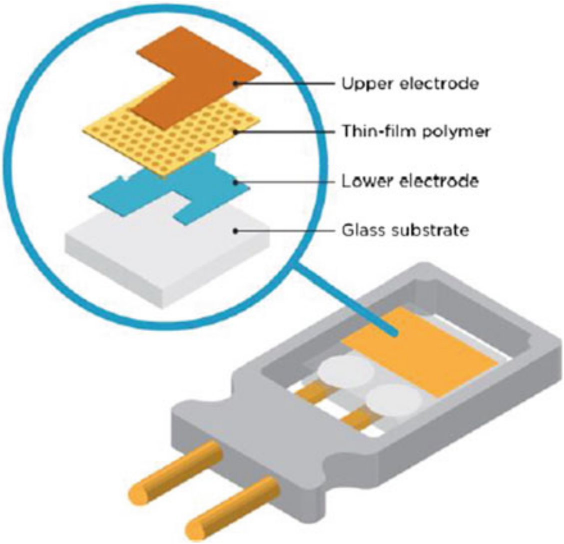
Fig. 31 Dependence between the breakdown voltage and % moisture in cellulosic solid insulation at different service temperatures, TB 741 [35]



measure moisture in gas phase. In late 1990’s, the same technology was introduced to measure relative moisture saturation in oils” [35].

Figure 32 shows that a capacitive moisture sensor is a parallel plate capacitor. At least one of the electrodes is permeable to water vapor and allows water molecules to diffuse into the dielectric polymer layer. Absorbed water molecules increase the

Fig. 32 Structure of a capacitive thin polymer sensor, TB 741 [35]



permittivity, and this can be measured as increased capacitance of the sensor element. The sensor is very selective to water, and almost no interfering effects of other molecules in oils are observed" [35].

The results of TB 741 describes also that it is important to know that moisture diffusion coefficients for natural esters and solid insulation are much higher than for mineral oil and solid insulation. Figure 33 shows as an example due to the different time constants for moisture exchange hysteresis curves (relative saturation (RS) versus temperature dependence) [35].

6.4.7 Advances in DGA Interpretation

Another important diagnostic tool is the dissolved gas in oil analysis (DGA).

The main methods used to identify faults (above typical values) or stresses (below typical values) in transformers and accessories filled with mineral oils are the Duval Triangles and Pentagons, IEC ratios, Rogers, Dornenburg, key gas methods, together with dozens of other, lesser-used published methods using for instance neural networks. They all primarily use hydrogen, methane, ethylene, ethane, and acetylene for fault identification. The Triangle and Pentagon methods [B5] have been used for fault identification in TB 771 rather than the IEC ratio method [B3] and the other methods listed above [28].

Table 3 shows examples for faults or stresses of type D1 in paper of windings which are more dangerous than faults D1 in oil, because paper here is often subjected to a high voltage and will lose its electrical insulating properties when carbonized by the arcing D1, resulting in dielectric failure. Indeed, ~8 cases of faults D1 in paper have been reported to the WG, where failure occurred when acetylene reached 120

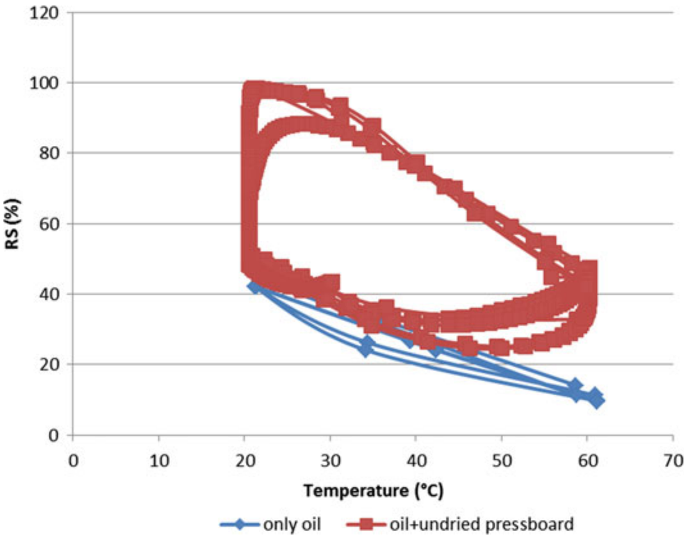


Fig. 33 Hysteresis loops of relative saturation (RS) versus temperature for natural ester, TB 741 [35]

or 45 ppm or less. Shown here is an example of sparking partial discharges D1 in paper of a 230 kV bushing [28].

7 Corrosion

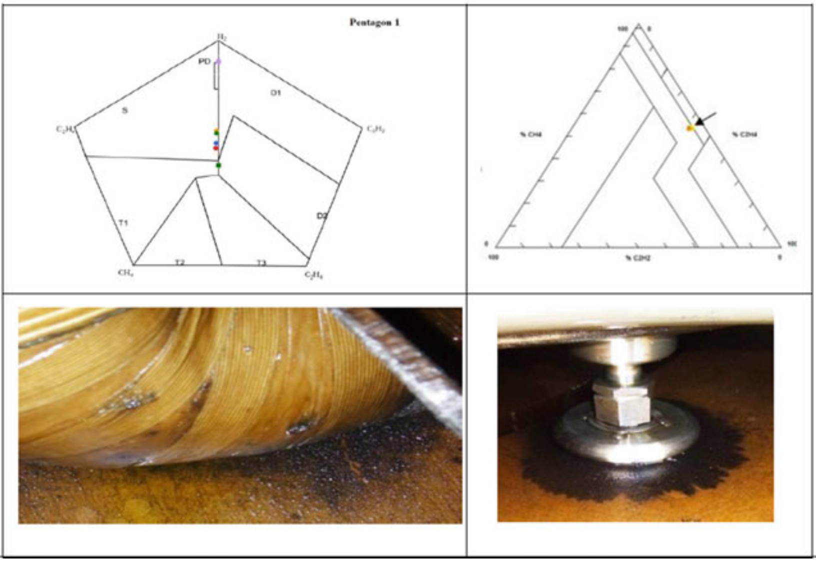
Finally, within the recent years, corrosion comes into the focus of SC D1. Originally, not in their scope, SC D1 was asked some years ago to collect data and information about this topic. This was finally successfully done by WG D1.71, “Understanding and Mitigating Corrosion,” and published in TB 765 in 2019 [36].

Within this brochure, the various corrosion mechanisms are presented and analyzed. As an example, Fig. 34 describes “pitting as one of the most destructive forms of corrosion as it can cause equipment failures due to perforation, while the loss of metal due to uniform corrosion is minimal. Generally, pitting occurs on oxide-covered metal surfaces such as stainless steels or aluminum due to the localized breakdown of the oxide film by aggressive anions, especially chloride ions. Pitting can also occur on steel in boilers and other water systems, when the oxygen content increases such as from leaks, so that the protective magnetite film breaks down locally causing pits or depressions on the steel surface. This is called oxygen pitting” [36].

The well-know rusting and its mechanism are shown in Fig. 35. The authors of WG D1.71 explained: “Steel corrosion is easily recognized because the product is red rust. As soon as any protective zinc plating is destroyed, the steel and oxidizing

Table 3 Example of sparking partial discharges, type D1, in paper of a bushing [33]

	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	Tr1	Tr4	Tr5	Pent2	
01 April	576	150	11	116	19	DT	S	T3	S/D1	●
15 April	433	115	9	92	15	DT	S	T3	S/D1	●
15 May	966	226	21	179	32	DT	S	T3	S/D1	●
12 June	1212	225	21	171	30	DT	S	T3	S/D1	●
Delta 15 Apr/15 May	533	111	12	87	17	DT	S	T3	S/D1	●
Delta 15 May/12June	246	0	0	0	0	-	S/PD	-	PD	■



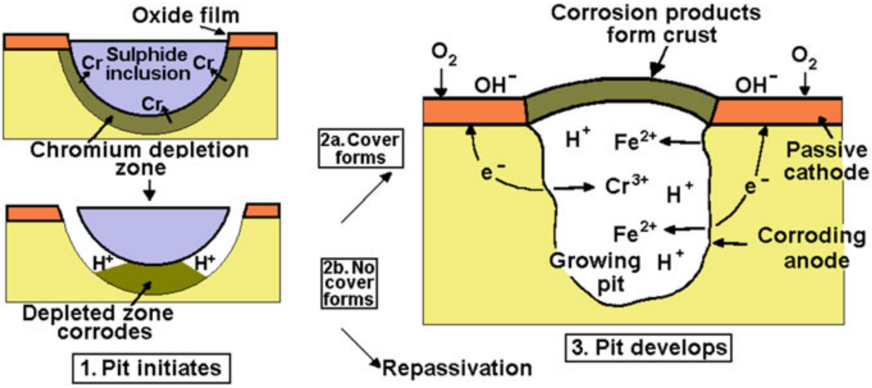


Fig. 34 Pitting corrosion mechanism in a stainless steel, TB 765 [36]

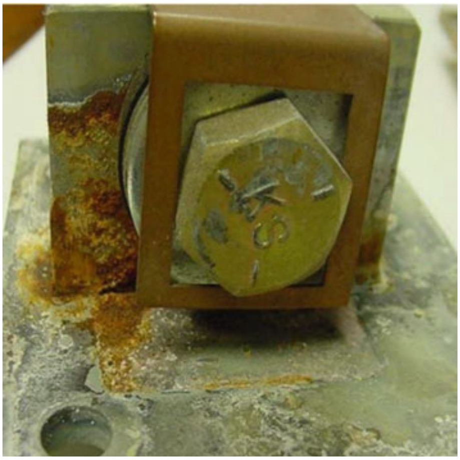


Fig. 35 Galvanized steel corrosion: mixture of “red rust” (Fe_2O_3), “black rust” (Fe_3O_4), and “white rust” of corroded Zn plating, TB 765 [36]

agents react to form rust on the surface. When iron base alloys corrode, dark corrosion products usually form first on the surface of the metal. If moisture is present, this ferrous oxide coating is converted to hydrated ferric oxide, known as red rust. This material will promote further attack by absorbing moisture from the air. The shade of iron oxides ranges from a dull yellow through various oranges and reds to a deep black. Red rust (Fe_2O_3) and black rust (Fe_3O_4) usually occur together: the deposit color reflects which oxide in the mixture predominates. Corroded galvanized steel parts may be also covered by so-called white rust, which is a white porous deposit formed on destroyed zinc plating. All three types of rust (red, black, and white) are seen” in Fig. 35.

8 Conclusion

As a summary, the main topics and directions of the future WGs in SC D1, which will support the challenges of the electricity supply of the future, are:

- Reduction of losses
- Increasing of lifetime
- Corrosion mitigation
- Less environmental influences (replacement of SF_6)
- Environmentally friendly insulation liquids for transformers
- Compact design which means higher electrical field stress
- Aging under high field stress (AC and DC)
- Influence of transient voltages stresses due the further increased application of power electronics
- New materials (nanomaterials), new insulation liquids, and improved solids
- Diagnostic tools and interpretation rules or guidelines
- New test procedures, as consequence of a broader use of power electronics.

9 Education

Finally, some brief thoughts about the education of the engineers and scientists and the various skills, which might be needed to support and realize the electricity supply of the future.

- System knowledge and thinking (HV engineering, power electronics, material science, physical concepts)
- System boundaries become more permeable or disappear completely
- Understanding of interaction between Hardware–design–manufacturing processes
- Handling and understanding of complex simulation tools (multiphysics)
- Out of the box thinking, overcome borders between power electronics, HV engineering, chemistry, physics, mechanics, and simulation
- Student should understand the basics of HV engineering, power electronics, electric fields, the statistical nature of breakdown and PD activity and further and new diagnostic parameters
- Simulation tools are principally limited on the available knowledge and theories, and therefore, time-consuming experiments and research are still needed and necessary.

Universities should adapt the courses, but they should not forget the classical "hardware," as this is still the backbone of the electricity supply systems.

References

1. CIGRE-S47-ScopOfWrk-N3: 2018 Scope of Work a Activities. https://www.cigre.org/userfiles/files/Knowledge_Programme/S47-ScopOfWrk-N3.pdf
2. CIGRE Technical Brochure **224**: Emerging Technologies and Material Challenges, final report of Joint Advisory Group DC15/D1-JAG 02TC & Study Committee Task Force SC15/D1-Tf03 (2003)
3. Hauschild, W., Lemke, E.: High-Voltage Test and Measuring Techniques, 2nd edn. Springer (2018). ISBN978-3-319-97459-0
4. Sundran, A., et al.: Establishment of 1200 kV national test station in India. CIGRE Science & Engineering, vol. 4, pp. 6–11 (2016)
5. Küchler, A.: High Voltage Engineering. Springer Vieweg, VDI book (2017). ISBN 978-3-642-11992-7
6. IEC 60060-1 ed. 3.0 (2010–09): High-voltage test techniques—Part 1: General definitions and test requirements, 2nd edn. Springer (2018). ISBN 978-3-319-97459-0
7. CIGRE Technical Brochure **502** High-Voltage On-Site Testing with Partial Discharge Measurement, final report of WG D1.33 (2012)
8. CIGRE Technical Brochure **751**: Electrical Properties of Insulating Materials Under VLF Voltage, final report of WG D1.48 (2018)
9. CIGRE Technical Brochure **703**: Insulation Degradation under Fast, Repetitive Voltage Pulses, final report of WG D1.43 (2017)
10. IEC 62895: 2017: High voltage direct current (HVDC) power transmission—cables with extruded insulation and their accessories for rated voltages up to 320 kV for land applications—test methods and requirements (2017)

11. Voß, A., Gamlin, M.: Superimposed impulse voltage testing on extruded DC-cables according to IEC CDV 62895. In: 20th International Symposium on High Voltage Engineering, Buenos Aires, Argentina, August 27–September 01 (2017)
12. Felk, M., et al.: Protection and measurement elements in the test setup of the superimposed test voltage. In: 20th International Symposium on High Voltage Engineering, Buenos Aires, Argentina, August 27–September 01 (2017)
13. CIGRE Technical Brochure: DGA Monitoring Systems, final report of WG WG D1/A2.47, to be published in 2019
14. CIGRE Technical Brochure **741**: Moisture Measurement and Assessment in Transformer Insulation - Evaluation of Chemical Methods and Moisture Capacitive Sensors, final report of WG D1.52 (2018)
15. Plath, R., et al.: Interim Report of WG D1.63: Progress on Partial Discharge Detection Under DC Voltage Stress. CIGRE Joint Colloquium on Study Committee A2, B2 and D1 in New Delhi (2019)
16. CIGRE Technical Brochure **730**: Dry Air, N_2, CO_2 and N_2/SF_6 Mixtures for Gas-Insulated Systems, final report of WG D1.51 (2018)
17. Conference of the Parties.: Methodological issues related to the Kyoto Protocol. Report of the Conference of the Parties on its third session, held at Kyoto from 1 to 11 December 1997 Addendum Part Two: Action taken by the Conference of the Parties at its third session. http://unfccc.int/resource/docs/cop3/07a01.pdf (1998)
18. CIGRE Technical Brochure **696**: MO Surge Arresters—Metal Oxide Resistors and Surge Arresters for Emerging System Conditions, final report of WG A3.25 (2017)
19. CIGRE Technical Brochure **661**: Functional Nanomaterials for Electric Power Industry, final report of WG D1.40 (2016)
20. CIGRE Technical Brochure **451**: Polymer Nanocomposites—Fundamentals and Possible Applications to Power Sectors, final report of WG D1.24 (2011)
21. CIGRE Technical Brochure **644**: Common Characteristics and Emerging Test Techniques for High Temperature Superconducting Power Equipment, final report of WG D1.44 (2015)
22. Sytnikov, V.E., et al.: On the possibility of using HTSC cable lines in creation of long-distance interconnections. CIGRE Session 2018, Paris, paper B1-301
23. Korsunov, P.Yu., Ryabin, T.V., Sytnikov, V.E.: Superconducting cables. HTSC CL Project for Connection of 330 kV Tsentralnaya Substation and 220 kV RP-9 Substation in St. Petersburg (Energy of the unified network, 2017, No. 3(32), pp. 28–36)
24. Koo, D.C., et al.: World first commercial project for superconducting cable system in Korea. CIGRE Session 2018, Paris, paper B1-303
25. Shang, B.Y., et al.: Measurement and modeling of surface charge accumulation on insulators in HVDC gas insulated line (GIL). CIGRE Science & Engineering, vol. 3, pp. 81–87 (2015)
26. CIGRE Technical Brochure **662**: Guidelines for Partial Discharge Detection Using Conventional (IEC 60270) and Unconventional Methods, final report of WG D1.37 (2016)
27. CIGRE Technical Brochure **676**: Partial Discharges in Transformers, final report of WG D1.29 (2017)
28. CIGRE Technical Brochure **771**: Advances in DGA Interpretation, final report of JWG D1/A2.47 (2019)
29. IEC 60060-1:2010: High-Voltage Test Techniques—Part 1: General Definitions and Test Requirements
30. Rickmann, J., et al.: CIGRE WG D1.50, Current state of analysis and comparison of atmospheric and altitude correction methods for air gaps and clean insulators. In: 19th International Symposium on High Voltage Engineering, Pilsen, Czech Republic, August 23–28 (2015)
31. IEC 60270:2000: High-Voltage Test Techniques—Partial Discharge Measurements
32. CIGRE Technical Brochure **654**: UHF Partial Discharge Detection System for GIS: Application Guide for Sensitivity Verification, final report of WG D1.25 (2016)
33. CIGRE Technical Brochure **525**: Risk Assessment on Defects in GIS Based on PD Diagnostics, final report of WG D1.03 (2013)

34. CIGRE Technical Brochure **738**: Ageing of Liquid Impregnated Cellulose for Power Transformers, final report of WG D1.53 (2018)
35. CIGRE Technical Brochure **741**: Moisture Measurement and Assessment in Transformer Insulation—Evaluation of Chemical Methods and Moisture Capacitive Sensors, final report of WG D1.52 (2018)
36. CIGRE Technical Brochure **765**: Understanding and Mitigating Corrosion, final report of WG D1.71 (2019)
37. Juhre, K., Hering, M.: Testing and long-term performance of gas-insulated systems for DC application. In: CIGRE-IEC 2019 Conference on EHV and UHV (AC & DC), April 23–26, 2019, Hakodate, Hokkaido, Japan

Ralf Pietsch was born in Germany in 1958. He studied physics at the University of Technologies of Aachen, RWTH Aachen, Germany, between 1979 and 1986. He received his Ph.D. (Dr. rer. nat.) at the Institute of High Voltage Technology, RWTH, Aachen, in 1992. Between 1992 and 1996, he worked as a Project Engineer at ABB Corporate Research in Baden-Daettwil, Switzerland. Main topics during this period were UHF sensor development, PD physics, measurements and interpretation of PD and breakdown in SF_6, decomposition products of SF_6, and investigations about replacement of SF_6. In the end of 1996, he moved to ABB High Voltage Technologies, Zürich-Oerlikon (Switzerland), to lead the type test and development laboratories, mainly for testing GIS with rated voltages above 170 kV up to 800 kV.

Since January, 2001, he worked for HIGHVOLT in different technical positions. Main activities lie on lightning impulse and DC test systems, electrical field calculations, and PD measurements. Additionally, since 1996, he is an active member of CIGRE SC D1 in various working groups (as specialist, secretary, or convener). He is the Chairman of CIGRE Study Committee SC D1 since September, 2016. Since 2004, he is a contract Teacher at Chemnitz University of Technology, giving lectures on “Diagnostics and High-Voltage Measurement Techniques.”

Information Systems and Telecommunications

Giovanna Dondossola, Marcelo Costa de Araujo, and Karen McGeough

Abstract Digital systems within electric power utilities have progressively received an increased attention in the last decades. With the contribution of SC D2 members, this chapter provides a snapshot of the state of art technologies for the sector, and builds up a vision of the envisioned developments for the future electricity supply systems, also taking into account diversities in the penetration of electricity infrastructures over the world. Both the state of the art and the future technologies are grouped into three interlinked SC D2 pillars: ICT systems, telecommunications and cyber security.

Keywords Data analytics · Artificial intelligence · Machine learning · Blockchain · Industrial internet of things · Network function virtualization · Cyber risk assessment · Preventive security measures · Anomaly detection · Cyber incident response

General Acronyms

ANN	Artificial neural networks
API	Application programming interface
BCP	Business continuity plan
BES	Bulk electric system

On behalf of CIGRE Study Committee D2.

G. Dondossola (✉)
RSE S.p.A, Milan, Italy
e-mail: Giovanna.Dondossola@rse-web.it

M. Costa de Araujo
Eletrobras Eletronorte, Brasilia, Brazil

K. McGeough
ESB Networks, Dublin, Ireland

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6_17

CEN/CENELEC/ETSI	European Committee for Standardization/European Committee for Electrotechnical Standardization/European Telecommunications Standards Institute
CDM	Canonical data model
CIP	Critical infrastructure protection
CNN	Convolutional neural networks
DER	Distributed energy resources
DNN	Deep neural networks
DSO	Distribution system operator
DT	Digital twins
EMS	Energy management system
ENISA	European Network and Information Security Agency
EPU	Electric power utility
GDPR	General Data Protection Regulation
GIS	Geographic information system
GPS	Global positioning system
HMI	Human–machine interface
ICS	Industrial control system
ICT	Information communication technology
IDS	Intrusion detection system
IEC	International Electrotechnical Commission
IED	Intelligent electronic device
IEEE	Institute of Electrical and Electronics Engineers
IIoT	Industrial Internet of things
IoT	Internet of things
IP	Internet protocol
ISO	International organization for standardization
IT	Information technology
LV	Low voltage
MV	Medium voltage
NERC	North American Electric Reliability Corporation
NLP	Natural language processing
NIS	Network and information security
NIST	National Institute of Standards and Technology
OT	Operational technology
PD	Partial discharge
PMU	Phasor measurement unit
PRPD	Phase-resolved partial discharge
QoS	Quality of service
RFC	Request for comments
RTU	Remote terminal unit
SCADA	Supervisory control and data acquisition
SG-CG	Smart grid coordination group
SIEM	Security information and event management
TC	Technical committee

TCP	Transmission control protocol
TLS	Transport layer security
TSO	Transmission system operator
XML	Extensible markup language
WAMPAC	Wide area monitoring protection automation control
WAN	Wide area network

Specialized Acronyms

2G	Second-generation cellular technology
3G	Third-generation cellular technology
4G	Fourth-generation cellular technology
5G	Fifth-generation cellular technology
ACSE	Association control service element
ADSS	All dielectric self-supporting
CIM	Common information model
DNP3	Distributed network protocol
EoS	Ethernet over SDH
GOOSE	Generic object-oriented substation events
GSM	Global system for mobile communications
LPWAN	Low-power wide area networks
LTE	Long-term evolution
MAC	Media access control
MASS	Metallic aerial self-supporting
MMS	Manufacturing message specification
MPLS	Multi-protocol label switching
MPLS-TP	Multi-protocol label switching-transport profile
NFV	Network function virtualization
OPGW	Optical ground wire
OPPC	Optical phase conductor
PDH	Plesiochronous digital hierarchy
PLC	Power line carrier
SDH	Synchronous digital hierarchy
SDN	Software defined networking
SMV	Sampled measured value
SV	Sampled values
TCD	Temporal causal diagram
TDM	Time-division multiplexing
TFPG	Temporal failure propagation graph
UHF	Ultra high frequency
VHF	Very high frequency

1 Introduction

In the era of processes and services digitalization, the role of electronic data and digital infrastructures in the power system management is undergoing an impressive, sometime disruptive, transformation. The opportunities and challenges offered by the capability of treating big amount of data through digital services and virtualized architectures will characterize the new generation of electricity supply systems.

As a contribution from CIGRE Study Committee D2 to tracking the smart grid roadmap for the future decades, this chapter provides an overview on the state of the art for the ICT, telecommunication and cyber security cross-cutting technologies, followed by their future-proof evolution. The vision of the digital future in the power system addresses the needs arisen by global energy transitions and new energy markets, tackling rapidly evolving ICT technologies when applied to slowly changing power infrastructures.

2 State of the Art

The state of the art of the ICT technologies which are relevant for the EPU infrastructures covers ICT systems, telecommunication means and cyber security measures.

2.1 ICT Systems for EPUs

2.1.1 Data Analytics and Artificial Intelligence

Data is available to EPUs from a great variety of sources. Protection relays and IEDs continuously collect and process data to detect the abnormal/fault condition on a power system and provide a high-speed tripping mechanism to isolate the fault from the rest of the power system. SCADA systems have been used by operation centers for a long time to monitor the power flow and make decisions based on the displayed alarms, like, for example, adding or removing capacitor banks for reactive power control and adjusting transformer tap changers. Sensors that monitor the condition of high voltage equipment, assisting maintenance teams in their tasks, are another type of data source. Synchrophasors, or PMUs, provide more precise readings on the state of the grid in real time. Also, external data, from a power system point of view, like work order history, disturbance reports, weather history, forecasts from weather service vendors, economy history, forecasts from economic analysis firms, end-use information from surveys, industry codes, equipment locations, land-use information from GIS and urban-development plans from local governments are very important to improve the situational awareness and assist EPUs in their decisions

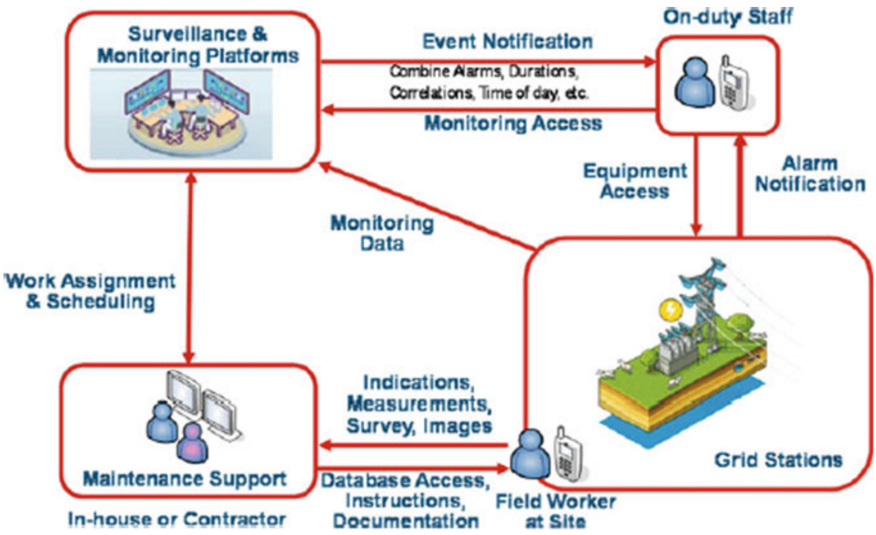


Fig. 1 EPU typical ICT infrastructure [3]

within the operational, tactical and strategic levels. More details are available in [1, 2]. Figure 1 illustrates a typical EPU ICT infrastructure.

From the customers' side, smart meters allow the offering of new services, like energy consumption in real time, with each load classified by type, available in different platforms, like smartphones, smart TVs and computers. The energy price can be reviewed in real time, according to the demand. With that knowledge in their hands, the hours during the day to use heavy electro domestic appliances may be chosen when it becomes more economical to customers. More can be seen in [4, 5].

However, data alone is not enough. In order to bring real benefits to utilities, this data must be properly processed to be translated into useful information, which has greater value and can provide insights to process owners in utilities. Data integration can provide a better view on grid status by making correlations among all factors that may influence system behavior. Data analytics and visualization techniques, combined with the expertise from professionals in the electrical sector can assure system resilience for many more decades to come. Figure 2 illustrates these concepts.

According to Stimmel [6], analytics models can be divided into four categories presented in Table 1.

These approaches can be used by themselves or combined, according to the specific kind of problem they intend to solve.

Machine learning is an artificial intelligence technique used to obtain predictive insights from data. In a high-level view, it is the process to collect data, label it and run it through an algorithm to train a predictive model, and after evaluating the model results, to deploy it in real-life applications (Fig. 3). Machines can be trained using supervised, unsupervised or reinforcement learning. In supervised learning, the data is previously labeled by a human (e.g., to identify damaged or undamaged

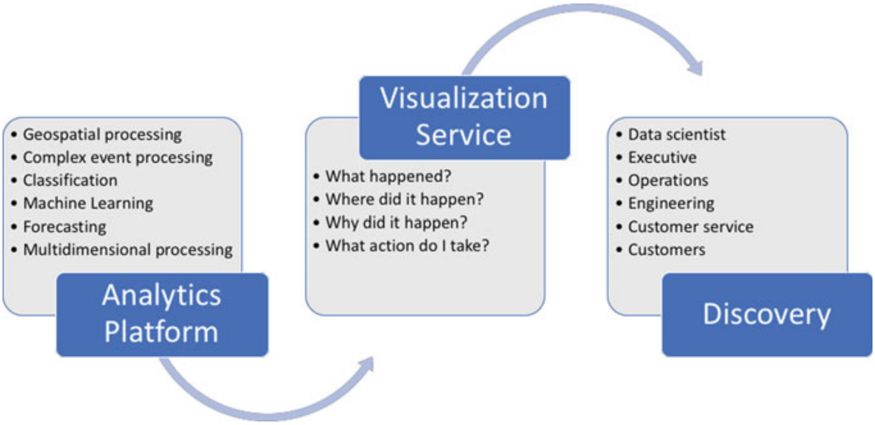


Fig. 2 Flow of data to actionable intelligence [6]

Table 1 Analytic models used in smart grid analytics [6]

Analytic approach	Function
Descriptive	What happened or what is happening now?
Diagnostic	Why did it happen or why it is happening now?
Predictive	What will happen next? What will happen under various conditions?
Prescriptive	What are the options to create the most optimal or high-value outcome?

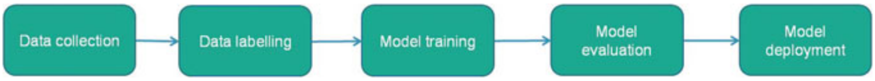


Fig. 3 Machine learning process

parts of equipment) prior to model training. In unsupervised learning, the algorithm itself creates clusters of similar features of the pattern it is trying to classify (for instance, separating components in a transmission tower). Reinforcement learning is a technique where machines are rewarded when they achieve the expected goals and punished otherwise. This technique has been used in the past to develop machines that could defeat humans in board games or videogames.

The main use cases for machine learning are:

- Computer vision
- Predictions in a time series or regression
- Natural language processing (NLP).

An example of machine learning is an artificial neural network (ANN), a computational network that tries to simulate the decision process that occurs in biological networks of neurons in a central nervous system [7]. It consists of three elements [8]:

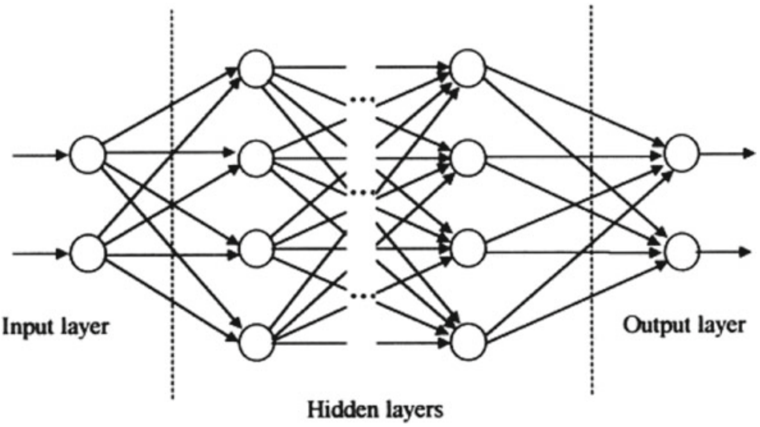


Fig. 4 Example of ANN architecture

input layer, hidden layers and output layer. Figure 4 shows an example of ANN architecture. Each neuron is connected to other neurons of a previous layer employing adaptable synaptic weights, and knowledge is stored as a set of connection weights. An ANN is composed of many nodes connected by links, where each link has a numeric weight [9]. Each artificial neuron in the ANN performs a weighted sum of its inputs (also called "features" in machine learning terminology), and passes this sum through a function to give an output (also called "label"), which feeds into other neurons. There are many different ANN architectures which can be used for different purposes, but all have the ability to learn relationships within data by adjusting the strength of signals passed from one artificial neuron to another [10].

In the training process, it is necessary a set or group of matched input and output patterns. Each produced output through the network is compared to the desired output, until the error is reduced to the desired tolerance and the network locks the weights constant. Then, it uses this trained network to make decisions, identify patterns or define associations in new input datasets [9].

A simple ANN is composed by the input and output layers with a single hidden layer between them. When more than three hidden layers are present, such architectures are called deep neural networks (DNN). One example of deep learning is convolutional neural networks (CNN). This technique has allowed researchers to solve more complex problems, like in computer vision, with automatic image recognition. Each layer increases the complexity of the features it extracts from images, and some algorithms do not require labeling made by humans. DNN applications were made possible by the advances brought by cloud computing, the increase in computational power and high bandwidth telecommunication networks. These elements combined allowed more data availability and the possibility to run more complex algorithms.

However, before using artificial intelligence, data analysts or computer scientists should verify if other techniques can be applied to accomplish their goals, like statistics or classic algorithms, like support vector machines (a hard classifier method that maximizes the distance between points in a dataset) and decision trees (a technique where a hierarchical tree is built from a root node connected by branches to internal and terminal nodes and classifications are made on each node by predetermined criteria), generating insights from historical data. The interested reader may find more information on these and other techniques in the references of this chapter.

Some conditions must be present before applying machine learning techniques. If large volumes of data are not available, it is not possible to train accurate prediction models. Also, the quality of the data used in the training phase is extremely important to obtain precise and unbiased results from the model. In an ideal scenario, there must be no data silos within the company, to avoid inconsistencies and to facilitate aggregations. A data governance process is fundamental to achieve the full potential of artificial intelligence.

Applications of Data Analytics and Artificial Intelligence in EPUs An ANN can be used for a regression (identifying the impact different inputs produce in the resulting output) or classification (identifying the categories of observed data) problem. Some applications of ANN in the electrical sector are: fault diagnosis in transmission lines (either by computer vision or analyzing IED data), partial discharge (PD) diagnosis and load forecasting in power systems.

Figure 5 illustrates how ANN, combined with decision trees, has been used to detected partial discharges in a stator insulator. Automated analysis generally operates on the phase-resolved partial discharge pattern (PRPD), where PD amplitude is resolved against phase of the high voltage waveform [10].

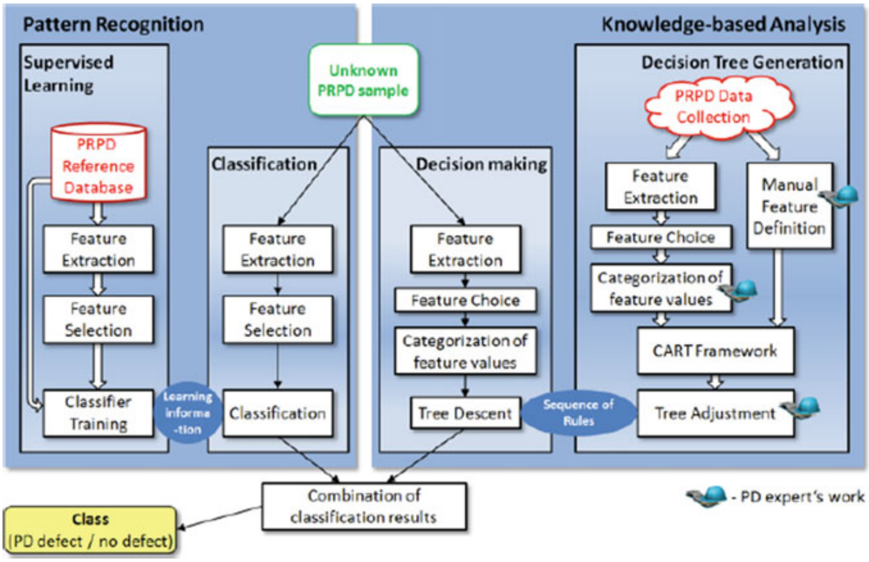


Fig. 5 PD defect identification architecture [10]

Fig. 6 Computer vision application in line inspections [11]

In [11, 12], a CNN was used to train a model to detect faults and defects of electric line and equipment in inspection images captured by helicopters or unmanned aerial vehicles (UAV). This application liberates maintenance technicians and engineers to find solutions to the detected problems, instead of taking considerable time analyzing the images. Figure 6 demonstrates some of the results from the developed system.

Another direct application in operation is in using natural language processing algorithms to automatically transcribe communication between maintenance teams and operators to include their conversations in disturbance reports. Another example using NLP are chatbots, with great application for distribution companies, that can replace humans to handle usual requests from consumers.

Data analytics can be used to identify the load profile in different neighborhoods in cities, by combining data from smart meters, geo-referenced data, demographic data and weather historical data. Examples of this application can be found in [13, 14].

2.1.2 Business Continuity Plans and ICT Architecture

The ICT infrastructure that supports these and other solutions is equally important to assure that utilities maintain the power flow for their customers. Contingency plans and installations must be part of the IT strategy of power utilities, in order to guarantee business continuity and fast recovery during disasters.

To create a business continuity plan (BCP), an EPU must first decide which are its most significant ICT services. To avoid service interruption, a power utility should follow the recommendations below [15]:

- Select a safe location, especially in terms of easy access during natural disaster events.
- Be sure that all needed data will be present at the backup facilities in case of disaster, through storage/database synchronous replication for the most critical information or through physical media restore for the less critical.
- Include in the backup facilities all the tools and applications that allow visualization capabilities that ensure that operating personnel have the situational awareness of the BES, and all those needed for the minimum business/corporate activities.
- Assure all data and voice communications needed for the regular service operation, including voice and control communications to the critical substations and power plants, and to communicate outside the organization including Internet access.
- Include reliable power sources such as access to redundant distribution power lines, diesel generators, diesel refill contracts, etc.
- Be sure that all the physical and cyber security requirements applied to the main facilities and control centers are also guaranteed.
- Implement an operating process for keeping the backup functionality consistent with the primary control center.

The platform architecture in Fig. 7 has been proposed to provide redundancy to support continuous operations while providing flexibility to react to component failures or disaster scenarios for EMS [16].

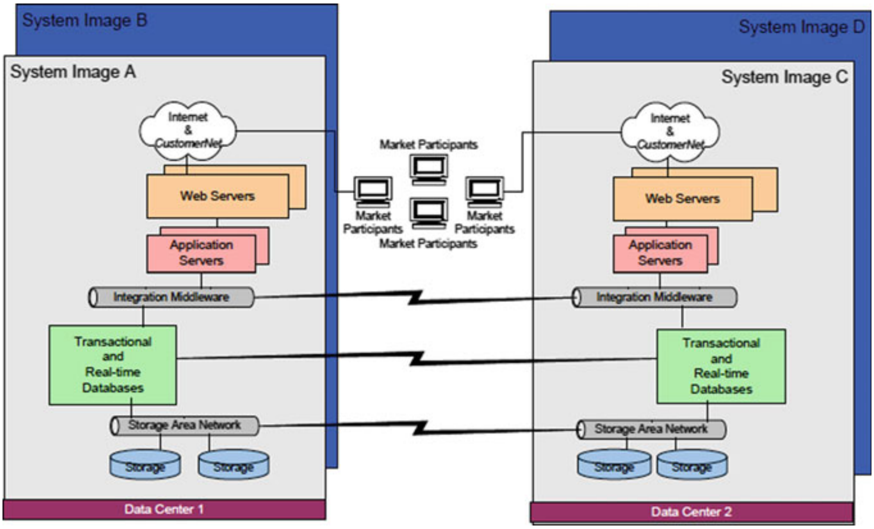


Fig. 7 Platform and business continuity logical architecture

Data synchronization ensures that data, including operational data such as alarms, operator tags and manual entries, are replicated and synchronized between production system images. It can operate either in peer-to-peer mode (both systems are active, and they may be redundant or non-redundant), split-mode (systems are segregated between both locations) or primary/secondary mode (the data in the primary system is periodically replicated in the secondary one). The architecture allows the use of storage hardware based on snapshots and data replication as a means for performing backups and fast recovery. That, allied with a robust and redundant communication system between sites intends to prevent utilities from losing the monitoring and control functions of the power grid.

2.2 Telecommunications for EPUs

2.2.1 Applications and Requirements

The operation of the electrical power system requires the exchange of information between different constituents of the system [17]. To design and to specify suitable telecommunications solutions for the efficient control of the power grid requires a deep understanding of the user applications and their attributes.

Figure 8 provides a basic model defining "user applications" interacting through a communication service delivered over a dedicated telecom infrastructure or provisioned through an operator (procured service). The service access point is the point of delivery, monitoring and management for the communication service and the interface between service user and provider [17].

As outlined in the Technical Brochure 732 [8] developed by the joint working group D2/C2.41, network reliability and coverage, bandwidth, packet jitter and

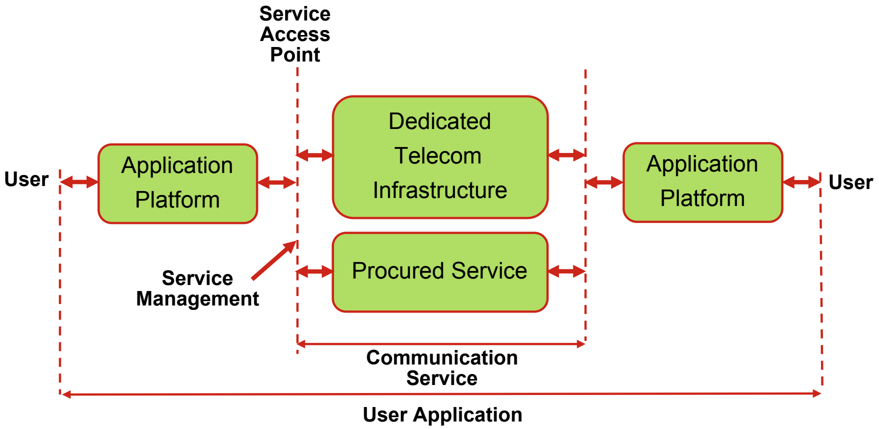


Fig. 8 Basic model representing communication of user applications [17]

latency requirements have been the most critical issues when developing the telecommunications solutions to meet the connectivity requirements for the power system for many years.

The applications can be categorized according to their information exchange perimeters and the Green Book published by Study Committee D2 in 2016 [17], suggested the following categorization of applications:

- Substation-to-substation applications
- Field device to central platform applications
- Inter-platform applications
- Office to field applications
- Producer/consumer to utility platform applications
- Energy farm communications.

The following list of applications are extracted from the comprehensive set of service requirements found in a typical EPU, as published in Technical Brochure 618 [18], compiled by the working group D2.35:

- Tele-protection
- SCADA services
- Data exchange between control centers
- Energy metering
- Event and disturbance recorders
- Real-time PMU
- Dynamic line rating
- Smart metering
- General site alarms, supervision and surveillance
- Remote management of communications network infrastructure
- Operational/black-start telephony
- Time distribution using IEEE 1588.

As discussed in Technical Brochure 732 [8], the communication network needs to provide real time, low latency, highly resilient and highly secure capabilities for many of the applications above, including tele-protection, substation SCADA and phasor measurement. Tele-protection [19] is one of the most critical applications due to its role in the safe operation of high voltage protection schemes during times of line faults [20] however, different applications have various constraints and demand different factors to be met. To select an example user requirement that differs from tele-protection, mobile field workforce applications tend to require higher bandwidth solutions and can generally tolerate higher latency. In order to classify applications based on their communications requirements, an accepted method is to categorize them based on traffic type. Technical Brochure 618 [18] suggests six categories of traffic type to allow the network provider understand the constraints of the application. The six traffic types are outlined below, including example applications for each category.

1. Very low latency, loss intolerant, sequence and symmetry determinant traffic
    (a) Differential tele-protection schemes.
2. Very low latency and loss intolerant
    (a) Distance Protection.
3. Very low latency and loss tolerant traffic
    (a) Time distribution
    (b) Real-time PMU
    (c) Inter substation event distribution.
4. Low latency sequence determinant traffic
    (a) RS485
    (b) IEC 61870-101–IEC 61870-103
    (c) DNP3.
5. Low latency and loss tolerant traffic
    (a) Voice
    (b) Video
    (c) WAMPAC.
6. Latency tolerant and loss tolerant traffic
    (a) Packet-based SCADA protocols
    (b) File transfer
    (c) Device management.

To meet the requirements of current application sets across EPUs, many utilities' networks are still composed of time-division multiplexing (TDM) technology; however, packet communications is steadily growing and rapidly replacing traditional telecommunications. The concept of a smart grid is increasing the demands on EPUs' telecommunications networks, and the emergence of recent protocols such as IEC 61850 along with the requirement to extract precision timing and connect more distributed applications deeper into the distribution network, and are all changing the type of communication solutions that are needed to manage the power grid.

2.2.2 Decision Factors in Selecting Communication Solutions

There are a range of decision factors involved in the selection of appropriate and suitable communications. Gathered from across the combined research carried out by study committee D2, the main factors are outlined below.

- Profile of the EPU
  - Where does the telecommunications provider reside in relation to the EPU, who owns the electrical and communications assets.
- Geographical spread of applications
  - Are the applications located in the high voltage, medium voltage or low voltage networks.
- Topology of the electrical network
  - Is the network configured in a ring, a spur or other topologies.
- Technical parameters of applications/traffic
  - Latency, jitter, bandwidth, availability and security.
- Separation requirements for different traffic types
  - Transmission network applications, distribution network applications, control applications and security applications.
- Users of traffic
  - Network managers, grid controllers and data analysts.
- Skills development for users who are designing, commissioning and maintaining the communications networks
  - For example, resources who are proficient in legacy TDM telecommunications that require significant re-training for latest IP systems.
- Capital and ongoing operational cost
  - Cost of infrastructure investment versus ongoing operational costs to lease a bandwidth service from third-party operators.

2.2.3 Determining the Physical Layer

In order to build a suitable telecommunications network for the operation of the power grid, a suitable physical layer must be selected. The following transport media are a summary of the physical layers on which a communications network can be built upon.

- Optical Fiber
  - Using optical fiber that is connected to the power grid is an efficient and secure way to build a wide area communications network in parallel to the power grid. Installation options for this fiber include utilizing metallic cables such

  as optical ground wire (OPGW), optical phase conductor (OPPC) or metallic aerial self-supporting (MASS), or by attaching dielectric cables such as all dielectric self-supporting (ADSS) or fiber wrap.
  - The fiber cable consists of a number of fiber cores which can be utilized by either directly lighting each fiber pair to create an end-to-end transmission link, or by utilizing optical wavelength division multiplexing to create scalability and provide flexibility. Such scalability and flexibility can be achieved by carrying separate end-to-end transmission links on each wavelength on a single fiber pair, where each transmission link can be design to varying bandwidths and varying protocols (i.e., TDM links such as STM-1, STM-4 and IP links such as 100 Mbps and 10 Gbps).

- Copper Cable
  - Due to the short transmission and lower bandwidth capabilities, copper is typically used to create local area networks within substations, or to provide narrowband communications between substations in urban areas.

- Power Line Carrier
  - PLC is utilized to provide parallel communications for protection relays, and the narrow excess bandwidth on the link is often utilized to provide communications for narrow band applications such as SCADA, more often as a diverse link to the primary communications link.

- Radio/Wireless
  - Radio networks are deployed when physical connectivity is not an option. Licensed radio networks required access to nationally licensed spectrum, and wireless networks can operate as point to point or point to multi-point links, using VHF, UHF and microwave radio frequencies.
  - Utilities also procure services from public operators of wireless networks offering GSM, 2G, 3G and 4G services. This option provides relatively higher bandwidth for lower capital cost, typically used for the connectivity of less critical, higher bandwidth applications in the power utility.

- Satellite
  - Satellite communications provides a valuable and cost-effective option for specialist utility applications, particularly when other fixed or wireless transport options are not accessible [21]. These services are typically provided by a third-party satellite operator, and can either be used to build a dedicate network for a single utility or can be shared by a utility with other users.
  - Satellite is often used as a last mile solution for hard to reach locations or to provide backup to primary links.

2.2.4 Communication Technology Options

Once the selection of the physical layer(s) is completed, selection of suitable communication technology protocol is required. Utilities have largely used TDM systems to transport data between destinations. SDH and PDH solutions are examples of TDM technologies which still exist in many power utility backbone communications networks due to their highly resilient and low latency nature. However, the growth in Ethernet applications and IP-based systems are demanding a migration to the deployment of IP-based communications solutions.

SDH and PDH technologies have been used for many years in utility networks to provide highly resilient and relatively high bandwidth networks that can produce deterministic delay. SDH and PDH use time-division multiplexing and there are a range of interface options available, including synchronous X.21, G703.1, E1 and C37.94, which are used to create point to point and point to multi-point links.

These TDM technologies provide communication links where the data is transmitted in serial basis. On the other hand, the packet transmission technology divides the incoming information, in a node, into packets which are sent or routed to other nodes. The effective path for each packet to reach its destination is decided node by node and the destination node reassembles the information as it was entered in the network.

For pure TDM networks that are required to provide connectivity and transmission bandwidth for IP-based applications, Ethernet over SDH (EoS) can be used to carry such IP applications on the TDM network by concatenating multiple PDH or SDH links to provide the required bandwidth. This offers some short-term solutions to allow the migration toward IP technology to commence, while maintaining the existing TDM backbone networks. Consideration must be given to the type of IP application that will use the EoS solution, as appropriate mechanisms to create a suitable transmission link, such as traffic protection and correct encapsulation schemes, must be applied [22].

However, as the serial-based telecommunications equipment reaches end of life, as IP applications are deployed across the EPU, and as bandwidth requirements begin to grow, expanding PDH and SDH networks is not an efficient method of network expansion and evolution to meet the future needs of the power grid. These technological developments are the main driver for the deployment of IP transmission networks. Pure Ethernet interfaces offer a wide range of data speeds ranging from 100 Mbit/s to 100 Gbit/s.

In the past multi-protocol label switching (MPLS) offered a good choice for the migration of legacy TDM-based applications to a packet network while in parallel providing Ethernet capability for newer IP-based applications, particularly as it catered for the integration of such legacy interfaces on the same network, providing “connection-oriented traffic handling and quality of service” and essentially providing “best effort IP networks” [17]. However, it can be described as an aging technology which does not fulfill the requirements of many applications, particularly with regard to jitter and delay.

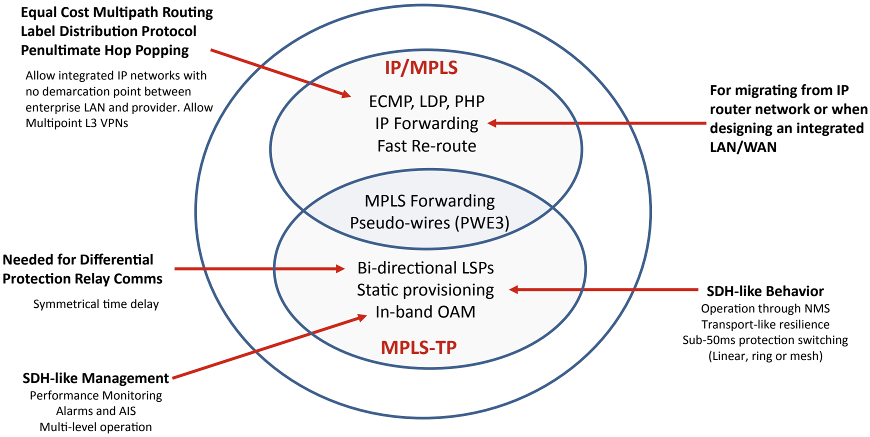


Fig. 9 Functional differences between IP-MPLS and MPLS-TP [17]

IP-MPLS networks are also replacing legacy TDM networks, particularly for deployment in multi-site enterprise networks. IP-MPLS uses no traffic engineering, but simply prioritizes traffic.

However, utilities have begun to deploy tele-protection services over IP-MPLS networks, through the use of TDM to IP protocol converters, quality of service (QoS) schemes and a method called MPLS-TE (traffic engineering) which creates symmetry over the IP links to ensure a deterministic and equal end-to-end delay, as required for correct operation of the tele-protection relays [23].

MPLS transport profile (MPLS-TP) is seen as a better solution to deploy to meet utility operational requirements, enabling "best features from TDM world like quality of service and constant latency, including flexibility of the packet switched networks" [23].

The differences of MPLS-TP and IP-MPLS are described in Fig. 9.

Each utility is at a different stage in the migration from TDM to IP, both in the applications within their EPU and in telecommunications networks that supports them, however, it is acknowledged across the industry that the transition to IP technology will continue, and legacy networks will continue to be replaced by more advanced systems at an growing rate.

Figure 10 describes options for connectivity of RTUs to their control center, to illustrate the possibilities for a single application type.

2.2.5 Network Management Facilities

Network management facilities have become an essential function of any operator of a critical telecommunications network for an EPU [21]. Having remote visibility of all network infrastructure provides the operator with real-time data for faults or issues that occur on the network. Performance monitoring can be carried out on an

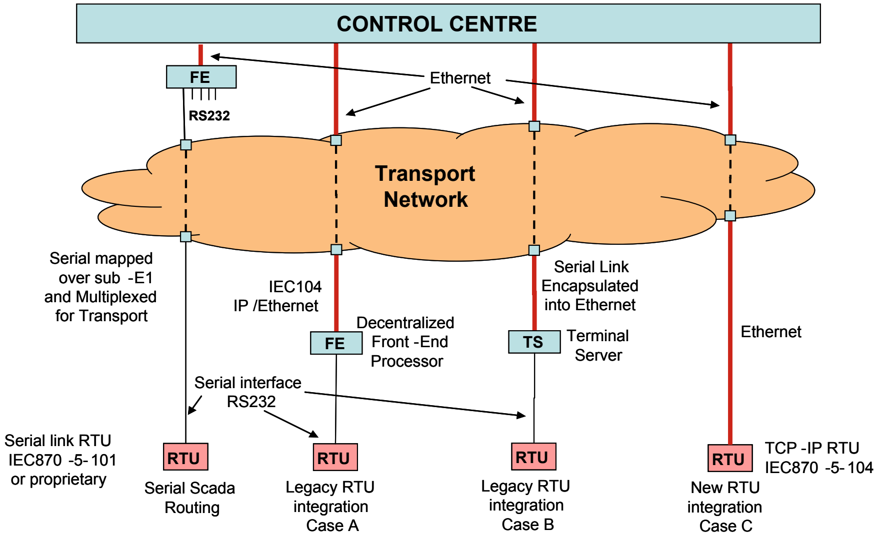


Fig. 10 SCADA RTU to control platform connection alternatives

ongoing basis from a central operations center location, highlighting any degradation of service that might occur, allowing proactive restoration preventing loss of service to the critical applications across the power grid.

Network management facilities also provides the ability to remotely configure services to speedily provide communications solutions such as bandwidth provisioning for new applications.

The selection of processes and tools to support an EPU's network management functions will depend on the organizational structure of the power company, particularly with regard to the separation or amalgamation of operational and corporate services, and also with regard to the configuration adopted for the provision of their telecommunications requirements, i.e., in-house or externally procured.

Power utilities with in-house provided telecommunications tend to operate multiple network management tools to support their multiple technologies and protocols. This presents many challenges in terms of maintaining a skill set for the operation and support of legacy systems and technologies, while continuing to develop the ability of network operators to ensure they can manage the technology evolution, specifically dealing with fault resolution and support within more complex network design. "Technology-agnostic network supervision is needed prior to assigning technology specialist interventions" [24].

2.3 Cyber Security for EPUs

Associated with the progressive digitalization of the grid control infrastructures, and to the technological convergence of information and communication technologies from the IT and OT worlds characterizing the smart grid control, cyber security has progressively become of paramount importance for EPUs.

The state of the art of cyber security within electrical utilities covers regulatory frameworks, reference standards, cyber security challenges, risk assessment methodologies, threat modeling, industrial control systems kill chains and best practices [25].

2.3.1 Cyber Security Regulations

Governments and public institutions in charge of safeguarding the countries, essential service providers, particularly operators of large electricity and gas infrastructures, equipment suppliers, but also energy producers and consumers, must support an adequate level of cyber security protecting sensitive data, control capabilities and other essential services from possible cyber risks.

In North America, the North American Electric Reliability Corporation (NERC) oversees eight regional reliability entities and encompasses all of the interconnected power systems of the contiguous USA, Canada and a portion of Baja California in Mexico. In 2007, NERC first developed critical infrastructure protection (CIP) security requirements [26] that are mandatory for bulk electric systems (BES), typically encompassing transmission systems, bulk power generation and larger distribution system assets (e.g., automated shedding of loads >300 MW). These NERC security requirements, which include significant monetary penalties if not met, have evolved over time to better meet the increasing complex security needs, but still do not yet cover all cyber security necessities of the smart grids. For instance, although distributed energy resources (DER) are increasingly connected to the grids and will provide significant energy and ancillary services in aggregate, they do not as yet fall under NERC security requirements (although often larger DER aggregations attempt to meet the NERC requirements in anticipation of future NERC CIP expansion). In addition, the NERC CIPs do not directly address communication network security across different facility electronic perimeters.

In Europe, the Directive on Network and Information Security (NIS Directive (EU) 2016/1148 [27]) has been adopted in July 2016 by the European Parliament to address the cyber security of essential service providers. The NIS Directive is the first set of IT security rules unique to the European Union, with a view to achieving an elevated level of security of systems, networks and information common to all European member states. Capacity, cooperation between states, risk management and incident reporting are the key areas of recommended activities. Among the NIS objectives is the setting up of National Computer Security Incident Response Teams (CSIRTs) for incident monitoring and a European cooperation working group coordinated by the European Network and Information Security Agency (ENISA) for cyber security and information sharing. The NIS Directive mandates the operators of essential services to adopt appropriate security measures and to notify the appropriate national authorities of serious security incidents, including the number of users involved, the incident duration and geographical spread. The security measures considered include risk prevention, security maturity of the systems, networks and information and the ability to manage incidents.

From the data privacy side, the European reference is the General Data Protection Regulation (GDPR) [28]. About privacy of sensitive data, one topic of interest is the protection of video data collected by surveillance cameras. These cameras are commonly used to monitor activities within closed security boundaries of EPU facilities. By some definitions, the video data is considered personal sensitive data and must be protected; “personal data means any information relating to an identified or identifiable individual (data subject).” Furthermore, there are restrictions on processing the video data as well as restrictions on information systems used. It is becoming clear that such restrictions will have an impact on EPU security policies, procedures and organizational directives, including telecom systems. The regulations of the European Commission have clearly stated the restrictions on information and communication technology processing and data storage.

In view of the preparation of a Network Code on cyber security, the Expert Group 2 of the European Smart Grid Task Force has recently issued a report [29] with a lot of recommendations to the European Commission for its implementation, including an overview of reference security standards and comprehensive cyber security certification schemes suitable for the electricity sub-sector.

2.3.2 Reference Cyber Security Standards

To address the recommendations from the EPU-related cyber security regulations, two different types of standards are needed for the EPUs. The overall cyber security governance of a given enterprise should be managed by a mature Information Security Management System [30] such as the one specified by the standard ISO/IEC 27001, ISO/IEC 27002 and ISO/IEC 27019 [31], and supported by function-oriented guidelines provided by NISTIR 7628 [32] and process, system and component level security requirements specified by IEC 62443 standard series. Although in different states of completion and addressing both procedural/organizational and functional requirements, several parts of the IEC 62443 framework are intended to serve as basis for certification or assessment activities. To provide an overall approach for certified security in industrial automation and control systems, the IEC 62443-4-1 [33] targets the secure development process and appropriate security features for individual components of an automation system, while IEC 62443-2-4 [34] and IEC 62443-3-3 [35] focus on a securely designed system (based on the components covered by the IEC 62443-4-1) and secure processes and procedures of solution suppliers for such system, or maintenance/upgrade service providers, and IEC 62443-2-1 [36] addresses security aspects in secure operation, strongly based on the security controls defined by ISO/IEC 27019.

The implementation of security controls specified by the EPU information security management systems is supported by a set of standard security solutions. An overview of most EPU-related security standards is presented in [37]. The rest of this section provides a synthesis of the security solutions specified by the IEC 62351 series.

The International Electrotechnical Commission (IEC) Technical Committee (TC) 57 Working Group (WG) 15 has developed the IEC 62351 set of standards [38] to provide security for power system data communications protocols, such as IEC 60870-6, IEC 61850, IEC 60870-5 and IEEE 1815 (DNP3). The development of the IEC 62351 standards has provided the ability to implement more secure versions of these communications protocols in supervisory control and data acquisition (SCADA) systems. Essentially, the IEC 62351 standards provide well-founded specifications of how to protect the ICT assets from possible ongoing threats at different layers.

Figure 11 depicts the relationships between the IEC TC57 communication standards and IEC 62351 parts. IEC 62351 parts have reached different maturity levels.

Security for profiles including TCP/IP (IEC 62351-3) and MMS (IEC 62351-4) network and system management (IEC 62351-7), key management (IEC 62351-9) and security for XML documents (IEC 62351-11) are already available as international standards. Parts 5 and 6 address the security of other communication protocols for smart energy systems are currently published as technical specifications and will be available as international standards in the next future. Parts 90-x and Parts 10, 12 and 13 are mainly technical reports of ongoing work providing guidelines, while and parts 100-x are related to testing the conformance with Parts 3, 4, 5 and 6.

Various mitigation measures are specified for the cyber security of these protocols concerned, including authentication, encryption and role-based access control. For example, in terms of IEC 61850 (MMS, GOOSE and SV), IEC 62351-4 and IEC 62351-6 specify those procedures, protocol extensions, and algorithms for securing

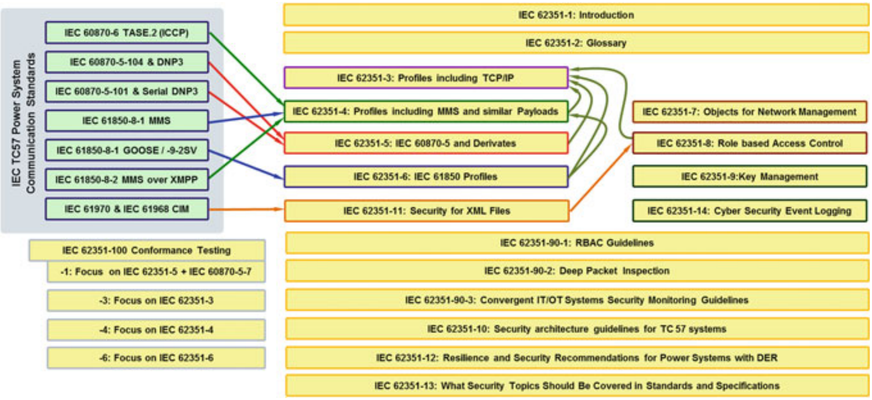


Fig. 11 IEC 62351 standard series [IEC TC 57 WG 15]

MMS, GOOSE and SV-based applications. For TCP/IP-based protocol stacks, we can utilize TCP/IP transport layer security (TLS) encryption as specified in IEC 62351-3 for securing the transmission layer and to protect against eavesdropping. This part specifies the features of the required implementation of TLS, defined in RFC 5246. Both Part 3 and Part 4 require the use of encryption keys (symmetrical and asymmetrical) and role-based access management. Therefore, Part 8 (role-based access control) and Part 9 (key management) are referenced standards as well. In practice, secure enhanced manufacturing message specification (MMS) associate service is implemented in the layer of association control service element (ACSE) using authentication with digital certificates for requests and responses, which can be used to protect against man-in-the-middle attacks. For application layers based on generic object-oriented substation event (GOOSE) and sampled value (SV), reserved fields are used to extend the normal GOOSE and SV protocol data units (PDUs) using digital signature for protecting against replay attacks.

Part 7 provides the technical base for the implementation of monitoring objects and in the future Part 7 will be complemented by Part 14 on security event logging specification, which is currently under development. Part 10 is a technical report providing a system level view for the deployment of IEC 62351 parts, and Part 12 is a technical report that specifies the security requirements and resilience engineering techniques for energy systems with DER.

Although the IEC 62351 standards define a framework for the provision of cyber security for the communications protocols, major manufacturers have not generally implemented such cyber security in their intelligent electronic devices (IEDs). In terms of IEDs and automation systems already in operation, it is difficult to apply these IEC 62351 solutions because of practical implementation restrictions such as the incapacity to take industry control systems offline for a long time to upgrade them, or the inability to update existing equipment because of limited functionality. Legacy systems without the IEC 62351 standards are likely to be in place for many years without updating. With vendors slow to respond, it has become essential that utilities are able to fill this security gap to enable them to detect and mitigate emerging threats.

2.3.3 Cyber Risk Assessment

Cyber security regulation and information security standards emphasize the importance of establishing a risk assessment process within the organization that allows to govern the management and evolution of the threat landscape. Figure 12 illustrates the general risk management process, which includes risk assessment, risk treatment and continuous feedback with reassessments of the security requirements.

According to the survey conducted by Working Group D2.22 [30], it resulted that the majority of utilities use qualitative methods for conducting business and impact assessment in their organization, such as the method developed by the Information Security Working Group of the CEN/CELEC/ETSI Smart Grid Coordination Group [37].

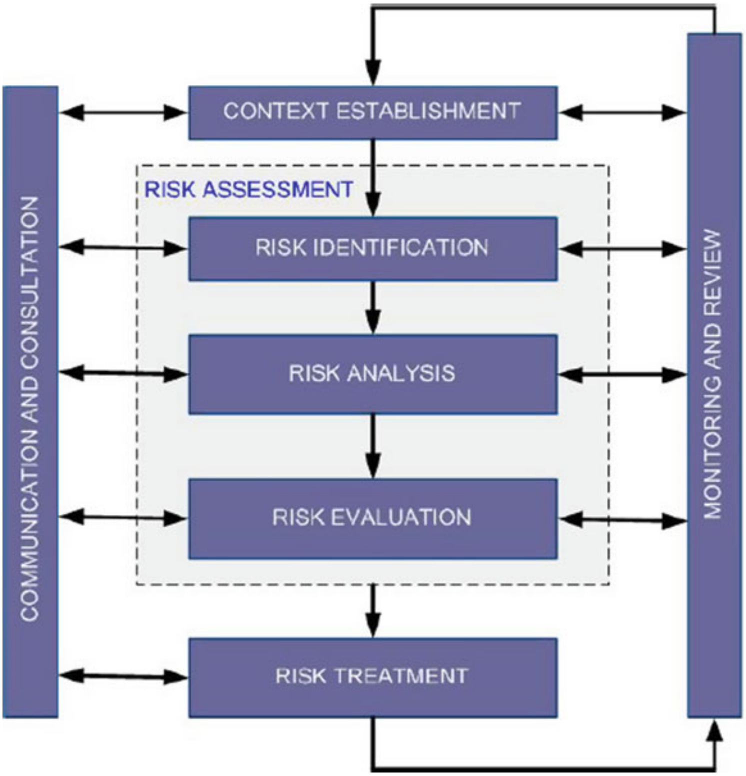


Fig. 12 Risk management process [ISO/IEC 27005:2018]

A critical phase within the risk evaluation process is the capability to characterize and model the most relevant cyber threats. Working Group D2.31 investigated about the tools available for analyzing the attack structure and their success probabilities [39].

As of today, most national level cyber security strategies uses the NIST Framework [40] as a reference framework for cyber resilience strategies of cyber-physical systems.

2.3.4 Cyber Security Best Practices

In addition to the cyber security policies, techniques and mechanisms specified by the mentioned security standards, there are also guidelines and technical brochures addressing the most mature practices in the cyber security operation of EPUs such as those about remote services in [41].

However, a rigid application of cyber security standards could cause some impact in the EPU operational procedures and daily routine, especially concerning the maintenance duties. Manage strong passwords, update patches, control network perimeters, avoid remote access, restrict the use of software, etc., usually are not part of the routine of usual maintenance staff. The dialogue between the security and maintenance staff must be encouraged in order to find matching solutions. At this aim, a good approach is to adopt maintenance-oriented strategies that understand and respect the reality of the operational environment such as the one reported in [42].

In order to identify the vulnerabilities and improve the security level of industrial control systems, some utilities in China have carried out cyber security testing for SCADA in substations, including HMIs, communication protocol gateways, relay protection devices, measure and control equipment and phase measure units from the mainstream manufacturers in China. The cyber security test items contain operating system testing, database testing, communication protocol testing, security configuration testing, port service testing, abnormal access behavior testing and vulnerability penetration testing. According to the cyber security testing results, numerous cyber vulnerabilities have been detected, such as weak password, buffer overflow, remote command execution, denial of service, information disclosure, unauthorized access, protocol stack vulnerabilities and lack of security audits. The manufacturers have eliminated the vulnerabilities that were found through of several rounds of cyber security testing, and a vulnerabilities library has been established tailored for the electric industry control systems. Before the substations are put into operation, cyber security testing of secondary equipment will be carried out to mitigate the potential cyber threats. Based on the practical testing, a cyber security test technical specification has been developed to specify security testing of the utilities, as well as to guide the security design and development of products for the manufacturers.

2.3.5 Cyber Security and Resilience

The definition of the term “resilience” depends of the field of interest. Focusing on EPUs, it could be considered that a resilient infrastructure is that one capable to be recovered after the occurrence of an adverse situation. CIGRE Working Group C4.47 introduced a definition of power system resilience that is achieved through measures to be taken before, during and after extreme events [43]. Transposed to the cyber world, we have to consider security protections to be taken before the occurrence of cyber threats and security measures that apply during ongoing attacks and after that a targeted attack succeeded in provoking a serious cyber incident to the EPU. Working Group C4.47 did an international survey that put cyber security as one of top three extreme threats that EPUs are focusing efforts on. This means, in simple terms, that to boost the EPU resilience is mandatory to increase the capabilities to face cyber attacks. This puts the cyber security issues in the strategic level of any EPU.

The strong connection between cyber security and resilience is confirmed by the North American Electric Reliability Corporation (NERC) when they state that resilience is a component of reliability in relation to an event [44] and once cyber security is a key issue to reliability as can be seen in the reliability standard CIP-008-5 (Cyber Security—Incident Reporting and Response Planning), for example.

The IEC System Committee Smart Energy, Working Group 3 Task Force Cyber Security considers resilience as the overall strategy for ensuring business continuity [45].

3 New Technologies and Requirements

3.1 New Technologies in ICT for EPUs

3.1.1 Blockchain

At its core, blockchain is a technology that permanently records transactions in a way that cannot be later erased but can only be sequentially updated, in essence keeping a never-ending historic trail [46]. It is a decentralized, distributed database that is used to maintain a continuously growing list of records, called blocks [47].

The definition in the paragraph above summarizes the key characteristics of a blockchain: *decentralization* (no intermediaries are needed to validate transactions), *persistency* (transactions cannot be altered or deleted once they become part of a blockchain), *anonymity* (users interact in the network without revealing their identities) and *auditability* (any transaction can be tracked).

Reference [48] makes a technical description of the blockchain architecture. A block consists of the block *header* and the block *body*, as can be seen in Fig. 13.

The block header includes [48]:

- **Block version**: indicates which set of block validation rules to follow.
- **Merkle tree root hash**: the hash value of all the transactions in the block.
- **Timestamp**: current time as seconds in universal time since January 1, 1970.
- **nBits**: target threshold of a valid block hash.
- **Nonce**: a 4-byte field, which usually starts with 0 and increases for every hash calculation.
- **Parent block hash**: a 256-bit hash value that points to the previous block.

The block body is composed of a transaction counter and transactions. The maximum number of transactions depends on the block size and the size of each transaction.

As an example of how a blockchain is created, transactions of cryptocurrencies will be used, since they are the most well-known application of the technology. Suppose user A sends money to user B. That transaction from A creates a new block that flows in a peer-to-peer network (i.e., one without a centralized server, with data traffic made directly between the nodes in the network). The nodes validate that transaction, time stamping it. Once user B receives the money transferred from A,

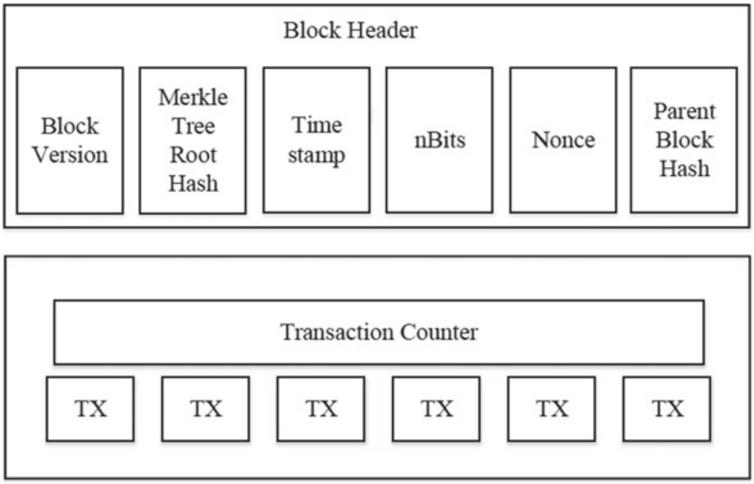


Fig. 13 Block structure [48]

another block is created and time stamped to record that transaction, generating a hash that points to the first block, and that second block is added to the previous one. As long as more transactions are completed between users in the network, more blocks are added to the chain, tracing the whole history of transactions that started with the original block, now named the *parent* block. The whole blockchain is stored in each node in the network, making it virtually impossible to tamper with the data, since it would be necessary to invade all computers to achieve that goal. Figure 14 illustrates the formation of a blockchain.

The security of the blockchain technology relies on the majority principle. That is, the information is disseminated in many servers and that provides a very high degree of security because the destruction of that information is considered quite impossible. The logical blocks, formed by a certain number of transactions, are stored in multiple servers called trusted servers.

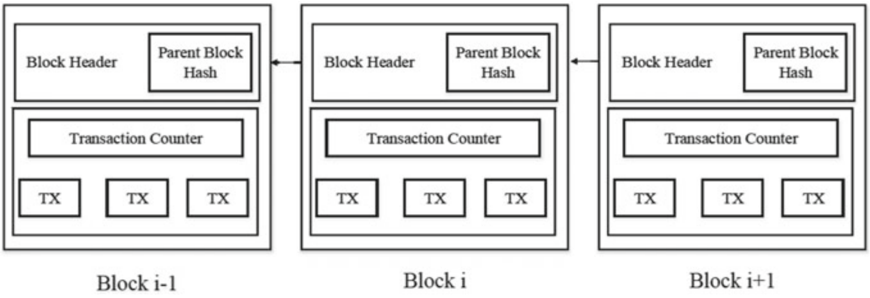


Fig. 14 Blockchain example [48]

Basically, there are two types of blockchain networks:

- Public or permission-less networks in which any blockchain user may attempt to publish transactions;
- Permissioned networks which are considered more secure and more suitable for EPUs. The behavior is the same and the only and important difference is that to become a member of the network the candidate should obtain a permission given by the system administrator or, more reliable, by the owner of the blockchain network.

A key aspect of the blockchain technology is the task of accept or reject to publish the transactions proposed by an user. When some users collide trying to publish transactions, the network applies consensus rules. Those rules establish priorities between users, one of the most common is according the age of the user. When a user joints the network, receives only the last trusted block, called genesis block, and starts to form the chain. When two or more users collide, it is easy to give priority in function of the respective age. The concatenation of the trusted blocks grants a high level of security because only the last block stills alive storing transactions. The consolidated part of the chain cannot be modified, and all the blockchain members have a common agreement of the chain contents. To add a new block, all the network members must come to agreement over the time; however, some temporary disagreement is allowed owing to the possible delays in the communication.

In permission-less networks, the consensus model must work even in the presence of possibly malicious which attempt to disrupt or take over the blockchain. The problem will take another dimension if the malicious users are the majority of the members.

Blockchain Potential Use Cases for EPUs

A peer-to-peer renewable energy exchange model has been tested with blockchain in 2016, with ten customers in a microgrid in the USA [49]. Prosumers with photovoltaic generation on their roofs can directly sell their surplus energy to consumers in their community, and the buying and selling transactions are recorded in a blockchain to which their meters are a part of, with no need for a third-party energy trader. A token is sent with the blocks, identifying the type of generation source and its respective price at the time. A variation of this model is being tested in Europe [50]. A network of home storage systems form a virtual energy pool. The blockchain solution records the transfer of energy between the grid and the flexible devices, so that a TSO always has visibility into the pool of available energy and storage capacity. The TSO can then use the devices to absorb or discharge excess power in a matter of seconds when and where required, integrating 24 MW of flexibility and helping reduce transmission bottlenecks in the grid [50, 51].

Another potential use case is controlling the transfer of energy between electric vehicles (a mobile load) and charging stations connected to a blockchain. The service allows users to charge their vehicles and make micropayments that are recorded in a blockchain [52].

3.1.2 Industrial Internet of Things (IIoT) and Digital Twins

Every day, new devices are being connected to the Internet or to a private, operational network. Advanced sensors collect data from physical assets. This data is sent through a communication network to be stored, processed and analyzed in the local premises or in the cloud. Data analytics provide insights to decision makers that will change the way their business and processes are structured. These are the enabling technologies of the industrial Internet of things (IIoT). Figure 15 illustrates a high-level view of IIoT and its elements.

The IIoT has made possible the creation of digital twins (DTs), which can be defined as a virtual representation of a physical object. Another definition for a digital twin is that it is an evolving digital profile of the historical and current behavior of a physical object or process that helps optimize business performance [53]. The concept is based on modeling assets with all their geometrical data, kinematic functionality and logical behavior using digital tools [54].

Digital models have been used by utilities in a long time. However, in this new concept, not only internal data from equipment is measured by sensors but also environmental or external ones (like the weather conditions) in order to study their impacts on the real twin (i.e., the physical asset). The digital twin is dynamic, evolving as more data is available to it. It may automatically intervene in its physical counterpart if the measured results do not correspond to the expected behavior of the system. Data processing and storage has become cheaper, and real-time simulations can be run to predict the behavior of real assets and how their components may wear out over time which, in turn, may give EPUs the opportunity to take actions that will prevent failures more effectively.

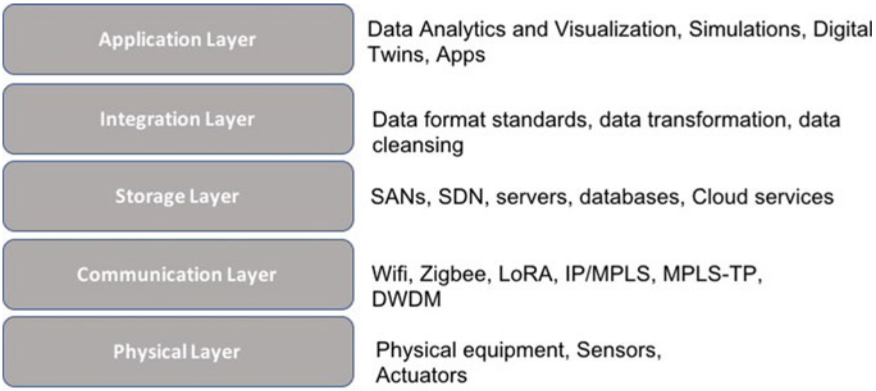


Fig. 15 High-level view of IIoT

One of the great benefits of this new technology is that the data analysis can be used as feedback for the design process, improving the overall life cycle of equipment. DTs can be generated at the component level, and they can be combined to represent a complete asset or system. Virtual commissioning will certainly be one of its applications, avoiding logistics costs that cannot be recovered in case of an unexpected behavior during this phase.

To ensure the information exchange between all systems that integrate with a digital twin, a canonical data model (CDM) is really important. A CDM is a common, enterprise-standard data structure [53]. In the electrical power sector, IEC 61850 and IEC Common Information Model (CIM) are examples of data models that allow this kind of interoperability between devices and systems from different vendors. Reference [8] provides a brief description of these standards. This technical or operational data can be integrated with enterprise IT systems to enrich the model and provide a better situational awareness to operators, maintenance field technicians, engineers and executives.

According to [55], a future digital twin may contain a simulation model, but also a 3D model, hundreds of properties, historical data, handbooks, installation guidelines, proprietary function blocks, interlockings, state models, alarm and event definitions, etc. It will become a powerful electronic data object with interfaces: it will hold or reference all useful data, some data will be semantically standardized (e.g., properties, geometry, topology), other data will be of a proprietary nature. Figure 16 represents the types of data that can be stored in a digital twin.

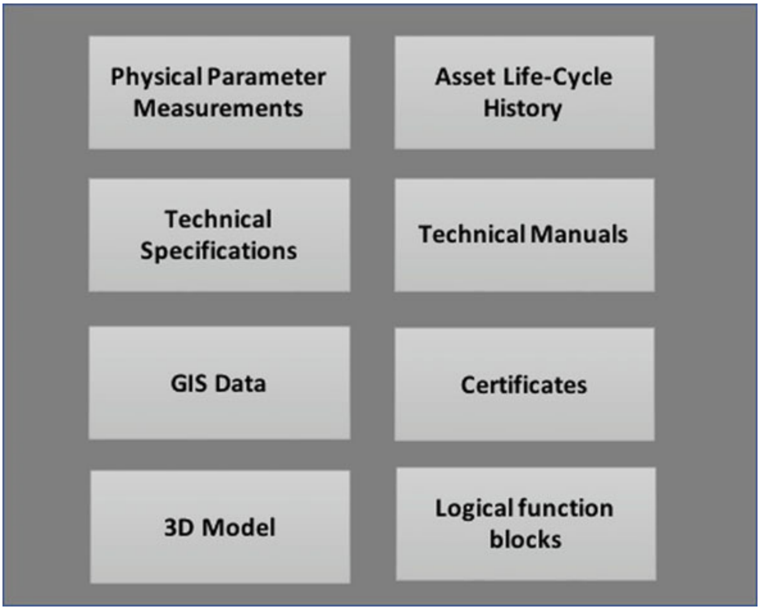


Fig. 16 Representation of a digital twin and types of data stored in it

Practical and Potential Use Cases of Digital Twins in EPUs

Some current practical applications are [56, 57]:

- Startup optimization: The continuous analysis from the state of the physical asset and simulations lead to better strategies of equipment startups.
- Asset lifecycle optimization: Predictive models permit to identify the optimal point of maintenance and replacement of an asset, extending its technical useful life, thus granting revenue to an EPU for longer periods. The creation of "What if" scenarios automates planning processes in all levels within the companies, assisting in the choice of new technologies, optimization of resources during preventive and corrective maintenances and in investment decisions.
- Single source of truth: The digital twin integrates data, and any kind of information is stored only once. All other locations of data are updated whenever the original registry suffers any change) for the enterprise, preventing inconsistencies regarding assets in EPUs. Different user profiles can have access to different levels of information details according to their needs.

Since digital twins may store sensitive data of the assets and components they are connected to, the traceability, accuracy and security of this information must be guaranteed. In [58] it is suggested that blockchain technology can be used for that purpose. By adding sensors that are part of a blockchain consortium network (for instance, between vendors and EPUs), all involved stakeholders would be certain that the historical information on the assets can be trusted, from the design stage to disposal.

3.2 New Telecom Technologies

3.2.1 Drivers of New Communications Solutions

The penetration of intermittent and distributed generation has influenced all facets of power system planning and operation. The traditional system with predictable flows and loads based on a large number of synchronous generators with predictable outputs will be replaced by a system with unplanned flows [59].

Increased penetration of renewable power systems across the world will, over the next decade, present both opportunities and risks for power management. The risks arise from the short-term unpredictability of wind and solar power which could lead to grid instability and even blackouts as dependency increases. Capability to detect frequency instability in the grid and responding on a time scale consistent with other methods of stabilizing frequency will be critical.

The power system will become much more dynamic and this will require additional analysis, both in real time and in the operational planning phase. Observability and controllability of the grid becomes more critical as the level of generation penetration on the system increases.

As a result, the level of communications to all parties on the system will need to be of extremely high quality at all times [59]. In addition, the traditional substation will need to develop, becoming an intelligent substation with the ability to process the various types of data that is generated [60].

On the other hand, applications such as automatic meter reading and acquisition of data beyond SCADA, which are more latency tolerant, could use less robust communications technologies such as unlicensed wireless mesh, broadband wireless, licensed wireless and satellite, however, the penetration of such applications across the power grid will be greater. Future trends and applications in generation, transmission and distribution systems present different class of requirements and challenges.

3.2.2 New Requirements and Technical Challenges

These drivers of change present challenges to the telecoms network operator in the provision of suitable solutions for the EPU of the future, and the following are a selection of issues to be addressed and overcome by such telecommunications solutions deployed now and into the future.

Connectivity of Larger Quantities of Network Applications in a Wider Geographically Dispersed and Remote Regions

The growing number of devices for the control and management of assets, and for the monitoring measurements and the gathering of information from across the distribution grid is driving the requirement to build suitable communications links beyond the transmission and distribution network substations. There is a growing requirement to install new devices deeper into the electricity networks, beyond the traditional substation down to medium and low voltage networks. As it is not feasible or cost effective to install optical fiber or fixed microwave radio links to provide this communications, other narrowband wireless solutions need to be explored.

Accurate Time Distribution

In wired communications networks, accurate time distribution is required for the effective operation of a number of applications, such as high voltage protection schemes, and this is achieved using the propagation and distribution of GPS signals from fixed GPS clocks across the networks using protocols such as IEEE 1588 [61].

As network applications become more dispersed and expand deeper into the electricity grid, where fixed wired WAN links are not feasible, such method of distributing time is not possible. The requirement for accurate time distribution is a growing requirement for many devices, particularly for applications such as phasor measurement units that are measuring voltage and current in the grid in order to detect faults on the grid [61]. Alternative methods of distributing accurate time to these applications are a growing requirement in the management of the grid.

Decentralized and Distributed Control

Whether connected to the grid, or in islanding mode, the introduction of microgrids demands changes to the control of such systems, moving some of the control functions from a centralized controller location, toward a decentralized approach where decision-making algorithms and automatic control functions will reside in transmission stations, even at distribution stations, with the traditional central control location providing a secondary control function to these parts of the grid. This changes the parameters that the communications channels need to meet in order to provide suitable communications. Higher bandwidth, lower latency and high security need to be designed into the communications links for such applications, where previously less robust communications technologies were suitable.

Convergence of IT and OT Environments

There are more types of users extracting data from the various distributed devices across the power grid. The data is being used for multiple purposes, including grid control, grid asset monitoring, fault recording, and as a result the destination of the data coming from the grid is changing. Many of the users now sit within the corporate environment or IT environment and are tasked with processing the data, whereas traditionally the data was normally only used by operators of the network residing in the operational or OT environment and their main function was control and operation of the electrical equipment. In addition, connecting to grid edge devices relies increasingly on Internet of things (IoT) technologies, resulting in further integration and interworking between the operational infrastructures with the IT environment. As a result, the convergence of the IT and OT domains is becoming a real requirement. Figure 17 provides a representation of what the future operating environment will look like. While this brings many challenges, particularly in the area of cyber security, it also presents opportunity for convergence of equipment and systems to create efficiencies.

3.2.3 Future Communications Solutions to Meet the New Requirements

5G

The 5th generation of cellular mobile will provide many improvements in the area of mobile radio networks. Bandwidth will increase, latency will reduce and it is expected that the system will be highly integrative and backward compatible with legacy systems such as LTE.

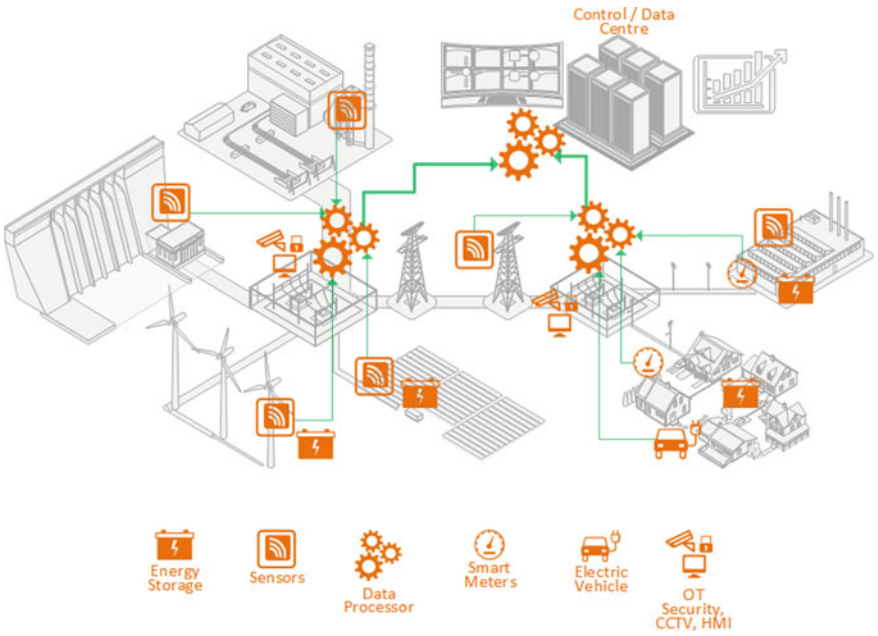


Fig. 17 Data processing and flow requirements of IT and OT in the grid, showing the variety of data sources being distributed throughout the power network [60]

5G is expected to support the future smart grid communications requirements due to its low latency attributes, the ability to connect a significant number of devices and its capability to support much larger data rates than the previous cellular technologies.

The requirement for separation of traffic types across the same telecommunications solutions will be possible through 5G's technological advancement, called network slicing. This will provide the telecoms operator the opportunity to create multiple logical dedicated networks on a common set of infrastructure, where the communications for each application type with varying requirements can be delivered effectively as a service. In addition, network slicing provides more efficient scalability options, to allow the service grow or reduce, as requirements change.

Software Defined Networking (SDN) and Network Function Virtualization

The current communications architecture for connectivity across the power grid involves a range of wide area network technologies as discussed in the state of the art section, with the communications within substations being achieved through local area networks using Ethernet switches and point to point connections. This architecture, while delivering the current requirements, is not suitable for the flexibility that is being demanded by the smart grid. "The smart grid will require "comprehensive overlay communication network and flexible software platforms that can process data from a variety of sources” [62].

Virtualization is well understood for ICT systems, such as servers, with room for development in the communications area. Software defined networking and network function virtualization offer virtualization in the networking environment.

SDN separates the control layer from the data layer and provides flexible communications through the provision of a centralized controller. This centralized controller has the ability to program communication devices directly and quickly, providing an efficient method of designing, reconfiguring and managing the network.

NFV uses the concepts of the ICT virtualization and implements these functions on network infrastructure to create communication services. Instead of having a number of nodes to carry out a function, these nodes can be deployed as software on a server, which can be located in a central location or at the edge of the network, such as a substation.

Both NFV and SDN are technologies that will complement each other, but can equally exist independently from the other.

Low-Power WAN

Low-power wide area networks (LPWAN) are wireless telecommunications networks that are specifically intended for wide reach communications for the connectivity of large volumes of low bandwidth devices that are typically battery-operated. There are a range of LPWAN technologies available, operating in the licensed and un-licensed spectrum bands, providing mostly bi-directional communications, with some only operating in very narrow band unidirectional mode. Such technologies are becoming more widespread in overcoming the challenge to connect the ever growing number of devices across the grid. While the geographical reach is achieved by these low-power wireless technologies, they are typically used to connect the applications which are of lower criticality to the operation of the grid and are more often used for asset management and asset condition monitoring tasks [63].

Optical Fiber on MV/LV Networks

While a costly option for most utilities, the deployment of fiber on the MV and LV network is being explored, particularly if the opportunity exists to sell fiber pairs or managed services to commercial broadband suppliers. Fiber technologies such as ADSS to attached fiber cable to the overhead networks, or standard underground optical cable solutions, are providing optical connectivity to control devices along the MV and LV electrical networks. In addition, such fiber can be used to act as a backhaul for wireless gateways to extend the geographical reach deeper into the network. Such wireless networks can be then used to provide connectivity for asset management and asset conditioning purposes, such as pole tilt sensors, or asset temperature monitoring.

3.3 Evolution of Cyber Security Within the EPUs

The value of cyber security is increasing every day and, with the progressive role that information technologies are playing in the global economy, its weight will increase more and more in the following years. In the digitalization era, the increasing dependence of power systems on large computer networks is an ongoing process that will accelerate along with the smart grid development. It is the increasing dependence on these computer networks, the new information platforms and communication technologies and the associated cyber assets that will make the power systems more and more vulnerable to cyber attacks, since power systems as providers of an essential service to the critical infrastructures and to the whole society, are a “first class target” for attackers. From the market perspective, the new market models for exploiting available generation and demand flexibilities require addressing the security of control architectures that interconnect network operators with those of distributed generation aggregators and active users from industrial, commercial, residential and domestic sectors.

3.3.1 Cyber Security Challenges/ICS Kill Chains and Lesson Learned

In [25] the 2010 Stuxnet real-world attack case was used to illustrate how malware can successfully propagate and gain access to process control networks. With its sophisticated and yet seemingly random access methodology, Stuxnet drew attention to the anatomy of attacks as time-extended processes, composed of a combination of preparation and development steps.

At the end of 2015, another attack case targeting the Ukrainian power distribution grids caused a power service outage for several hours to hundreds of thousands of citizens in the region [64].

The new challenge for defenders is to rapidly discover anomalies in networks and systems, to shorten the time needed to become aware of attackers’ malware, to determine what this malware is or could be doing in the given operational environment, and to fine-tune and execute adequate countermeasures. Industrial control system defenders, in addition, must consider how they could hunt for multiple copies of such malware tools on different control system hosts and assess the threat of pre-set scheduled attacks on multiple installations.

From the analysis of ICT architectures deployed by EPUs, it is clear that modern power systems are facing increasing challenges and risks from cyber vulnerabilities and malicious attacks. In [65] the impacts of new attacks to SCADA systems in smart substations were analyzed and a number of cyber attacks were simulated and investigated.

EPU-related cyber attacks such as Stuxnet and Ukraine motivate the deployment of network intrusion detection systems (IDS) to identify abnormal behaviors launched by an attacker who has already attained a foothold in SCADA because of an infected HMI, engineering laptop, or a similar initial vector. Attackers are likely to scan the network, enumerate hosts and gather intelligence about IEDs using the reconnaissance attack on the SCADA system. If they have not gained enough intelligence from other sources they could well attempt fuzzing activity on the SCADA network to establish responses from devices of interest. If cyber security preventive procedures have failed and this cyber attack has actually occurred, it is critical that deep packet inspection be used to react to the above-mentioned intrusion activities in the highly reliable and time critical SCADA networks.

3.3.2 Intrusion Detection Systems for Future Control Centers and Substations

The control center receives the data acquired at various substations through remote terminal units (RTUs) or gateways of the supervisory control and data acquisition (SCADA) systems. Vulnerabilities of SCADA systems with respect to cyber intrusions have been evaluated with different attack experiments [66]. Indeed, testbed-based studies have been conducted to demonstrate how breaker operation commands can be falsified to open-circuit breakers in substations [67]. In 2015, cyber intrusions into SCADA systems caused major power outages in Ukraine [68]. Another scenario of cyber intrusions is to inject false measurements at substations and transmit the data from substations to the control center through the SCADA system [67]. These falsified measurements can mislead system operators to take actions that degrade the operating conditions. The cyber intrusions at substations or control centers can lead to severe cascading events in a power system. Therefore, intrusion detection systems (IDSs) are critical tools for secure monitoring and control of the future transmission, distribution and automation systems.

IDSs for Future Control Centers

Analog and status measurements from substations are received at the control center. The network environment illustrated in Fig. 18 indicates that the control center network is connected to other networks and substations. Remote control commands issued by system operators at the control center are delivered to the substations via information and communications technology. The control center IDS should be deployed to inspect the data and commands to identify falsified contents. Falsified measurements are part of the raw data that can mislead system operators and energy management system applications, such as state estimation and security assessment. Falsified control commands are a threat to power system security.

The detection algorithm is designed to correlate the detected anomaly events from both cyber and physical systems to identify cyber intrusions. To achieve this goal, detectable anomaly events need to be defined based on events, security logs, and behaviors at control centers. Then, cyberattack patterns (e.g., geographic relation and criticality of targets) can be established based on the defined abnormal behaviors. For

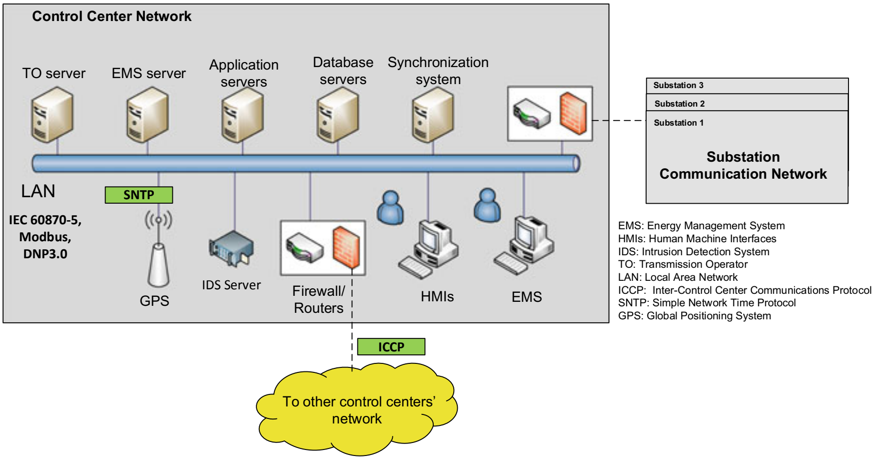


Fig. 18 IDS in a control center environment

instance, a false measurement attack may observe extra packets into a control center's communication network. The packet rate increases during an attack. Then, the measurement may have abnormal readings since two different sets of measurements (from attackers and substations) are recorded in an EMS server. According to the temporal relation of anomaly events, an attack table can be developed to describe the steps to launch cyberattacks in a control center environment. By comparing detected anomaly events and the attack table, the IDS determines the similarity of the two patterns. If the level of similarity is high, anomalies are reported. Temporal failure propagation graph (TFPG) [68] and temporal causal diagram (TCD) [69] are useful techniques to model the cause-effect relations for cyberattacks. To develop a comprehensive view to identify cyber intrusions, more types of cyberattack patterns need to be incorporated.

IDSs for Future Substations

An IDS for IEC 61850-based substations is an effective tool to detect both external malicious attacks and internal unintended misuse. Yang et al. [70] has proposed and developed a hybrid IDS that focuses on the specific physical environment and application data of the smart substation. This detection mechanism blends physical knowledge and behavioral logic of modern power systems integrating with emerging IT cyber security methods. The proposed new IDS provides a significant advancement in protecting modern substations against the growing threats.

Modern substation automation is dependent on intelligent electronic devices (IEDs) that are based on multicast messages, e.g., sampled measured value (SMV) and Generic Object-Oriented Substation Event (GOOSE). Due to the fast data transmission between the station level and bay level of the substation network, the standard IEC 61850-9-2 introduces the process bus interface for digital data exchange. Multicast communication is used in the process bus to improve the efficiency for GOOSE and SMV communications between sensors, actuators, protection and IED devices. However, the non-encrypted Ethernet network also causes vulnerabilities. If an intruder manages to capture the SMV packets and modify the measurements before they are transmitted to the station bus, then the MMS packets can be falsified accordingly. These malicious packets can pass the security authentication and eventually arrive at the control center.

Due to the unique features of IEDs, i.e., embedded systems with limited computational resources, the attacks targeting the GOOSE network are different from those in the TCP/IP based network. Thus, conventional IDSs may be inefficient against most malicious intrusions at the substations.

The IDS utilizes either a network- or a host-based approach to identify abnormal activities in the substations. For the network-based methods, the IDS analyzes the data network to detect abnormal behaviors. A class of machine learning techniques can be used to classify the attacks. The network-based method [71] introduces a statistical classifier to detect the anomalies based on data collected from the network. For the host-based methods, the IDS monitors the files logs, user access logs and security event logs in the substation network to correlate the events. The work of [72] proposes a detection system for coordinated cyberattacks at multiple substations. The IDS identifies the relations of abnormal activities based on the security logs.

The IDS for the substation should be capable of monitoring the data stream between merging units and IEDs. The IDS inspects the data stream (SV and GOOSE) to detect anomalies based on the counter number or destination MAC address [73]. According to the different process bus communication architectures in IEC 61850-9-2, the location of IEDs in the substation is critical for detection of anomalies.

3.3.3 Cyber Incident Management

IDS tools provide useful source of information for wider security analysis environments called SIEM. Ongoing research activities are targeting the development of EPU-specific SIEM tools which are able to analyze and correlate IT/OT data sources [74].

New technologies for future security operation centers are related to security monitoring, incident detection and response, data analytics and machine learning. The Technical Brochure 698 [75] provides a framework to manage the response to a cyber-initiated threat to EPU critical infrastructures, while the Technical Brochure of Working Group D2.46 [76] introduces concepts and architectures of integrated and federated security operation centers.

3.3.4 Cyber Security in the New ICT Platforms and Telecommunication Technologies

The new ICT platforms and telecommunication technologies presented in the previous sections provide several challenges to the cyber security of future EPU infrastructures.

Industrial IoT and augmented reality devices demand adequate level of security; virtual platforms, services and functions have to be security proof; connectivity through 5G and low-power wide area networks has to integrate mostly mature security technologies.

3.3.5 Cyber Security and System Resilience

The advance of new digital threats will push increasingly the development of new tools and models to keep the reliability and the resilience in secure levels. Research and development efforts are needed for developing attack modeling tools that support the simulation of resilience scenarios in cyber-power systems, including cyber security also during power system restoration.

A key aspect and important topic to the near future is the necessity to the IT/OT people start to think in a strategic and business level and not only on the technical and operational level.

3.3.6 Summary on Cyber Security Priorities

From the analysis of ICT architectures deployed by EPUs, it resulted that there are a number of cyber attacks that, if successful, would have critical impacts on power system operation. The anatomy of real-case attacks suggests that the improvement of intrusion detection and security management capabilities would be beneficial to decrease the probability of attacks with most critical impacts. Increasing the security and responsibility awareness of most sensitive data owners has been recognized as a priority by the cyber security regulations in the energy sector. Cyber security testing and product certification is another area of cooperation between industrial users, product manufacturers, system integrators and governmental institutions. A huge effort is devoted to the development of cyber security standards for the EPUs, covering the overall cyber security governance within an organization, the security requirements for systems and components, the cyber security certification and assessment activities, and cyber security technologies. New generation applications for the digital energy should exploit the most advanced cyber security solutions when their deployment is technical and economically sustainable. Well-defined cyber security practices have to be agreed between security and maintenance staff to guarantee a smooth integration of security solutions in the daily power system operation. Such priorities shall be in the focus of digital energy regulators, vendors and operators in the upcoming years.

4 Standardization and Education

The coming years will be characterized by relevant innovations in the digital infrastructures of the EPUs. The evolution of digital technologies within EPUs will necessarily consider their typical life cycle issues, such as long deployment cycles in substation networks, technology and device obsolescence in telecommunications, IT and OT environments, long life cycles for communicating power system applications and devices. Preferred solutions will avoid vendors as well as digital service providers lock-in.

To ensure device interoperability, enable platform integration and maintain up-to-date cyber security capabilities, it is necessary to develop applications and deploy technologies that conform to widely recognized international standards from energy sector committees. The set of reference standards for data models and information exchanges within the power industry are traditionally developed by IEC and IEEE organizations. The standard series IEC 61970, IEC 61968, IEC 62325, IEC 61850, IEC 62443 and IEC 62351 are considered the minimum standard series enabling the implementation of interoperable energy data hubs and control platforms. Given the convergence of information and operational technologies and the need to integrate IoT devices, wireless network technologies and cloud-based services into energy platforms, standardization organizations from the information technology and telecommunication sectors, such as IETF, ITU, 3GPP, ETSI and W3C, become more and more relevant standardization communities for the energy sector. Following the rapid technology evolution and the new needs from energy transition and digitalization, these organizations have to continually update existing standards, introduce new ones and make them interoperable with innovative information technology platforms.

In addition to the set of technical and organizational requirements presented in the chapter, some separate considerations have to be done regarding the need of new technical skills and professional profiles, such as IoT integrators. This need should be supported by specific education programs and training laboratories allowing, for example, to evaluate security measures in realistic and non-operational environments.

Acknowledgements The authors would like to acknowledge the contributions received from the following members of the Advisory Groups D2.01, D2.02 and D2.03: Alenka Kolar (SI), Chan-Ching Liu (USA), Alexandre Pinhel (BR), Yi Yang (CN), Jaume Darne (ES), Jasmina Mandic Lukic (SR), Merhdad Mesbah (FR), Hidetomi Takehara (JP), Victor Tan (AU).

A special thanks to the Study Committee D2 Chair, Olga Sinenko (RU) for her precious support and suggestions during the preparation of the Chapter. Also thanks to Iony Patriota de Siqueira (BR) and Nikos Hatziargyriou (GR) for their helpful reviews and comments.

References

1. Working Group D2.17, Technical Brochure 341: Integrated Management Information in Utilities (2008)

2. Joint Working Group B2/D2, Technical Brochure 369: New Developments in the Use of Geographic Information as Applied to Overhead Power Lines (2009)
3. Utility Communication Networks and Services-Specification, Deployment and Operation. Springer (2017)
4. Working Group D2.18, Technical Brochure 459: Metering, Revenue Protection, Billing and CRM/CIS Functions (2011)
5. Wang, Y., Yu, J., Han, Q.: Analysis and visualization of residential electricity consumption based on geographic regularized matrix factorization in smart grid. CIGRE Paris Session 2018, Paper D2-103 (2018)
6. Stimmel, C.L.: Big Data Analytics Strategies for the Smart Grid. CRC Press (2015)
7. Graupe, D.: Principles of Artificial Neural Network. World Scientific (2013)
8. Joint Working Group D2/C2.41, Technical Brochure 732: Advanced Utility Data Management and Analytics for Improved Operation Situational Awareness of EPU Operations (2018)
9. Russel, S.J., Norvig, P.: Artificial Intelligence: A Modern Approach. Prentice Hall, 13 Dec (1994)
10. Working Group A2.44, Technical Brochure 630: Guide on Transformer Intelligent Condition Monitoring (TICM) Systems (2015)
11. Gao, K.: An Intelligent Power Line Inspection Image (Video) Analysis System. SC D2 Colloquium (2019)
12. Katsura, K.: Research and Application of Deep Learning for Improving T&D Maintenance Efficiency. SC D2 Colloquium (2019)
13. Guo, N.: Residential Electricity Demand and Heterogeneity—Analysis Based on the Finite Mixture Model. SC D2 Colloquium (2019)
14. Koponen, P.: Combining the Strengths of Different Load Modeling Methods in Short–Term Load Forecasting of a Distribution Grid Area with Active Demand. SC D2 Colloquium (2019)
15. Working Group D2.34, Technical Brochure 668: Telecommunication and Information Systems for Assuring Business Continuity and Disaster Recovery (2016)
16. Working Group D2.24, Technical Brochure 452: EMS for the 21st Century—System Requirements (2011)
17. Mesbah, M.: Utility Communication Networks and Services. SC D2 Green Book (2016)
18. Working Group D2.35, Technical Brochure 618: Scalable Communication Transport Solutions Over Optical Networks (2015)
19. Working Group B5.14, Technical Brochure 664: Wide Area Protection & Control Technologies (2016)
20. Tan, V., Cole, J: Teleprotection over Multiprotocol Label Switching (MPLS): Experiences from an Australian Electric Power Utility. Paper D2-305, Paris Session 2018 (2018)
21. Working Group D2.26, Technical Brochure 461: Telecommunication Service Provisioning and Delivery in the Electrical Power Utility (2011)
22. Working Group D2.23, Technical Brochure 460: The Use of Ethernet Technology in the Power Utility Environment (2011)
23. Viro, A.: Network Evolution Towards Packet Switched Technologies. Paper D2-303, Paris Session 2018 (2018)
24. Working group D2.33, Technical Brochure 588: Operation & Maintenance of Telecom Networks and Associated Information Systems in the Electrical Power (2014)
25. Zerbst, J., et al.: Status of Cybersecurity. Electra n. 276 (2014)
26. NERC CIP standards. http://www.nerc.com/pa/Stand/Pages/CIPStandards.aspx
27. Directive (EU) 2016/1148 of the European Parliament and of the Council of 6 July 2016 concerning measures for a high common level of security of network and information systems across the Union. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2016.194.01.0001.01.ENG
28. Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation). http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0679&from=IT

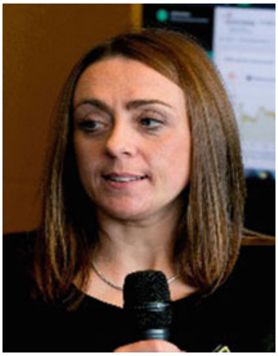
29. Smart Grid Task Force Expert Group 2: Recommendations to the European Commission for the Implementation of Sector-Specific Rules for Cybersecurity Aspects of Cross-Border Electricity Flows, on Common Minimum Requirements, Planning, Monitoring, Reporting and Crisis Management. https://ec.europa.eu/energy/sites/ener/files/sgtf_eg2_report_final_report_2019.pdf
30. Working Group D2.22, Technical Brochure 419: Treatment of Information Security for Electric Power Utilities (EPUs (2010)
31. ISO/IEC JTC 1/SC 27, ISO/IEC TR 27019:2013: Information technology—security techniques—information security management guidelines based on ISO/IEC 27002 for process control systems specific to the energy utility industry. https://webstore.iec.ch/publication/11303 (2013)
32. NISTIR 7628: Guidelines for Smart Grid Cybersecurity: Vol. 1, Smart Grid Cybersecurity Strategy, Architecture, and High-Level Requirements (2013)
33. IEC TC65, IEC 62443-4-1:2017 PRV: Security for industrial automation and control systems—Part 4-1: Secure product development lifecycle requirements. https://webstore.iec.ch/publication/61938 (2017)
34. IEC TC65, IEC 62443-2-4:2015 + AMD1:2017 CSV: Security for industrial automation and control systems—Part 2-4: Security program requirements for IACS service providers. https://webstore.iec.ch/publication/61335 (2017)
35. IEC TC65, IEC 62443-3-3:2013: Industrial communication networks—network and system security—Part 3-3: System security requirements and security levels. https://webstore.iec.ch/publication/7033 (2013)
36. IEC 62443-2-1:2010: Industrial communication networks—network and system security—Part 2-1: Establishing an industrial automation and control system security program. https://webstore.iec.ch/publication/7030 (2010)
37. CEN/CENELEC/ETSI Smart Energy Grid-Coordination Group: Cyber Security & Privacy, December 2016. ftp://ftp.cencenelec.eu/EN/EuropeanStandardization/Fields/EnergySustainability/SmartGrid/CyberSecurity-Privacy-Report.pdf
38. IEC TC57, IEC 62351:2018 Series: Power systems management and associated information exchange—data and communications security—ALL PARTS. https://webstore.iec.ch/publication/6912
39. Working Group D2.31: Technical Brochure 615, Security Architecture Principles for Digital Systems in Electric Power Utilities (2015)
40. NIST Framework for Improving Critical Infrastructure Cyber Security (2017)
41. Working Group D2.40, Technical Brochure n. 762: Remote Service Security Requirement Objectives (2019)
42. Dondossola, G., et al.: What may Electric Power Utilities (EPUs) do to mitigate the cyber threat landscape? CIGRE Science and Engineering (2018)
43. Working Group C4.47, Reference Paper: Defining Power System Resilience in CIGRE Future Connections Newsletter (2019)
44. NERC Reply Comments on FERC Grid Resilience Proceeding: Grid Resilience in Regional Transmission Organizations and Independent System Operators. Docket No. AD18-7-000, 9 May 2018
45. IEC System Committee Smart Energy, Working Group 3, Cyber Security Task Force: Cyber Security and Resilience Guidelines for the Smart Energy Operational Environment, 22 October 2019. https://basecamp.iec.ch/2017/01/26/publications-2/
46. Mougayar, W.: The Business Blockchain: Promise, Practice, and Application of the Next Internet Technology. Wiley (2016)
47. Zheng, Z., et al.: An overview of blockchain technology: architecture, consensus, and future trends. In: 2017 IEEE 6th International Congress on Big Data
48. Bruyin, A.S.: Blockchain, An Introduction (2017)
49. Controlling weather-dependent renewable electricity production with blockchain. Available at https://www.tennet.eu/fileadmin/user_upload/Our_Key_Tasks/Innovations/blockchain_technology/Artikel_IBM.pdf

50. LO3 whitepaper: Building a Robust Value Mechanism to Facilitate Transactive Energy, December 2017. Available at https://exergy.energy/wp-content/uploads/2017/12/Exergy-Whitepaper-v8.pdf
51. Regulators: unblocking the Blockchain in the energy sector. Available at https://www.ceer.eu/documents/104400/-/-/c1441b50-3998-2188-19f3-14dab93649d3
52. Partnering with RWE to explore the future of the Energy Sector. Available at https://blog.slock.it/partnering-with-rwe-to-explore-the-future-of-the-energy-sector-1cc89b9993e6
53. Deloitte University Press: Industry 4.0 and the digital twin: manufacturing meets its match. Available at https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/cip/deloitte-cn-cip-industry-4-0-digital-twin-technology-en-171215.pdf
54. Sauer, O.: The Digital Twin—A Key Technology for Industry 4.0. Fraunhofer IOSB VisitIT. Available at https://www.iosb.fraunhofer.de/servlet/is/14330/visIT_1-26-03-2018_web.pdf (2018)
55. Drath, R.: The Digital Twin: The Evolution of a Key Concept of Industry 4. Fraunhofer IOSB VisitIT. Available at https://www.iosb.fraunhofer.de/servlet/is/14330/visIT_1-26-03-2018_web.pdf (2018)
56. GE Digital Twin: Analytic Engine for the Digital Power Plant. Available at https://www.ge.com/digital/sites/default/files/download_assets/Digital-Twin-for-the-digital-power-plant-.pdf
57. Siemens Electrical Digital Twin: A single source of truth to unlock the potential within a modern utility's data landscape. Available at https://www.siemens.com/content/dam/webassetpool/mam/tag-siemens-com/smdb/energy-management/services-power-transmission-power-distribution-smart-grid/consulting-and-planning/power-systems-simulation-software/electrical-digital-twin/electricaldigitaltwin-brochure-final-intl-version-singlepages-nocrops-hires-1.pdf
58. Deloitte and The Blockchain Institute: IoT powered by Blockchain: how Blockchains facilitate the application of digital twins in IoT. Available at https://www2.deloitte.com/content/dam/Deloitte/de/Documents/Innovation/IoT-powered-by-Blockchain-Deloitte.pdf
59. Working Group C2.16: Technical Brochure 700, Challenges in the Control Centre (EMS) due to Distributed Generation and Renewables (2017)
60. Tan, V.: Substation Virtualisation: An Architecture for Information Technology and Operational Technology Convergence for Resilience, Security and Efficiency. CIGRE Session Paper D2-201 (2018)
61. Bag, G., et al.: Challenges and Opportunities of 5G in Power Grids. Institute of Engineering and Technology (2017)
62. Donohoe, M., Jennings, B., Balasubramaniam, S.: Context-awareness and the smart grid: Requirements and challenges. Comput. Netw. **79**(14), 263–282 (2015)
63. Hatziargyriou, N., Vlachos, I., Kiokes, G.: Evaluation of a LoRaWAN Network for AMR. CIGRE Session Paper D2-101 (2018)
64. SANS and Electricity Information Sharing and Analysis Center (E-ISAC): Analysis of the Cyber Attack on the Ukrainian Power Grid. Mar. 18, 2016 [Online]. Available http://www.nerc.com/pa/CI/ESISAC/Documents/E-ISAC_SANS_Ukraine_DUC_18Mar2016.pdf
65. Yang, Y., McLaughlin, K., Gao, L., Sezer, S., Yuan, Y., Gong, Y.: Intrusion detection system for IEC 61850 based smart substations. In: 2016 IEEE Power and Energy Society General Meeting (PESGM), pp. 1–5. Boston, MA (2016)
66. Dondossola, G., Garrone, F., Szanto, J.: Cyber risk assessment of power control systems—a metrics weighed by attack experiments. In: 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA (2011)
67. Liu, C.C., Stefanov, A., Hong, J., Panciatici, P.: Intruders in the Grid. IEEE Power and Energy Magazine **10**(1), 58–66, Jan–Feb (2012)
68. Abdelwahed, S., Karsai, G., Mahadevan, N., Ofsthun, S.C.: Practical implementation of diagnosis systems using timed failure propagation graph models. IEEE Trans. Instrum. Measure. **58**(2), 240–247 (2009)
69. Abdelwahed, S., Karsai, G., Biswas, G.: A consistency-based robust diagnosis approach for temporal causal systems. The 16th International Workshop on Principles of Diagnosis, Pacific Grove, CA (2005)

70. Yang, Y., Xu, H.Q., Gao, L., Yuan, Y.B., McLaughlin, K., Sezer, S.: Multidimensional intrusion detection system for IEC 61850-based SCADA networks. IEEE Trans. Power Deliv. **32**(2), 1068–1078 (2017)
71. Hall, J., Barbeau, M., Kranakis, E.: Anomaly-based intrusion detection using mobility profiles of public transportation users. In: WiMob'2005, IEEE International Conference on Wireless and Mobile Computing, Networking and Communications 2005, vol. 2, pp. 17–24. Montreal (2005)
72. Sun, C.C., Hong, J., Liu, C.C.: A Coordinated Cyberattack Detection System (CCADS) for multiple substations. In: 2016 Power Systems Computation Conference (PSCC), pp. 1–7. Genoa (2016)
73. Hong, J., Liu, C.C.: Intelligent electronic devices with collaborative intrusion detection systems. IEEE Trans. Smart Grid **10**(1), 271–281 (2019)
74. Dondossola, G., Terruggia, R.: A monitoring architecture for smart grid cyber security. CIGRE Sci. Eng. J. (10) (2018)
75. Working Group D2.38, Technical Brochure 698: Framework for EPU Operators to Manage the Response to a Cyber-Initiated Threat to Their Critical Infrastructure (2017)
76. Working Group D2.46, Technical Brochure: Cybersecurity: Future Threats and Impact on Electric Power Utility Organisations and Operations (2019)

Giovanna Dondossola (female) received her M.Sc. Degree in Information Science from the University of Milan in 1987. She is currently a staff member of the Department Transmission and Distribution Technologies of the company Ricerca sul Sistema Energetico, RSE S.p.A (Italy), where as Leading Scientist she technically leads National and European projects on the evaluation of cyber risks in smart grid communications and is responsible of the RSE Lab for the power control system resilience testing. Since 2004 she is an active member of CIGRE working groups on information systems and telecommunications security, where currently is the Italian SC D2 representative and chair of the Advisory Group D2.02 on Cyber Security. She contributed to smart grid standardization activities for the European Mandate M/490 and she is a member of the Working Group 15—Technical Committee 57 of the International Electrotechnical Commission. Co-authored hundreds publications on electrical control systems cyber security including papers, articles and chapters in international conferences, journals and books, made several speeches and lectures at panels, tutorials and training courses for academies and utilities.

Marcelo Costa de Araujo (male) graduated in Electrical Engineering in 2002 (Universidade de Brasília—UnB), with post grad in Administration (FGV-2004) and MBA in Public Companies Management (Franklin-Covey/Fundação COGE-2014). Since 2001, he has been working in the Brazilian electrical sector, with experience on projects, operation and maintenance in telecommunication systems. Since 2007 he works at Eletrobras Eletronorte, where he managed the telecommunications maintenance and planning department from 2015 to 2017. He currently works as an electrical engineer in the technical coordination and asset management department. He has been an individual member of CIGRE since 2008. Since 2014, he is the Brazilian member of SC D2, where he participates in WGs and is the convener of Advisory Group D2.01 that focuses on Core Business Technologies. Since 2018, he is also Vice-President of CTSMART, a Brazilian Scientific Institute that focuses on technologies for Smart Cities and Smart Grids.



Karen McGeough (female) graduated with a Telecommunications Engineering Degree in 2001 (Dublin City University, Ireland), with an MBA Technology Management (Open University, 2012) and achieved the chartered engineering professional title in 2014. Karen began her career as a transmission engineer working at a mobile operator between 2001 and 2007, moving to the electricity utility sector in 2007 where she joined the Irish utility, ESB. Since 2007 Karen has been working in the provision of utility specific telecommunications services to the DSO, TSO, and also to the generation business unit. Leading a team in the design and deployment of wide area networks for over 6 years, she has worked on a wide range of telecommunications systems and technologies covering multiple protocols across radio, optical and satellite networks. Her current role involves the development of the strategic direction of the telecoms business unit within ESB Networks to ensure the evolution to a Smart Grid is achieved through suitable and scalable communications, enabling the digitization of the Irish grid. Collaboration has been a key feature of her role, through regular engagement with industry partners. Karen has been an individual member of CIGRE since 2015, and has recently, in 2018, taken on the role of convener of Advisory Group D2.03 that focuses on Telecommunications.

Index

N. Hatziargyriou and I. P. de Siqueira (eds.), *Electricity Supply Systems of the Future*, CIGRE Green Books, https://doi.org/10.1007/978-3-030-44484-6