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Antonio Carlos Zambroni de Souza
Bala Venkatesh *Editors*

Planning and Operation of Active Distribution Networks

Technical, Social and Environmental Aspects

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Preface

Joseph Wright of Derby was a passionate painter who captured the fascination and direct impact of science in society. Many years later, Salvador Dali candidly delivered his "Family Scene by Lamplight," where a family gathered under a simple, though vital, lamplight for a reading. On the other hand, Photographer Sebastião Salgado has dedicated his career to show how excluded people struggle to meet their minimum demands to survive. The lack of electricity and its devastating effects are clear in his work. Art, therefore, shows that science, in general, and electricity are key factors in our society. Several events around the world show that the lack of energy may drive people to a primitivism behavior that seemed unlikely under normal conditions. This is a source of discussion among social scientists but is most of the time neglected by "technical professionals." A broader background urges since multidisciplinary tasks are going to be, very soon, a demand for engineers. In this sense, understanding the effects of engineering will be as vital as knowing basic and complex technical concepts.

Technological transformations have always played a major role in the way people live and interact. We take as a grant the daily tools available for our comfort related to the way we live and work. They are the result of a tremendous effort and sometimes even heroism of some people. The war of currents, for example, despite all its absurdities, has shaped the application of electricity all over the world, with the prevalence of alternate current systems that enable the transmission of large blocks of energy through long distances. The advent of smart grids and the growing penetration of renewable-based energy are changing this reality. Emerging power systems are hybrid, with electric vehicles, solar panels, direct current loads, and so many other characteristics, which are still unknown nowadays.

This book attempts to discuss key features of emerging power systems, with a special focus on practical aspects relating to their implementation. It covers classical features of those systems, such as reliability, efficiency, and cost-effectiveness, together with new requirements for creating sustainable, smart, and flexible networks supporting energy transition. Several experts bring their views on different aspects of active networks, proposing solutions for supporting their future planning and operation. Besides technological aspects, social issues of power systems are addressed, with the intention of offering a holistic view of the topic of energy transition, and stimulate a multidisciplinary approach to the most urgent problems in power distribution systems. More specifically, market issues, optimization, reliability, state estimation, demand response, and communications, which are classic problems of power systems, are now considered by adding the challenging characteristics of an active network. And, new features are included since the role of storage, low carbon emissions, the complementarity of renewable sources, hosting capacity, and autonomy of isolated microgrids tend to be part of the background of the next generation of engineers.

Writing this material coincided with the pandemic time that took place in December 2019, which demanded an extra effort for all the authors. The pandemic brought despair, hunger, inequality, and unemployment to an unacceptable level around the world, which triggered several remedial actions from governments. Electricity played a crucial role, enabling people to work from home and providing comfort for relaxing hours. More important, however, energy supply to hospitals enabled the medical teams to assist the millions of patients in search of treatment. Therefore, the importance of electricity poses a challenge to future engineers, who must design a reliable power system keeping in mind the social importance of its service to society. In this sense, one could say that engineers should be educated about their importance to society since they disregard this aspect most of the time.

This book is then a fruit of a joint effort of researchers from Brazil, Canada, Chile, France, India, Italy, Portugal, Spain, and the USA. The writers involved are experts of the topics addressed here. The emerging importance of this book regards the impact of active networks in the coming years. Thus, it covers a wide range of aspects involving active networks. It starts by describing the "philosophy" of these new systems. For this purpose, the concepts of passive user, active user, and prosumer, and their role in emerging distribution systems are introduced and discussed in detail in the first chapter of the book, which also introduces some key aspect of the energy market. A comprehensive analysis of the next-generation electricity market at the distribution level is, in turn, further elaborated in the chapter "Retail Electricity Markets for Active Distribution Systems." The way paved by the two first chapters enables one to discuss the problem of demand response and the reliability of active networks, addressed in the chapters "Practical Aspects of Active Distribution Networks" and "Reliability Analysis of Active Distribution Systems." The role of electric vehicles is discussed in the chapter "The Role of Electric Vehicles in Smart Grids," where the efficiency of vehicle to grid power flow is assessed. Electric vehicles pose a charging problem for utilities, but they also may be used as emergency sources to the system. In this sense, a discussion about battery energy storage plays a key role. This is explored in the chapter "Battery Energy Storage Systems for Applications in Distribution Grids," where a mathematical model is shown, and several applications are described. Operating an active system certainly demands a knowledge on different areas, and optimization cannot be overlooked. Chapter "Smart Grids Optimization: Demands and Techniques" discusses the concept, structure, and resources of a smart grid, identifying opportunities for optimization applications in the planning and operation of smart grids. It also highlights some likely applications in active networks, encouraging students to explore this area. Planning and operation of active networks may follow the regular track of power systems, but the energetical planning window may be associated with few hours or minutes, in case these systems operate in islanded mode. Chapters "Load Flow in Microgrids" and "Microgrid Operation and Control: From Grid-Connected to Islanded Mode" address some important particularities about these systems when operating in both connected and islanded modes. A conventional distribution system becomes an active network when local generation, along with communication devices, is considered. The problem of hosting capacity is crucial, since active networks must operate within nominal values. Chapter "Hosting Capacity and Grounding Strategies in Microgrids" proposes a method to determine the microgrid hosting capacity based on frequency response and frequency protection elements. Smart metering is also a new feature of active networks. Chapter "Smart Metering in Distribution Systems: Evolution and Applications" discusses the benefits of using smart meters for operation and planning of modern distribution systems. Since active networks are still in their cradles, experimental laboratories have a great importance in simulating the scenarios of operation. Chapter "Communication in Active Distribution Networks" takes an experimental point of view to analyze the operation and reliability of an islanded inverted-based low-scale laboratory microgrid (MG). For this sake, a set of inverters driven by digital processors is considered subject to failures such as loss of communications. Communication is also important for a grid of microgrids. In this sense, complementarity among renewable sources also deserves a special attention, as studied in Chapter "Renewable Sources Complementarity." Such a chapter reviews the concepts regarding the complementarity of renewable energy sources, by describing some of the existing indexes from the literature so that they can be evaluated in different time and space scales. The complexities of active networks place a growing concern about state estimation, since an effective monitoring is required. Chapter "State Estimation and Active Distribution Networks" presents an overview of some distribution system state estimation (DSSE) approaches available in the literature. It also presents the main challenges for enabling DSSE in active networks, focusing on how state estimators can aid these functions. Chapter "DC Microgrids for Ancillary Services Provision" may be faced as a peace flag on the war of currents, since it is dedicated to DC microgrids application to provide ancillary services to weak AC grids. The problem of low inertia is also addressed with the help of an application example that illustrates the performance of the microgrid in the context of virtual inertia control. We, authors, have in mind that a better electricity grid is meant to provide service in comfortable and sustainable manner. Hence, Chapters "Sustainability and Transformative Energy Systems," "The Role of Smart Grids in the Low Carbon Emission Problem," and "Smart Grids from a Holistic Perspective" focus on the sustainability, policies, low carbon emission, and a holistic discussion of smart grids, respectively. Chapter "The Coming Trends and What to Expect" provides some highlights of the coming trends.

One may note that the authors placed a great effort to provide a useful material for students and engineers. One should also note that this emerging power system is a technological revolution carried out by "an" engineer with different backgrounds. It is, indeed, a new world that demands new knowledge. Mankind has accomplished several milestones along with history, which were fruits of a pile of contributions gathered for several years or even centuries. The technological jumps we currently witness are recent in human history. Thus, we hope this book brings important contributions to technical aspects of engineering by incorporating new advances and technological progress associated with this topic. But we hope as well that this book provokes future engineers, the necessary fascination to perform its profession as a social blessing. Such a blessing may help the industry to work in an uninterruptible way creating the most complex devices for customers in general. But this blessing may also be faced as something that enables people to keep their food in good conditions in the refrigerator, hospitals keep running to help and save patients, and why not, gather together in the living room for reading under a lamplight.

Itajuba, Brazil — Antonio Carlos Zambroni de Souza
Toronto, Canada — Bala Venkatesh

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Introduction—Advances and Challenges in Active Distribution Systems

Gianfranco Chicco, Alessandro Ciocia, Pietro Colella, Paolo Di Leo, Andrea Mazza, Salvatore Musumeci, Enrico Pons, Angela Russo, and Filippo Spertino

Abstract Many drivers are determining continuous changes in the structure and operation of distribution grids. In addition to the now long-lasting effects introduced by the smart grid paradigm, a number of new trends are emerging. This chapter provides an overview of how distribution systems are changing. Modernisation is the key point to pass from network infrastructures designed in a rather different context to new solutions that incorporate advanced features. For this purpose, the concepts of passive user, active user, and prosumer, and their role in emerging distribution systems, are introduced and discussed. Relevant aspects addressed include the impact of the diffusion of renewable energy sources in the operation of distribution systems and microgrids, as well as the current trends towards establishing local energy markets and energy communities. Further aspects refer to the development of

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local solutions for the generation, management and storage of energy at small- and micro-scale, the increasing attention towards grid-side and demand-side flexibility, and the provision of grid services.

Acronyms

ADN	Active Distribution Network
ADS	Active Distribution System
AS	Ancillary Services
BMS	Building Management System
CHB	Cascaded H-Bridge
CHCP	Combined Heating, Cooling and Power
CSC	Current Source Converter
DER	Distributed Energy Resources
DG	Distributed Generation
DLMP	Distribution Locational Marginal Price
DR	Demand Response
DS	Distributed Storage
DSO	Distribution System Operator
EMI	Electromagnetic Interference
ESP	Energy Service Provider
ES	Energy Storage
EV	Electric Vehicle
FACTS	Flexible Alternating Current Transmission Systems
FLC	Flying Capacitors
GTO	Gate Turn-Off
HV	High Voltage
HVDC	High Voltage Direct Current
ICT	Information and Communication Technologies
IEGT	Injection Enhanced Gate Transistor
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate Commutated Thyristor
LCC	Line Commutated Converter
LV	Low Voltage
MG	Microgrid
MGMS	Microgrid Management System
MMC	Modular Multilevel Converter
MMG	Multi-Microgrid
MV	Medium Voltage
NG	Nanogrid
NOP	Normal Open Point
P2P	Peer-to-peer
PCC	Point of Common Coupling

PCT	Phase-Controlled Thyristor
PDS	Primary Distribution Substation
PV	Photovoltaic
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
RMS	Root Mean Square
SC	Self-Consumption
SDS	Secondary Distribution Substation
SGAM	Smart Grid Architecture Model
SS	Self-Sufficiency
SST	Solid-state Transformer
TE	Transactive Energy
THD	Total Harmonic Distortion
TSO	Transmission System Operator
V2X	Vehicle-to-Everything
VPP	Virtual Power Plant
VSC	Voltage Source Converter
WBG	Wide BandGap
WoC	Web-of-Cells
WT	Wind Turbine

1 The Main Drivers for Distribution System Modernisation

The restructuring of the electricity business has taken place since the last years of the last millennium, and has become widespread around the world since the beginning of the current millennium. The unbundling of the electrical generation, transmission, distribution, and retail sectors has required establishing new operators inside each sector. In particular, the electricity distribution sector has been generally managed by partitioning the territory into different areas of competence. After unbundling, the role of the Distribution System Operator (DSO) was assigned to a unique entity in each area of competence. Meanwhile, historical areas in which there were more electricity distributors were re-organised by specific agreements (or legal arbitrages) to maintain only one DSO. The distinction between distribution and retail has led to the birth of a competitive framework in the retail sector, and to the establishment of DSOs as the technical operators that act on their distribution networks.

The unbundling of the electricity sectors required to deeply analysing the characteristics of the value chain inside each sector, with the aim of clearly identifying the specific costs and benefits. For the distribution systems, the situation that emerged was generally the one of an electricity distribution infrastructure designed many years before and operated in a centralised way. The need for modernising this infrastructure was clearly highlighted by the concomitant appearance of a number of factors, among which:

- Growing attention towards environmental impact issues, in particular after the Kyoto Protocol.
- The development of technologies for energy production from renewable energy sources (RES), which reached an appropriate technological maturity.
- The possibility of introducing distributed generation (DG) in the distribution systems, not only supplied by RES.
- The evolution of technical solutions for electrical storage, including the progressive introduction of electric vehicles (EVs).
- The disclosure of the possibility to supply power to the grid, leading to enabling active distribution networks (ADN) with power injections not controllable by the DSO, and connection limits determined by newly established regulators and authorities.
- A fast evolution of the information and communication technologies (ICT), which made available advanced communication systems and controls, and several tools to assist the distribution system analysis, operation and planning.
- The development of an extended economic framework based on competition among various players, also with the creation of new players with various roles.
- The changing role given to the demand side, also considering the *participation* of the users to the provision of electricity, either with the combined role of producers-consumers (or *prosumers*) or depending on the users' willingness to provide *demand response* (DR) services based on price signals or incentives.

A few years later, many of these principles were considered under the smart grid paradigm [3], applied in the Smart Grids Technology Platform of the European Union [29] and in the U.S. Energy Independence and Security Act of 2007 [117]. Under the smart grid paradigm, some aspects were further emphasised, including cybersecurity, energy conversion through power electronics devices, and flexibility of the supply and demand. It is worth noting that the terms "smart" associated to "grid" was used, probably the first time, in the document [121] as an acronym for Self-Managing And Reliable Transmission Grid, to indicate a monitoring, control and protection automated system that, with the use of ICT and new algorithms, allows improving the reliability of the transmission system. Nowadays, the term smart grid mainly indicates the evolution of the *distribution* system, which needs to be modernised more than the transmission system. The term Distributed Energy Resources (DER) is also typically used to define the merging of DG, DR, and Distributed Storage (DS).

In addition to the classical attributes of reliability, stability, security, efficiency and cost effectiveness, the new systems have to be smart, sustainable, resilient and interoperable, contributing to the energy transition in progress, in which the role of electricity is going to become more and more significant for all the end uses (residential, industrial, commercial, and transportation).

Specific aspects are detailed in the next sections:

- active distribution networks
- network structures
- renewable energy sources
- energy conversion

- operational aspects
- economic aspects
- energy management aspects
- grid services.

2 Active Distribution Networks

The past distribution system was an infrastructure than aimed to connect the upper level (high voltage) system to the *passive loads* of customers that required active and reactive power from the grid. The auto-production was limited to very large customers connected at high-voltage system, and the possible injection of active power into the grid was always agreed with the system operator. Consequently, most of the analysis carried out about the distribution systems so far considered only the *demand level of the system* [52]: aspects such as the maximum and average demand, the load factor, the *diversity* of the demand, the design based on voltage drop and/or power losses took a relevant part in any book. The presence of *time-variant load* was not taken into account because it was sufficient to consider the worst-case scenario for design. For this reason, there was no interest to investigate the *operation* of the system at the planning and design stages.

However, the innovation in the generation side, with the introduction of new local generators that exploit RES, changed dramatically the idea of distribution system operation: for the first time after the introduction of the alternating currents, researchers and technicians started thinking that producing locally could conveniently drive the change in the paradigm of the whole electricity system operation. Hence, two different paradigms started to face each other, based on completely different visions of the electricity system: on the one hand, the future shape of the system could be based on the development of the *super-grids* [96], whereas on the other hand the future system could be seen as composed of *micro-grids* [58]. In the former case, the main infrastructure is the transmission system, which is developed to cover long distances and brings the electricity where it is needed, by exploiting the time shifts among different regions in the world. Vice versa, the latter paradigm points to develop local production and consumption, with the transmission system as the “back-up” infrastructure. In the middle of these two visions, there is enough space for another framework, based on Active Distribution Networks (ADNs) that form an Active Distribution System (ADS). The ADN (and consequently the ADS) is composed of a *number of sets* including different *entities*:

- *passive equipment*: it is the set that forms the *power hardware* of the electrical network. In this set one can find all the elements that allow secure and reliable electricity flows, i.e., transformers, cables, overhead lines, circuit breakers, relays (as components, not as logics), switches, fuses, current transformers, and voltage transformers.
- *non-flexible prosumers*: this set contains all the prosumers, which manage loads or generators whose behaviour cannot be easily changed.

- *flexible prosumers:* it contains all the prosumers that somehow can modify their *net load* shape and thus are seen as source of *flexibility*.
- *market players*: even though they are not part of the ADNs, they are fundamental for managing with market-based rules the ADS. As geographical extension, they can act on one or more ADNs, and their intervention helps exploiting the flexibility of the prosumer at a system level.
- *control system*: this indicates, with a general term, all the equipment that allow the interactions among the different entities, from the ICT infrastructure to the information codification and the control logics.

The *motivation* to have an ADS is to enable the connection of a larger share of DER to the electricity system, by properly managing the uncertainties characterising the primary sources (from solar and wind energy, above all). The proper handling of the uncertainty is required for making them *fully compatible* with the operation of the electricity system: being operated in AC, the real-time balance between load and generation must be guaranteed (with small deviations recovered thanks to the existing control systems). To some extent, at the distribution system level the system operation is shifting from a *load-following* operation to a *generation-following* operation [90], where the *load* may be modified (also involving DS) to accommodate the evolution in time of uncertain generation.

The co-existence of flexible and non-flexible prosumers leads the network operating conditions to be different in different parts of the network. A given zone or *neighborhood*, composed of one or more feeders under the same primary substation, can present voltages completely different from another zone supplied by the same substation. Furthermore, the evolution in time of the zone composition, as well as the values of current and voltage existing in each zone, may change in a non-predictable way. This characteristic does not allow finding a unique "rule", unlike it was in the past for the voltage profile, which had always a decreasing trend along the feeders. This new condition requires the introduction of new control approaches (more distributed and decentralised) and new measurements (for example on the basis of the *net load*, considering the different devices that can be connected to any node such as storage, local generators and passive load). Indicators such as the losses allocated to the system nodes [13] can be useful to understand whether in a given zone there is an excess of local generation, such that to reduce the system losses it would be needed to increase the local load—a solution that had never to be considered in a distribution network with passive loads only [76].

All the above-listed characteristics of the ADNs can be summarised by saying that they allow to create a *multi-layer* ADS, in which technical, economic and social dimensions co-exist. This multi-layer structure is well represented by the *Smart Grid Architecture Model* (SGAM) [104], which is a three-dimension structure including domains, zones and layers:

- *Domains*: the domains are the *sectors* that compose the value chain for the electrical system, i.e., Bulk generation, Transmission, Distribution, DERs and Customers.

- *Zones*: the zones reflect a hierarchy that consider the aggregation and the functional separation in power system management, and are defined according to the information managed by each of them. The zones are Process, Field, Station, Operation, Enterprise, and Market. While the first zone includes all the power system equipment and energy conversion, the other zones manage information.
- *Layers*: the layers allow highlighting the different aspects where the interoperability among systems is required. In particular, the layers cover Components, Communication, Information, Function and Business.

It is worth noting that the role of *communication* and *information* becomes fundamental for properly managing the ADS, but also to guarantee a fruitful interaction between the different players of the electricity system.

However, *which kind* of information is required? A distinction should be made between the information *for managing the network* and the information *for enabling services*. In the first case, the information concerns the network constraints, i.e., node voltages and branch currents. This kind of information was available also in the past, but the introduction of DG shaped the electrical variables in the network differently. As a matter of example, the presence of DG at the end of a rural line can create *overvoltage* problems, which before were not even considered as potential issues [45]. Thus, the technical measurements are able to report the existence of the problem, but the classical control actions put in place by the DSO and based on the field measurement may not be sufficient. Thus, new kinds of information are required, to engage the *prosumers* (i.e., the players that may create network issues) into the *system operation* [30, 31].

This paradigm shift requires conceptually different actions:

- the definition of the *types* the information to be collected and with which *temporal resolution*;
- the collection of the information by the prosumers through the installation of *smart meters*;
- the definition about *who* is using this information and for doing *what*;
- the clear definition of the roles of DSO, prosumers and other players (such as aggregators) that are involved into the ADS operation.

The definition of the information to be collected is linked to the *services* offered by the prosumers. The types of services are strictly dependent on the market architecture and the prosumer's equipment. As a matter of example, from a technical point of view, refrigerators showed to possess all the characteristics for offering both power and energy services to the grid, spanning from frequency regulation to load shaping [22, 115]. Thus, the *value* of the services offered is not negligible. However, due the unclear definition of the roles in a new market framework (which implies, among others, interactions between the Transmission System Operator (TSO) and the DSO, the presence or not of local markets, and the method of ancillary service provision), the potential *revenues* from those services cannot be easily evaluated, unless making a number of assumptions. As recently defined in Thomson and Perez

[114] for the Vehicle-to-Everything (V2X) application, new applications and/or technologies cannot be evaluated in terms of revenues, but certainly on the *value stream*, in particular seen as *stacked stream* (i.e., possibility to provide more than one service with the same technology). The same concepts are valid for the services that, in general, the players forming the ADNs can provide to each other or to third parties (in particular to the transmission system).

Furthermore, it is worth noting that, while all the services are based on the *flexibility* of the prosumers, how this flexibility may be exploited is strictly correlated with the *willingness* of the prosumers to deviate from their baseline. According to the equipment installed at the prosumer's premises (that usually includes both generation and load, and sometimes also storage systems), the evaluation should be made on the *net load*, because the prosumer interacts with the grid with a bi-directional energy exchange. However, considering the net load can lead to some issues in the evaluation of the service value due to the scarce representation of positive and negative peaks that can be reached with the usual interval-metering paradigm that adopts time resolution of approximately tens of minutes [17]. Hence, at the measurement level, the proper exploitation of the prosumer's flexibility may require a large number of data, by creating problems related to data management and data transmission. New paradigms of measurement are required for the next generation of smart meters. One of the possible solutions (already commercially available) is based on the *event-driven* energy metering [101, 102]. This solution enables tracking the demand peaks in an effective way, opening new prospects for setting up new options for tariffs or contracts for flexibility [16].

Once the information is collected, *who* is in charge to use it? The current role of the DSO is basically to guarantee the proper planning, operation, and maintenance of the network, as well as the quality and security of the supply. This means that it cannot act as a *market player*, as it has to guarantee the *neutrality* the network. However, the information related to the potential flexibility of the prosumers is anyway collected through the smart meters linked to the DSO ICT infrastructure. Hence, this information should be made available to market players (such as aggregators or suppliers), which can properly manage the explicit flexibility [105] of a group of prosumers collected together. The explicit flexibility is committed by participating in incentive-based programs that rely upon direct load control. These programs may be managed by the supplier or by another entity (e.g., an aggregator). Conversely, the implicit flexibility is delivered according to the sensitivity of the customer to the price signal.

Thus, the role of the DSO requires an evolution: beyond guaranteeing the *neutrality* of the electrical infrastructure, it will be responsible of the neutrality of the *measurement* infrastructure, taking care of the *security of the data* as well. Managing the information implies also the use of a proper *information model*, which defines the codification of the information: this aspect implies a great engagement of the *standardisation bodies*, which have to act for guaranteeing the maximum *interoperability* of the systems. The way in which the information is physically exchanged among the different devices is based on the *communication protocols* that can be evolved during the time (but this does not affect the information model preliminarily defined). An example of architecture which is becoming more and more common is the IEC61850, whose areas of use are becoming wider and wider.

As the last remark, the introduction of these new aspects poses key challenges also to the research field [19]. For example, the usual benchmark networks did not consider any time-variant load behaviour, and do not include any local generation. So, new methodologies have been suggested to create case studies (see for example [75]). Furthermore, the operational constraints of the different devices have to be taken into account into the optimisation procedures, by creating more and more complex solution spaces that require new conceptual frameworks [6].

3 Distribution Network Structures

3.1 From Traditional Distribution Network Structures to Smart Grids

A power system consists of a set of interconnected parts to generate, transmit, and distribute electricity to the end users. These parts are interfaced by a set of transformers, which adapt the voltage to the appropriate level, suitable for the functioning of the system.

From its beginnings in the early twentieth century, the structure and the organisation of the power grid underwent a very slow evolution. The generation was only based on fossil fuel and located in a central location away from the load centres; the transmission featured a mesh network structure, and the distribution was organised as a radial network to provide electrical energy at the low voltage level to the end users. Figure 1 summarises this well-known conventional structure, showing the major components of the power system: production, transmission, distribution, and consumers, interconnected through the power lines and substations.

In this conventional power system, the electrical power is generated by centralised large-scale power generation plants and it is injected, through a step-up transformer, into the transmission network at High Voltage (HV) level (230 kV, 400 kV). The transmission network delivers electrical power to the regional distribution networks, through the Grid Supply Points (GSP), which transform (step down) the voltage to the distribution HV level (100–230 kV). The distribution network delivers the received power to the end-user consumers of the networks at lower voltage levels. The voltage is first stepped down to Medium Voltage (MV) level (1–100 kV) [43] at Primary Distribution Substations (PDS). Then, Secondary Distribution Substations (SDS), steps down the voltage into the Low Voltage (LV) levels (<1 kV), required to supply the three-phase and single-phase end-users (400 V three-phase and 230 V single-phase). Large industrial users could be connected at High Voltage [103].

The MV distribution networks start after the PDS and terminate at a secondary distribution substation. The LV networks start from the secondary distribution substation, where the voltage level becomes 400 V in the three-phase networks.

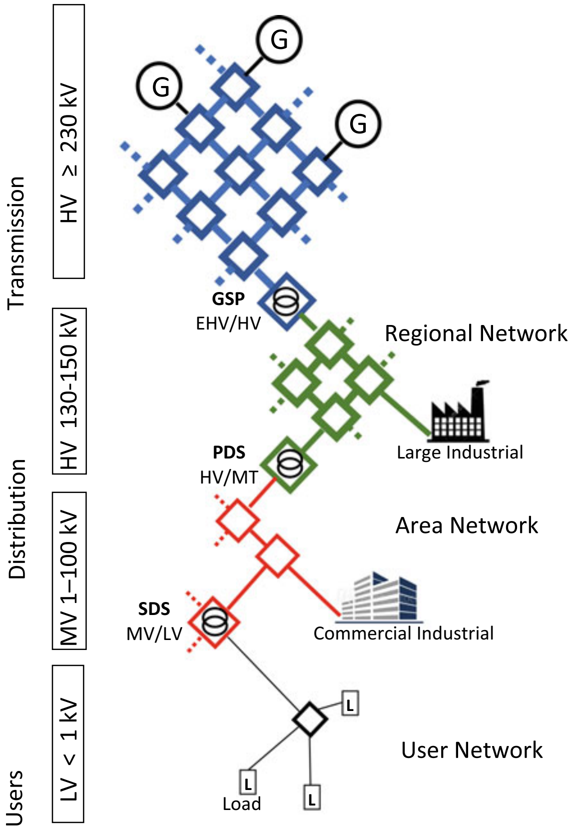

Fig. 1 Conventional power system structure

Finally, through the LV networks (230 V line to neutral), the electricity reaches the single-phase end-users [56].

The distribution networks can supply the different areas of the system in a variety of ways, depending on system voltage level and the load density. The three main topologies used to design distribution networks, are illustrated in Fig. 2:

1. radial
2. ring/weakly-meshed
3. meshed.

In a radial network, each node is connected to the substation via one path only. Typically, the radial network topology is used in LV distribution networks and in MV long rural lines that connect isolated load areas. The ring topology (with radial operation, by keeping the redundant branches open, to simplify the protection schemes) is adopted in most MV feeders to improve the security of the supply in the event of circuit outages during faults or scheduled outages due to maintenance. Indeed, the Normal Open Point (NOP) is located between the two interconnected feeders (A and B in Fig. 2) to ensure radial operation for each feeder. The location of the NOP can be

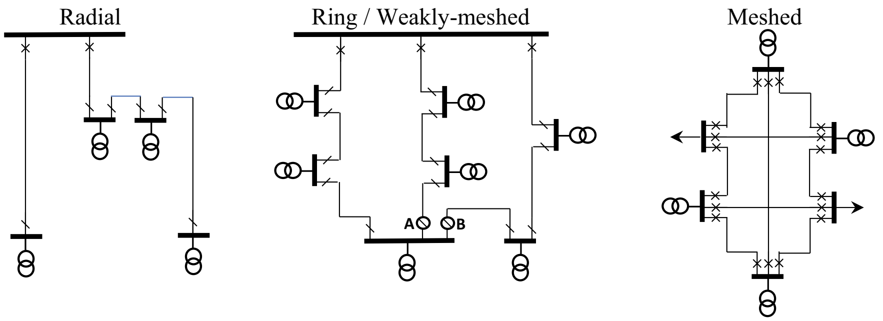

Fig. 2 Distribution network topologies

moved following the occurrence of a fault, such that the faulty section is isolated and power is restored to all users connected to the two interconnected feeders. Sometimes, distribution feeders serving high-density load areas (e.g., urban areas) could contain few loops created by closing NOP switches. Rings and weakly mesh systems may be operated split with normally open points, or closed to improve security, although the latter solution requires more circuit breakers and more sophisticated protection.

Greater security could be achieved by meshed topology. The connection of multiple substations in parallel can reduce the total transformer capacity into the group. Such an arrangement can accept the loss of one in-feed without interruption of supplies within the network, if subject to satisfactory network circuit loadings [56]. However, parallel operation of the laced points can result in reverse power flows through the in-feed transformers under outage conditions on the higher voltage system: care must be taken that the fault levels within the network are acceptable. The meshed topology is adopted at the HV level, due to the large distribution areas (regional networks). Depending on the regulation in place in various jurisdictions, HV regional networks can be managed by the DSO or by the TSO.

In the last decades, the fast changing nature of the end-user loads and distributed RES, the smart grid concept has been developed as illustrated in Fig. 3, with the addition of DG, DS, and an information infrastructure that goes beyond the traditional system control and data acquisition and energy management systems. In the smart grid scenario, generation will largely shift from centralised transmission systems to decentralised connected distribution system generation. The connection of additional energy sources into existing distribution systems leads to a series of technical troubles, such as possible inversion of power flows, possible overvoltages, modification of short-circuit currents, stability problems, among others [9, 78, 83].

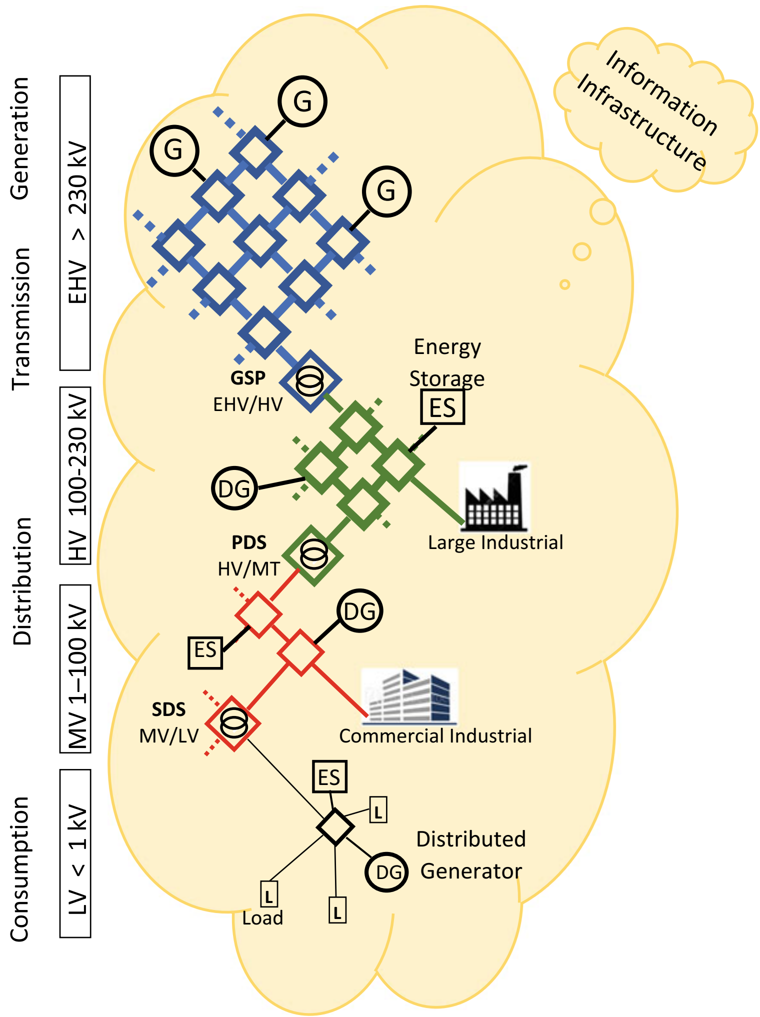

Fig. 3 From conventional structure to smart grid concept

3.2 Microgrids, Nanogrids and Picogrids

Due to the challenges of integrating DER in the distribution systems, a decentralised control concept is emerging to solve local problems and address fundamental changes in future grids.

Microgrids (MGs) are one way for providing that decentralisation of the generation resources [57]. There are many definitions of MG, most of which agree with some aspects that MGs may share. A MG can be defined as a cluster of micro-generators, ES, and loads, that operates as a single system [58], with clearly defined boundaries, with island capabilities. The MG can be connected or not to a main grid through a Point of Common Coupling (PCC) [20, 44]. A MG can operate independently from the grid in "island" mode or connected to it [87]. When the MG has a connection to the main power grid, all power deficit or surplus can be absorbed or delivered to the power grid. On the other hand, the balance must be satisfied locally by the MG itself, if it is autonomous or if it is operating in island mode.

As a natural extension of the MG concept [72], two less used concepts to configure a new hierarchical scheme are:

- *Nanogrid* (NG) can be defined as the grid of a building with DER and DS systems.
- *Picogrid* (PG) can be defined as an aggregation of the manageable loads connected in a household.

This hierarchical approach encompasses all the chain from households up to the distribution networks. In other words, PGs, NGs and MGs are the electricity grids which usually correspond to households, buildings and neighbourhoods respectively, and which are finally connected to the power distribution grid or to another MG.

PGs objectives are to carry out load management to minimise energy purchase costs (e.g., peak-shaving, load-shifting by price signals) and to execute orders resulting from the NG. Therefore, PGs do not include generation systems. These management systems could belong to an energy service provider (ESP) or an aggregator.

NGs not only use energy management algorithms in order to manage their loads, but also try to maximise DER integration. Thus, NGs are in charge of controlling local generation (e.g., small wind turbines and small photovoltaic generators), loads and PGs. NGs may also include DS (e.g., batteries from EVs). NGs could use building management system (BMS) from an ESP or aggregator/retailer to carry out their services.

MGs control NGs and micro-generation (micro-wind turbines, biomass boilers, Combined Heating, Cooling and Power—CHCP). MGs may be either connected to the electricity distribution network, or connected to another MG. Therefore, the main functions of MGs are to maximise DER integration and to assure isolated operation of the system when required. Thus, there will be two systems in this network: a MG Management System (MGMS) hosted by the DSO to guarantee stability and security in the network and an Aggregated Management System owned by an ESP or aggregator to manage the energy and economic exchanges of the MG and provide energy efficiency services.

3.3 Multi-Microgrids and Web of Cells

In the development from MG to smart grid, the new challenge becomes how to coordinate efficient and reliable operation of multiple sub-MGs. With more MGs interconnected to the power grid, the neighbouring MGs in a certain region form a multi-microgrid (MMG) system.

It is possible to classify MMGs from many technical aspects such as voltage level, AC/DC constitutional forms, phase-sequence constitutional forms, and functional aspects such as remote-area type, residential-area type, office-building type, industrial-park type. The optimal operation of MMGs is the core and hot issue of MMGs, which mainly includes islanded optimal operation and grid-connected optimal operation [125]:

(1) Islanded optimal operation of MMGs: the big difference with single MG is that MMGs can achieve optimal operation when off-grid through rationally allocating the idle resources of each sub-MG. In fact, continuous optimisation requires a combination of source/load power forecasting, and arranges the charge/discharge plan of ESS and switching of load based on the actual MMG operation states, to extend the running time of MMGs.
(2) Grid-connected optimal operation of MMGs: different from grid-connected operation control of single MG, MMGs can use a sub-MG as a decision-making individual to achieve the overall efficiency. Considering uncertainties in both RES and forecast electric loads, Hussain et al. [42] proposed a robust optimisation-based scheduling strategy to reduce the operation cost of MMGs system in grid-connected mode. Through the combination of source/load power forecasting, an optimal operation model can be established by considering the generation capacity of DGs, information of electricity price, load expectation of users, comfort, and other factors [128].

Web-of-Cells (WoC), [73] is a decentralised control scheme proposed to manage the power flow deviations of the local inter-cell connection line rather than the system frequency. The task of detecting and correcting these deviations in real time is delegated to the local operators. This results in less computational complexity and less communication. To limit the number of reserve activations, a peer-to-peer intercellular coordination mechanism has been proposed to obtain a compensation result of the localised imbalance. Local voltage problems will increase, and a local cell operator will have to handle them, due to their local nature. This opens up opportunities for more active voltage control, where local optimal set-points are repeatedly determined based on updated local information and forecasts.

4 Renewable Energy Sources

The development of ADNs includes the appropriate grid integration of the main RES, which nowadays are the solar energy by means of the PhotoVoltaic (PV) generators, and the wind energy by means of the Wind Turbines (WT).

In an electric power system, the grid integration of intrinsically intermittent power production means that a large amount of power generation (up to the majority of the total), with respect to the global power consumption, shall not create worsening, from both short-term and long-term perspectives, in the two fundamental tasks of the TSOs and the DSOs, that is:

- the stability of the common frequency in the voltage and current waveforms;
- the stability of the amplitude or root mean square (RMS) values of the voltage waveforms at the various voltage levels (HV, MV, and LV) in the networks.

The tasks can be accomplished by the so-called controls of *active power and frequency* (with adjustment at the global level) and *reactive power and voltage* (with adjustment down to the local level) [124].

Concerning the frequency stability, the global balance of the electric power systems between generation and consumption, including the power losses in the transmission lines, is achieved in real time, using the spinning reserves, under the control of the TSOs. They obtain this equilibrium by activating reserves according to the primary, secondary and tertiary controls, respectively with increasing time constants [26, 116].

Regarding a generation unit (centralised power station) involved in the control of active power and frequency, the local regulation consists of a speed droop characteristic by means of the speed governor. It is an analytical relationship (usually linear) between the speed of the synchronous generator (linked to the electric frequency) and the active power generated by the unit [124]. This curve provides the amount of speed reduction, as the required power is increased, starting from the no-load speed that corresponds to a frequency higher than the rated frequency of the grid.

On the other hand, the control of *reactive power and voltage* can be managed not only at HV by synchronous compensators but also at the MV and LV levels by capacitors or static var compensators. Therefore, intermittent RES like PV plants and WT parks can certainly participate to achieve the stability of the network voltage. In this sense, both active power and reactive power of users, at the end of the distribution lines, with their own sign, can cause either a voltage rise or a voltage drop over the distribution transformers and lines. As a voltage drop corresponds to a passive user that consumes both active power and reactive power (inductive behaviour), a voltage rise corresponds to an active user that produces both active power and reactive power (capacitive behaviour). Opposite signs of active power and reactive power of the users determine a compensation, with consequent reduction of the voltage perturbation.

Recently, on a national basis some TSOs have published technical specifications, for DG and in particular for PV plants, which provide rules regarding the following items during possible transient evolutions of frequency and voltage amplitudes:

- regulations of active power as a function of power frequency to reduce the generated power in the case of transient over-frequency event;
- regulations (both local and centralised ones) of reactive power with both capacitive and inductive behaviours, to counteract the transient under-voltage and over-voltage events.

In the sequel of this section, *five* specific subjects addressing the typical technical aspects of grid integration regarding the PV generators and wind turbines are presented.

The *power quality* of LV grids in case of PV generators, with rated power of some hundreds of kilowatts in normal operation and under partial shading of their

PV modules, is investigated in Spertino et al. [108], to provide details about the development of a new grid code in Italy to take into account the remarkable weight of PV and WT systems with intermittent production. This article discusses the power quality of LV grids in case of PV generators with rated power of some hundreds of kilowatts in normal operation and under partial shading of their PV modules. For real three-phase systems, the harmonic content of the current waveforms injected into the grid and the corresponding grid voltage waveforms, together with the unbalance and power factor evolutions, is assessed by extensive measurements from an experimental campaign. The results demonstrate that the harmonic content, the unbalance, and the power factor of PV generation do not create issues at the point of common coupling.

Unbalance of the three-phase currents in building-integrated PV systems may concern structural aspects of the installation, the effect of partial shading, or both. In Chicco et al. [14], specific unbalance indicators are given on the basis of measurements on a large building-integrated PV system that includes different types of unbalance. The values of indicators distinguish the balance and unbalance components that are affected by waveform distortion. These indices extend the usual definitions of unbalance, well-known from the power quality standards. The results show that the unbalance cannot be considered negligible, even with no single-phase inverter, and it is more significant if non-linear loads add a contribution to both harmonic distortion and unbalance from the viewpoint of the distribution transformer.

Considering *voltage control,* the centralised and distributed solutions at the LV level in the presence of strong PV generation are compared in Ciocia et al. [21]. The centralised devices under study are static var compensators and on load tap changers of MV-LV distribution transformers. The distributed devices are the grid-connected inverters for coupling the PV generators at LV level. An appropriate control of the inverters, proposed by managing their reactive power, permits to maintain the voltage fluctuations within prefixed limits over the distribution lines without an expensive investment on centralised devices at the MV-LV substation level. The simulation results show how the centralised and the distributed *voltage controls* interact over the length of the distribution lines.

From the viewpoint of *intermittent RES*, the joint production of PV and WT systems with electrochemical batteries is addressed for power stabilisation in Spertino et al. [109]. Starting from the estimation of the availability of the solar resource and wind resource for two sites in southern Italy, it is found that the global availability of the RES exceeds two thirds of the yearly hours. Then, to exploit this availability of at least one of the two resources, particularly the solar energy, the best type of load pattern is represented by the tertiary sector loads, as for example the commercial loads (in the specific case, communication companies). The capacities of the generation and the storage are determined in such a way as to minimise the power injection into the public grid, and to maximise the self-sufficiency of the users.

Considering a future perspective, the *planning* of PV and WT power is performed in Spertino et al. [110] with a simulation procedure to meet the consumption of aggregate users. The planning procedure is applied with the usage of batteries for large areas of sunny and windy regions (for instance the Mediterranean zone), taking into account not only the costs of investment, operation and maintenance, but also the revenues from the energy savings. The sites studied are five, located in Southern Italy, with mutual distances exceeding one hundred kilometers, while the solar resource and the wind resource are accurately measured by meteorological stations. The results are presented with respect to two objectives, namely, the maximisation of the electrical self-sufficiency for the aggregated users, and the optimal solution from the point of view of the economic investment.

5 Energy Conversion

In the energy conversion scenario, power electronics is an enabling technology. In recent years, power electronics applications continuously gained importance in the field of RES, electrical distribution systems and MGs. Moreover, many applications such as in the field of traction, data centres or telecommunication systems, use power systems with batteries and/or fuel cells to store energy and supply the required loads. In all these technical areas, power converters and related electronic switches have allowed a paradigm shift in the development and performance behaviour, improving power and energy systems. Remarkable advantages arise in the power converters extensive use, due to the increased availability of several converter topologies and power switches technologies choices, growing in the last decade. The improved converter switching capability and the feasibility of a suitable and redundant converter design allow advances in the dynamic performance, with extended operating range, reduced line harmonics, and adjustable power factor parameter.

5.1 Power Electronic Switches for Grid Applications

Silicon-based high-voltage semiconductor devices play the crucial role of switches applications in the conversion of high-power electronics (megawatt until gigawatt applications). The areas of use are related to traction drives, industrial applications, grid and microgrid systems. Instead, in lower power applications the wide bandgap (WBG) components, Silicon Carbide (SiC) and Gallium Nitride (GaN) are the next generation switches for high-performance power conversion. These high-performance devices are gradually replacing pure silicon Insulated Gate Bipolar Transistors (IGBTs) and Metal–Oxide–Semiconductor Field-Effect Transistors (MOSFETs) in different power electronics applications. The technology-developing trend leads that SiCs and GaN will be increasingly present in high power and high voltage applications in the next years. For very high-power applications such as the electrical power transmission, the Phase-Controlled Thyristor (PCT) is the electronic bipolar switch mainly used [120]. The PCT is applied mainly in controlled rectifiers and inverters. The PCT in the series connection is implemented in very high voltage converter or circuit breaker applications (hundreds of kV). Triggering the gate terminal can turn on these devices. The turn-off transient is obtained by natural commutation in AC converter circuit and forced commutation way in DC applications [65]. The Integrated Gate Commutated Thyristor (IGCT) and Injection Enhanced Gate Transistor (IEGT) are based on Gate Turn-off Thyristor (GTO) technology and allow turn-off and turn-on capability by the gate triggering [120]. The switching frequency is in the range of 100 Hz to few kHz. The bipolar gate-controlled devices applications are in the field of hundreds of megawatts. The IGBT is a flexible device with low-voltage and low-power gate-controlled switching transients [122]. The switching transients from a few kHz to one hundred kHz in the case of very speed low power devices. The IGBTs are mainly applied in medium and high-power converter topology. The breakdown voltage is up to 6 kV. In this high voltage switching scenario, it is important to not forget the power diode contribution, which covers the whole power range for rectification, snubber or freewheeling purposes.

The SiC devices feature high-switching performance and very favourable temperature behaviour [46, 79]. The SiC devices are the best competitors for the super-junction silicon MOSFET in their applications. Furthermore, the SiC technology today is getting closer and closer to the areas of application of IGBTs and is increasingly replacing it in applications such as battery chargers and converters for the automotive sector [46]. The GaN devices were born for the wireless and high-frequency electronic system applications. In recent years, the high switching performance is bringing the device to be used above all for low voltage applications (<100 V where the size of the electronic converter systems need to be optimised. The trend of growth of the GaN breakdown voltage and power management capability is high, consequently, the WBG switch in the next years will be more and more competitive with SiC devices [48].

5.2 Power Converter Topology for High Voltage Applications

The electrical energy is used in industrial, transportation, commercial and residential applications. In several uses, the electrical quantities need to be converted by suitable converter circuits in an appropriate electrical form, from AC to DC (AC/DC) or vice versa (DC/AC). The DC or AC voltage and current need to be controlled and regulated, from which there are DC/DC and AC/AC converters topologies. The range of energy conversion covers a few tens or hundreds of watts until tens of GW.

In medium and high-voltage applications, power electronics have a growing importance for industrial and traction applications as well as RES and power transmission. Several converter topologies are developed based on the conversion form need and power level rate. In the power transmission environment, the flexible alternating current transmission systems (FACTS) and high voltage direct current (HVDC) transmission use different power semiconductor-based circuit topologies such as Current Source Converters (CSC) and Voltage Source Converters (VSC). The power devices used in the converter topologies, employed for the DC/AC or AC/DC conversion process depending mainly on the transmission distance and power levels involved. Generally, the PCT devices in series connections are used in applications with very high-power demands such as cycloconverters, grid-commutated converters, or load-commutated converters [68]. Furthermore, CSC uses PCT because it is a kind of Line Commutated Converter (LCC) and the PCT is switched off when the current through it crosses zero, therefore, it requires line voltage for commutation. For long distances transmission equipment, CSC topologies are widely preferred due to their overall low system losses. In high-voltage industrial application, the pulse width modulation (PWM) current source inverter is applied to overcome the LCC drawback such as low-input power factor and distorted input current waveforms. In PWM controlled converter the VSC is predominant on the CSC solution [68]. With the advances in the technologies of the gate-controlled semiconductor switches, the VSC has become the cornerstone for industrial power conversion, while increasingly emerging as a viable option for HVDC applications. The VSC solution is mainly used at short transmission distances. In PWM VSC topologies the power switching devices are driven by a modulated square wave control signal. The capability of the device to be switched on and off as quickly as possible is very important for the converter dynamic performance, whereby devices from the GTO family or more performant IGBTs can be chosen over PCTs based on the required power level.

A series connection of semiconductor power electronic switches does not improve the power quality of the AC waveforms and is increasingly complex to implement, as the number of devices to be connected in series increases according to the voltage required by the electrical bus. The main issue is the different distribution of the voltage on the series-connected devices due to the unequal static and dynamic characteristics of the semiconductor components. The correct sharing of the static and dynamic devices blocking voltage is obtained with an additional circuit that increases the power losses and lowers the system reliability.

The multilevel power converter topologies are a viable solution to these drawbacks. The multilevel converters are an evolution of the two-level converter concept. In the multilevel solution, the power semiconductor switches are not connected directly in series. Modular Multilevel Converters (MMCs) are based on an identical basic cell, replicated n-times and interconnected with a few other components, usually diodes and capacitors, until the specific structure of the converter is obtained. The output of the MMC is a step stepped waveform voltage, which depends on the converter levels. The switching of the power devices allows the addition of the capacitor voltages, which reach high voltages at the output, while the power semiconductors have to withstand only reduced voltages [1]. The MMCs are useful for the possibility of splitting the total voltage of the DC-link on several active devices. In this way, they can withstand very high voltages (hundreds of kilovolts) contributing overall to drive loads of extreme power (hundreds of megawatts). Furthermore, in a multilevel converter, the availability of different voltage steps allows to more accurately emulate the trend of a sinusoidal voltage. For this reason, the harmonic level that can be calculated according to the Fourier analysis is naturally more contained in the multilevel reconstruction than the only two square wave levels (obtained in the two-level inverter). This results in a reduced Total Harmonic Distortion (THD). The THD decreases the more the voltage steps are numerous, increasing the power

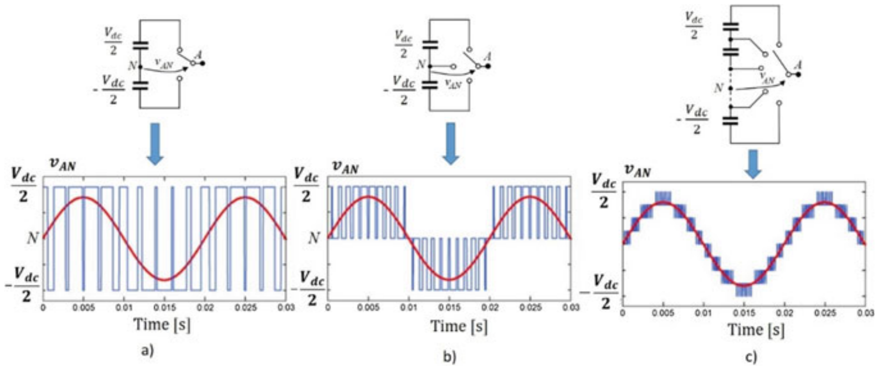

Fig. 4 Multilevel principle and output waveforms: **a** two-level switching pole, **b** three-level switching pole, **c** n-level switching pole and output waveforms with $n = 9$ [93]

quality. In Fig. 4 the evolution concept of the multilevel solution is shown [93]. In Fig. 4a the two-level switching pole is reported with the output voltage waveform, while in Fig. 4b there is the principle of the three-level switching pole with the improved output waveform quality. Finally, in Fig. 4c the concept of multilevel switching pole is generalised for n levels. The output voltage of Fig. 4c is related to 9-levels converter, the output voltage THD, in this case, is even more reduced than in the previous case.

In the area of the MMCs for high voltage inverter applications, mainly three multilevel topologies have been developed:

- diode-clamped (or Neutral Point Clamped—NPC);
- capacitor-clamped (flying capacitors—FLC);
- cascaded multicell with separate DC sources.

The NPC multilevel converter is composed of a stack based-on the switching pole (inverter leg) typical of two-level VSCs (Fig. 5a) arranged with a suitable clamping diodes connection to obtain the output step voltage. The three-level TPC topology switching pole of a single-phase VSC is depicted in Fig. 5b. The number of clamping diodes needed to share the voltage increases dramatically with the growth of the number of converter levels. For this reason, together with the increasing difficulty to control the dc-link capacitor unbalance, the industrial applications with TPC arrangement are mainly oriented on the three-levels converters.

The FLC topology is quite resembling the NPC converter. In FLC arrangement, the clamping diodes are replaced by flying capacitors. The most important difference with the NPC topology is that the FLC has a simpler modular structure, and it can be more easily extended to achieve high voltage multilevel converter [93]. In higher voltage applications, to increase the output voltage the multilevel solutions, the single switch of one leg of the switching pole is also made with two or three devices in series connection.

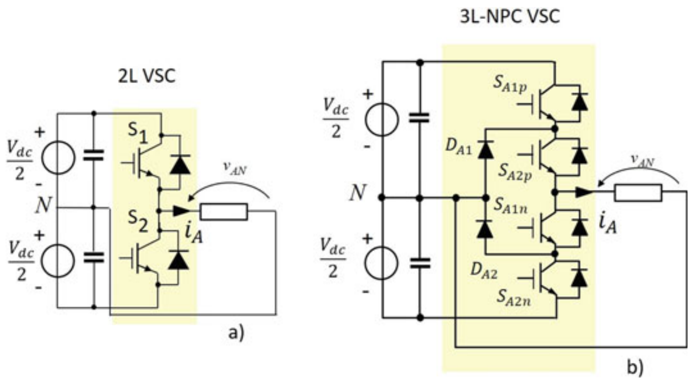

Fig. 5 **a** Two level VSC inverter leg switching pole, **b** three-level TPC topology switching pole for a single-phase VSC

NPC and FCC inverters have some difficulty relating to the management of high voltage capacitors and their voltage balancing. For this reason, other topologies have been investigated. The topology of multilevel converters based on serial single-phase converters (H-bridge) is a useful converter structure without the capacitors management drawback.

The Cascaded H-Bridge (CHB) converters with separate DC sources are multilevel converters composed of the series connection of two or more single-phase H-bridge inverters, hence the name. The CHB converters are capable to reach both higher voltage and power levels, but the converter topology requires a large number of isolated DC links. Every isolated DC link is achieved by a suitable isolated secondary path of a transformer with a rectifier circuit. Furthermore, the several H-bridges allow operation of the converter at lower switching frequencies and also facilitate loss distribution among all the power devices. Other multilevel promising topologies based on 3L T-Type Converter Topology or matrix converter have appeared in recent years, but industrial use is currently not very extensive [123]. Furthermore, hybrid multilevel converters have been investigated to mix the best features of various topologies [129]. A classification of the various power converter topologies for high voltage is reported in Fig. 6. To control the output waveforms in addition to the listed topologies, several modulation strategies have been developed to optimise the performance of the multilevel converters, such as multilevel sinusoidal PWM, multilevel selective harmonic elimination, and space-vector modulation [93].

5.3 *Converter Topologies in Microgrid Applications*

In a MG, numerous power converters are involved to integrate DER (i.e. microgenerators), energy storage devices (e.g. batteries, flywheels, super-capacitors, fuel-cell), and critical or flexible loads. In a MG, the whole resources and load interface are

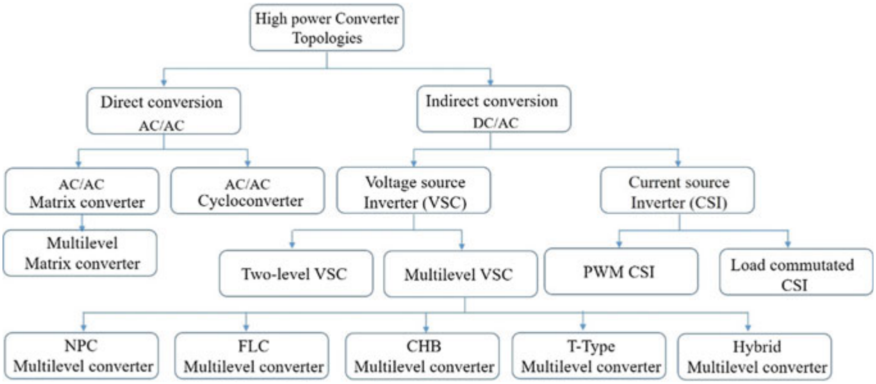

Fig. 6 Classification of power converter for high-voltage applications

managed by a suitable control system. The control system manages the fault conditions disconnecting the MG from the utility network as fast as possible [53]. MGs are generally interconnected to LV or MV utility grid by a direct connection or through an interfacing power converter. A basic network structure of an AC MG and its main components is shown in Fig. 7. The RES (wind and photovoltaic) are connected by a controlled rectifier circuit and an inverter to control the frequency and the voltage level at the AC network. A controlled AC/DC converter with a suitable power factor

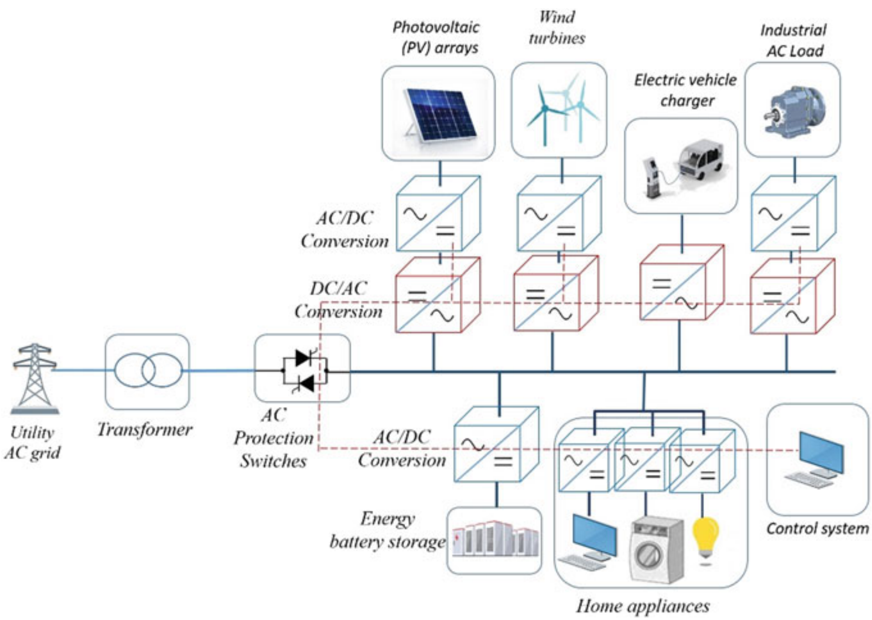

Fig. 7 AC microgrids and main power converter involved in the energy conversion

corrector are arranged to connect the EV battery charging station. The energy storage useful to obtain dispatchable sources is connected via a DC/AC converter to the AC main. The Industrial AC load needs a suitable AC/DC/AC conversion to control both the frequency and the power level to drive the AC motor. Furthermore, the AC loads in the residential home need several suitable power supplies.

The dynamic characteristics of the power converter allow improving the control of the specific load and the quality of the AC waveforms in the grid as well as the Electromagnetic Interference (EMI) content. In this direction, in recent years, the power converter has been used in the AC network to improve the power quality by a virtual synchronous generator [71]. Traditional electromagnetic transformers are also beginning to be replaced with solid-state transformers (SSTs) achieved through an AC/AC conversion circuits composed for example of two H-bridges with bidirectional devices, galvanically separated by a much smaller high-frequency transformer compared to a corresponding low-frequency electromagnetic transformer. The SST disadvantage (increasing complexity) is offset by the flexibility of the electrical quantities management and the possibility of full control that allows MG to be made increasingly smart and safety [41]. In DC MGs the power converters involved are shown in Fig. 8. In the DC network, the number of power converters is optimised. From Fig. 8, for example, it arises that the level three charging station and the energy storage system are interfaced through directly with a DC/DC converter to regulate both the voltage and current to the main DC link. Finally, the AC protection switches in the AC MGs are replaced by a further power converter (DC/AC) to allow and control the interconnection with the AC grid.

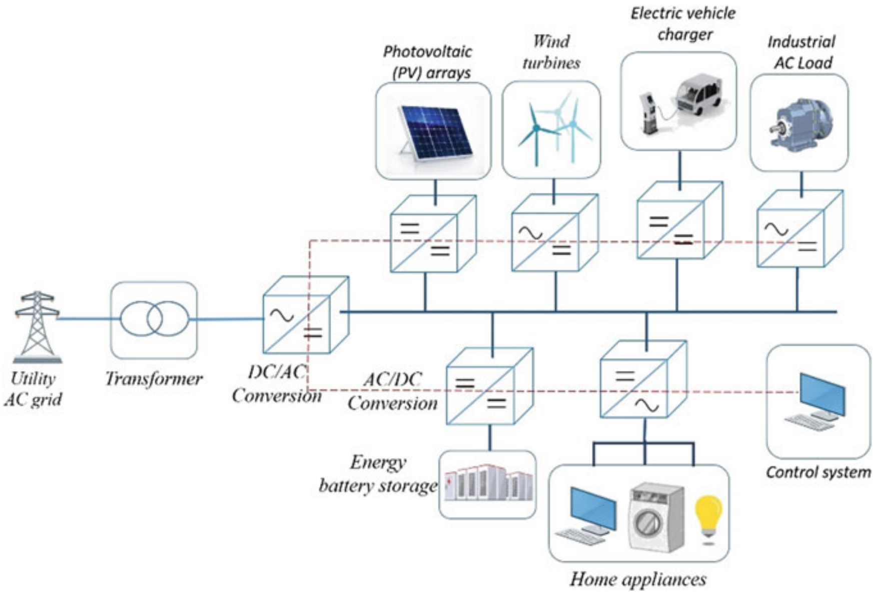

Fig. 8 DC microgrids and main power converter involved in the energy conversion

6 Operational Aspects

From the operational point of view, in ADNs some interesting aspects are gaining more attention in the recent years. In particular, the concept of Virtual Power Plant (VPP), the network optimisation, the supports to frequency and voltage control, and stability. In the next paragraphs, these four main aspects are briefly discussed.

6.1 Virtual Power Plants

Nowadays, significant changes in the way energy is generated can be observed. For example, the production from RES is significantly increasing due to the ambitious decarbonisation programmes imposed by governments to reduce the global warming, and due to the technological evolution. Moreover, thanks also to the energy market liberalisation, large generation power plants are being replaced by small distributed generators. Due to these changes, the electrical networks and the operational strategies of both DSOs and TSOs are, in turn, changing, with the aim of dispatching electrical energy with high quality standards.

From a technical point of view, this evolution is made necessary by the intermittent nature of some resources, such as wind and solar, which causes uncertainty in the electrical energy production. To face this problem, an innovative solution was proposed in 1997: the Virtual Power Plants (VPPs) [5, 91]. The idea consists of grouping together various small size DERs, including for example small size distributed power plants, RES, storage, controllable loads and EVs. Within a certain VPP, DERs can lay in large geographical areas [82]. The DERs are then managed by an energy management system [51]. Basically, the activities of this energy management system can be summarised in three steps. Firstly, it receives as inputs data about the actual productions and signals from the market at a certain time. Secondly, it forecasts the values of uncertain parameters, such as for example the renewable output power and the load demand [82, 126]. Thirdly, it coordinates the interconnected RES to maximise its objective function, in fact, optimal generation schedules for the management of a DER portfolio can be formulated by considering several objectives, such as the reduction of the internal operating cost structure or the maximisation of the profits [82]. In the optimisation problem, both the technical and the economical specifications of the system components can be considered.

From an external point of view, VPPs act as a conventional transmission connected power plant, and therefore are characterised by parameters such as scheduled output, ramp rates and voltage regulation capability [91]. Important examples of VPPs are already developed in Germany and UK, where thousands of units are interconnected together.

In conclusion, VPPs facilitate DER trading in the wholesale energy markets and can provide services to support transmission system management (e.g., various types of reserves, frequency and voltage regulation).

6.2 Optimisation

Optimisation is mainly related to the network configuration and to the DG dispatch in the operation phase, and to network reinforcement and DG placement in a planning phase.

ADNs can be active in terms of real-time optimisation of the network topology, the so-called network reconfiguration. Different optimisation objectives have been proposed in the literature, such as reducing network losses, improving the voltage profiles, load balancing, reducing service interruptions and therefore improving reliability indices, minimising fault currents, maximising local consumption of renewable energy, etc., or reconfiguration can be performed for service restoration after a fault. In addition, different optimisation algorithms have been proposed, based for example on simulated annealing, linear programming or heuristic techniques, tabu search, fuzzy reasoning approaches, genetic algorithms, vector immune systems, ant-colony, etc. Researchers often study multi-objective optimisation, usually based on the Pareto optimality criterion. In order to be able to perform ADN optimisation and reconfiguration, real-time data from the DN should be available, provided by an Advanced Metering System supported by a proper data management infrastructure [88, 89].

A second aspect of ADN optimisation is active dispatching of DGs. An optimised dispatch of DGs could significantly improve the acceptance of a large level of DER, mostly of the renewable type, into distribution grids [12].

A different aspect of ADN optimisation is the planning stage. Many researchers worked on active distribution systems expansion planning, e.g., rewiring, non-real-time network reconfiguration, installation of new protection devices, etc. In this case, it is extremely important to take uncertainties of loads and generation into account [25, 74], typically with scenario studies to represent the variability of the possible uncertainties on different parameters.

6.3 Frequency and Voltage Control, and Stability Issues

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subject to a physical disturbance, with most system variables bounded so that practically the entire system remains intact [55]. TSOs and DSOs shall ensure frequency and voltage stability. These tasks can be accomplished by the so-called “control of active power and frequency” and “control of reactive power and voltage”.

In electrical networks, the active power has to be generated at the same time it is consumed. Disturbances in this balance, causing a deviation of the system frequency from its set-point values, is offset initially by the kinetic energy of the rotating generating sets and motors connected. Later, primary controllers of the regulating units respond within few seconds, increasing or decreasing (according to the sign of the frequency deviation) the power delivered. Thanks to primary controllers, the balance between demand and generation is re-established, and consequently the frequency stabilises and remains at a quasi-steady-state value, even if it differs from the set-point. To restore the original frequency and the original power exchanges to their programmed set-point values, the secondary controller reacts in some tens of seconds. TSOs draw resources from primary, secondary and tertiary control reserves, which are pre-allocated powers dedicated to keep the frequency at the desired set-point [116]. All the power units with rated capacity greater than a specific threshold (e.g., 10 MW in Italy) shall contribute to the primary control reserve. Only those that are fed by non-programmable renewable sources do not contribute [113].

ADNs, if not correctly operated and controlled, can create problems in terms of voltage and frequency stability to the bulk power system. On the contrary, if properly controlled and operated, ADN can provide support to the frequency and voltage stability of the bulk power system. ADNs, in certain cases, may also operate in islanded mode. In this specific situation they should be controlled in order to guarantee the island voltage and frequency stability.

Frequency stability is a critical aspect especially in islanded ADNs. In the bulk power system, frequency stability is dominated by governors' responses. Frequency stability has been studied in "small" islanded power systems, for example in [39], considering as small a portion of the transmission network. However, in ADNs with high shares of RES, the problem of islanded operation is still to be studied in depth.

In ADNs the DGs and ES connected to the grid through VSCs may in the future provide support for frequency stability thanks to synthetic inertia and fast frequency responses, especially in low inertia power systems [27]. These are quite popular topics, being studied by researchers worldwide.

In a scenario with high RES penetration, frequency instability is a concrete risk for two reasons: firstly, the inertia of the system is lower; secondly, the primary control reserve is reduced. Moreover, in this kind of scenario, TSOs could need larger secondary and tertiary control reserves to stabilise the frequency, which means extra costs to find these services. RES power plants with high capacity can help the system in the frequency control thanks to the so-called *synthetic inertia*, which is the controlled response from a generating unit to mimic the exchange of rotational energy from a synchronous machine with the power system [27]. A different instrument that can contribute to stabilise the frequency is DR [24]: prosumers change their load/production to receive economic benefits. DR is a strategy that will have more and more importance in the next future, thanks also to the development of smart grid technology, controllable loads and DG [81]. In order to exploit numerous small energy resources, such as household appliances, aggregators are required, their tasks are to trade on the ancillary service market and to coordinate all the resources [34].

DERs can also have an impact on the voltage profile, determining voltages at certain nodes of the network that cannot be tolerate. Traditionally, voltage control is performed through the load tap changers of HV/MV transformers, in order to increase and decrease the turn ratio to compensate voltage drop along the feeders; power factor capacitor banks and static var compensators are equipment that can contribute to control the voltage profile as well. In case of a distribution network with DERs, this strategy could not be enough. This occurs when the power injected by local generators may cause an unacceptable voltage rise at one or more nodes, while the power withdrawn at load nodes causes an unacceptable voltage drop at these nodes. The probability of this scenario increases in case of long feeders and high injected/withdrawal power. To overcome these issues, innovative strategies shall be adopted, such as for example the decentralisation of voltage control, which however has to be coordinated to avoid the negative effects of independent decisions on the voltage profiles.

One of the key points related to voltage stability is voltage control and reactive power support, which could be provided in an active distribution grids, in addition to traditional controls from synchronous machines, by VSC-interfaced DGs [21, 70]. For this purpose, different control strategies could be applied, resorting to centralised or distributed control, both having advantages and disadvantages. A good compromise could in fact be a double layer hierarchical control, with a high level centralised control and a low level distributed control with the possibility of working autonomously in case of failure of the centralised control and communication system.

An important issue related to voltage stability is the interaction between transmission system and ADNs, especially in stressed network operating conditions. In case VSCs and DGs are not properly controlled in the distribution network, their behaviour may undermine the voltage control actions (e.g., tap changes) operated in the transmission system or at the HV/MV substation [4].

7 Economic Aspects

The significant presence of DERs in an ADN poses also problems related to the economic aspects. Indeed, when integrating responsive loads, DERs as well as prosumers in a distribution network, the economic framework is expected to change from a centralised approach to a distributed approach. One aspect which has been recognised as one of the most important is the novel approach to the *trading*, while an issue that accompanies this transformation is the determination of value-based signals together with the determination of adequate price signals to promote the participation of DERs into several operational problems of ADNs.

Along with the transition of distribution networks in ADNs, it arises the necessity of a transition of the energy markets in order to exploit the opportunities provided by the integration of all the entities connected to ADNs. The efficient integration of DERs into ADNs from an economic point-of-view will provide many benefits to end-users, among them, the possibility of increasing their flexibility, of reducing the electricity costs, of promoting RESs. Since existing energy market arrangements do not facilitate active coordination within distribution networks, new energy market mechanisms are emerging to allow the coordination in the distribution networks.

A local energy market is defined as "a platform on which prosumers and consumers trade energy supporting regional scopes such as a neighbourhood environment" [60, 132]. Following the classifications provided in Morstyn et al. [77], the local energy markets can be classified into markets based on a centralised approach, a distributed approach, the unidirectional pricing and, finally, on peer-to-peer energy trading. While in a centralised approach the DERs are directly scheduled by a central operator (e.g., the DSO), in the distributed approach iterative negotiations and local decision making are adopted. A different approach is based on the determination of adequate prices based on day-ahead forecasts that will be sent as unidirectional price signals to prosumers. Finally, some recent proposals lay the foundation on the application of transactive energy concepts, such as peer-to-peer energy trading, to make possible the direct negotiation among prosumers and active end-users connected to a distribution network. In this respect, the GridWise Architecture Council [37] has broadly defined transactive energy as "a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter".

Some insights with respect to the determination of prices in an ADN and concepts related to the transactive energy are provided in the next subsections.

7.1 Distribution Locational Marginal Prices

When designing an energy market in the new context of ADNs, it is crucial the choice of the pricing mechanism that should assure competition among the operators involved. Some authors have dedicated contributions to the extension of the concept of locational marginal prices from transmission level to distribution level by defining the so-called Distribution Locational Marginal Prices (DLMPs) [7, 61, 77, 86, 127].

As highlighted by Papavasiliou [86], price signals at the distribution level are needed to establish incentives for improving the efficiency of the generation, limiting losses in the distribution system, optimising the use of renewable sources, avoiding overloads or managing congestions, they are also essential for valuing ancillary services provided by distributed resources (e.g., responsive loads, generators and storage systems). Pricing energy and services at the distribution level is becoming an increasingly important aspect of electricity market design. The market design as well as the prices at distribution level have some peculiarities that do not belong to transmission markets; indeed, when a distribution system is considered, line losses, reactive power values and voltage levels have to be accounted for.

Li et al. [61] proposes a method based on the computation of the DLMPs for a distribution network integrating aggregators of EVs. In particular, the objective of the proposed method is to relieve congestions due to the charging of the EVs. The EV aggregators are assumed to behave as price takers in the local market and an optimisation of the social welfare is performed to calculate the values of DLMPs. Bai et al. [7] proposes a day-ahead market-clearing model for smart distribution systems including several types of DERs (i.e., DG, DS, MGs, and load aggregators). The DERs are supposed to be able to bid into the day-ahead distribution-level electricity market. When the day-ahead market is solved, the DLMPs for both active power and reactive power are determined. Since the model takes into consideration active power, reactive power, congestion, voltage levels and losses, the output of the day-ahead market will provide price signals for DERs to participate to the congestion management and voltage support.

A hierarchical mechanism is considered in Yuan et al. [127] to evaluate the DLMPs. In particular, the considered levels are the transmission network, the distribution network, and, at the lowest level, the local embedded networks or MGs. A probabilistic computation of DLMPs has been recently proposed in Morstyn et al. [77] with the application of the Point Estimate Method.

7.2 Transactive Energy for ADNs

Transactive Energy (TE) is a framework that can help the transformation of the distribution networks, which allows the effective integration of DERs and the active participation of the end-users in an ADN [40, 92]. TE refers to direct energy exchanges among prosumers by extending competitive market mechanisms at the electricity wholesale level down to the retail level [50, 92]. These relatively new concepts aim at developing an open-access, distribution-level retail market where prosumers will have access to a competing market, another objective is a more economic and efficient management of the ADN operations. Local energy markets are organised in such a way DERs and end users will be able to participate in the market to trade the energy or ancillary services without affecting the grid functionality [54].

In the TE framework, peer-to-peer (P2P) schemes, based on the concept of decentralised energy trading between peers, allows a better deployment of the DERs also using decentralised energy markets [36]. Conceptually, these schemes allow the prosumers to directly share their electrical energy and investment. Such markets lay their foundation on a consumer-centric and bottom-up perspective and consumers will have the opportunity of buying energy (and services) as they prefer [107].

The deployment of markets developed in the framework of TE need some emerging technologies, such as blockchain and other distributed ledger technologies [36, 132]. When the energy trading is involved, these technologies are needed for secure virtual transactions among users without intermediaries. Guerrero et al. [36] and Siano et al. [100] provide an overview on the enabling technologies for TE-based projects.

There are many proposals in the relevant literature and, also, some projects undergoing in the world. Many schemes and mechanisms have been proposed in the relevant literature to apply the TE concepts. Some of them are reviewed below.

A proposal for a TE market, for the optimal integration of DERs and MGs, is provided in Khorasany et al. [49]. A new market framework for DERs is required because value-based signals are needed. In the framework of the TE market, end-users and producers can exchange energy and other services in the distribution network under market rules. Khorasany et al. [49] present and discuss the Monash MGs as a real-world implementation of a TE market with the detailed description of the layered enabling architecture that extends the physical MGs. The pricing mechanisms based on the proposed design is simulated.

The P2P energy trading platforms for distribution networks proposed in Morstyn et al. [77] aims at setting a local energy market based on unidirectional locational pricing. To do that, a day-ahead locational pricing is proposed and solved in a probabilistic modelling in order to handle with demand uncertainty and upstream price uncertainty. The formulation of the problem includes network constraints and losses too. Local P2P energy trading platforms are integrated to additionally enable multi-period day-ahead P2P trading and single-period intra-day P2P trading, with transaction fees penalising energy transfers according to the probabilistic differential DLMPs.

Some proposals of TE markets rely on the MMG scenario; for instance in Kumar Nunna and Srinivasan [54] every MG trades its energy with neighbouring MGs in the market and, in the frame of a TE framework, a comprehensive energy management system is set with the aim of managing auxiliary energy resources such as DR and DS for several smart MGs. Another proposal is provided in Liu et al. [67] that considers a distributed day-ahead trading method for ADNs based on the technology of P2P, the method focuses on the congestion management in a MMG scenario.

Further insights and overviews can be found in Sousa et al. [107], that provides a review of peer-to-peer electricity markets, giving also a perspective on the community-based markets (i.e., a community is formed by prosumers which collaborate), and in Zia et al. [132], which is more focused on TE concepts applied to MGs.

8 Energy Management Aspects

8.1 Self-Sufficiency and Self-Consumption

In the recent decades, climate change has been raising concerns at the international level. In order to limit the global warming, the European Union has set climate and energy targets, which include the increase of the renewable energy share in the energy mix, the improvement of energy efficiency and the reduction of greenhouse gas emissions progressively up to 2050 [28]. Over the last years, energy policies led to the realisation and the cost reduction of technologies for renewable energy generation, for both large and small-scale use. As a result, businesses and households can produce electricity, fully or partially meeting their energy demand. Through the processes of Self-Consumption (SC) and Self-Sufficiency (SS), passive consumers are becoming active prosumers by totally or partially satisfying local consumption of energy by on-site production. The Self-Consumption $SC = E_{\text{lgc}}/E_{\text{gen}}$ is the ratio that quantify the on-site exploitation of the energy produced, calculated as the amount of electricity locally generated and consumed (E_{lgc}) with respect to the total local

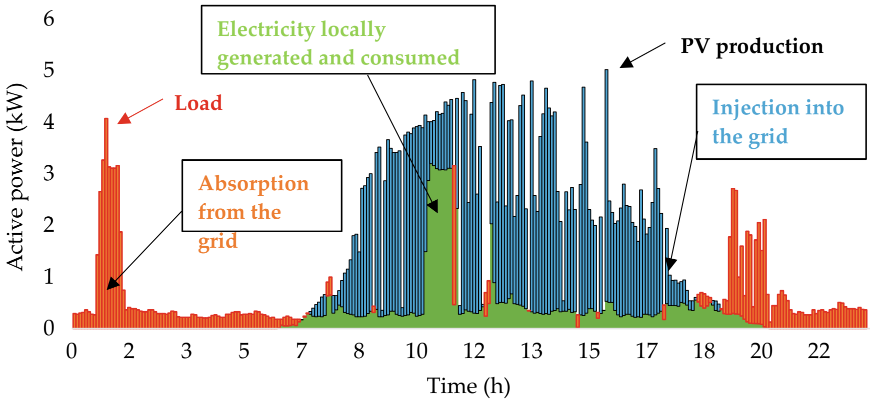

Fig. 9 Measured PV generation and load profiles in a house in Northern Italy

generation (E_{gen}) [112]. The user independence of the grid is calculated by the Self-Sufficiency $SS = E_{lgc}/E_{load}$, as the ratio between the energy locally generated and consumed (E_{lgc}, the same numerator of the SC) with respect to the total consumption (E_{load}).

In order to clarify the difference between self-consumption and self-sufficiency, PV generation and load profiles of a monitored house in Northern Italy are used as an example in Fig. 9. The time step is 5 min, in which the average values are considered.

The grid-connected PV plant with a rated power of 6 kW is used to supply the electric loads consisting of domestic appliances, induction cookers, and a heat pump for the production of domestic hot water. In this example, a cloudy summer day, the energy production from the PV system is 28.6 kWh. The total energy consumption is 14 kWh with power peaks at 1 a.m. and at 11 a.m. due to the heat pump, filling the storage tank of hot water, when its temperature is low. The green area is the PV electricity locally generated and consumed $E_{lgc} = 6.9$ kWh, the green area identifies the surplus energy generated by the PV system and injected into the grid $E_{surplus} = 21.6$ kWh, and the orange area indicates the energy absorbed from the grid $E_{abs} = 7.1$ kWh. The total load $E_{load} = 14$ kWh is the sum of E_{abs} and E_{lgc}. As a result, the self-sufficiency during this day is 50%, while the self-consumption is 24%. As a conclusion, during this day, the load is quite totally supplied by PV generation during light hours, with high surplus. The goal in future grids is to obtain both high SC and SS, i.e., the reduction of grid exchanges, both absorptions and injections. The consequences of high levels of SS and SC are several: higher acceptable capacity of renewable distributed generation into the electrical system, reduction of grid energy losses, mitigation of congestion problems and a less need for upgrading the electrical infrastructures [97]. The growing success of self-consumption is also related to the economic savings for energy users. Indeed, in some countries the renewable electricity has achieved *grid parity*, i.e., the expected unit cost of self-generated electricity is equal to or lower than the unit cost for electricity purchased from the grid.

Several techniques are used in order to obtain high self-consumption and self-sufficiency rates. They can be maximised by storing the generated energy for a later use, acting on the consumption or production profiles. A short description of these concepts is presented in the next paragraphs.

8.2 Energy Storage Systems

In recent years, the number of studies regarding the combined use of energy storage systems and generation systems from RES has grown. The use of RES to produce electricity makes the role of storage systems strategic [85]. RES energy generation cannot be set to meet the users' needs, because it strictly depends on the availability of the resource. A proper charge and discharge logic stores energy when generation is high, in order to use it in low production hours. The action of storage systems reduces the amount of energy absorbed from the grid to satisfy users' demand, and high self-consumption can be achieved. Furthermore, since higher RES penetration threatens grid stability and power quality, the use of proper storage technologies mitigates these negative effects [63].

There are several types of energy storage systems. They can be electrochemical, mechanical, electromagnetic or thermal storage. An overview of the energy storage technologies used in electric power systems can be found in Ould Amrouche et al. [85] and Mahatkar and Bachawad [69]. Each technology has its own characteristics, such as lifetime, costs, energy density, charge/discharge times and efficiency. For example, batteries have a time of response within seconds and a limited power output, while pumped hydroelectric storage and compressed air energy storage have a time of response of minutes, can provide more power, but they require a geographical location with specific features. The choice of the right storage depends on the application [69, 131]. The recent research is working on using storage from EVs to increase the self-sufficiency of the prosumers [33].

8.3 Load Shifting

Load shifting is the temporal translation of the peak hours demand towards periods characterised by low demand. It attenuates the maximum and minimum of the daily energy consumption curve, and optimises the use of existing generation resources. Load shifting can be obtained through the adoption of policies that encourage the use of energy in certain time slots, such as specific tariff structures, or through the direct control of electrical appliances, the use of which is not tied to a specific moment of the day [8].

In the case of self-generation of energy from intermittent RES, load shifting contributes to the increase in self-consumption, allowing the user to get an economic benefit and to better exploit the local energy resource. The economic savings obtained through the application of load shifting under time-varying energy pricing schemes are investigated in Farzambehboudi et al. [32], Sinha and De [106], and Vagropoulos et al. [119]. Moreover, load shifting and the other DR techniques help alleviating grid congestion problems, bringing benefits to the national grid [66].

8.4 Peak Demand Shaving

The generated power needs to match the demanded power at every time instant to avoid grid instability, voltage fluctuations and failures. For economic reasons, energy providers privilege the use of cheaper generating capacity, while more expensive power plants are turned on in case of peak demand conditions. The reduction of the peak load allows reducing the use of expensive generation capacity and increases providers' financial benefits. Thus, energy suppliers provide economic incentives for users to reduce peak loads [10]. For the case of self-generation of electricity, a better match between load and production profiles through peak demand shaving can enhance the exploitation of the local resource, increasing users' independence of the grid. In the literature, a large number of articles propose two methods for reducing load peaks: the use of energy storage systems and the application of DR techniques. Batteries are suggested for peak demand shaving for industrial customers [11, 84], residential applications [59] and tertiary sector users [111]. Dlamini and Cromieres [23] and Shen et al. [98] propose DR as management strategy of energy systems in order to provide peak load reduction.

8.5 Power Generation/Injection Curtailment

In the literature there are several articles that show strategies for curtailing the energy generation from RES, especially wind energy [64, 80, 99]. This limitation provides benefits for the electrical grid, avoiding overload and overvoltage events [94]. At the local level, power generation curtailment can contribute to match the energy production and consumption profiles in order to reduce the energy surplus. In PV generators, curtailments can be done by setting a limit to the inverter output, and the limitation is performed by moving away from the maximum power point in the current–voltage characteristic of the generator [2]. In wind turbines, generation can also be reduced by changing the blades orientation of the turbines from the optimal one. These solutions are the simplest, but not the most efficient, because they do not take into account the energy balance with local loads and battery operation. In fact, a more advanced and expensive solution could be the continuous monitoring of the power injected in the grid, and the consequent limitation in the generation.

9 Grid Services

9.1 Ancillary Services

The term *Ancillary Services* (AS) is typically used in the international power systems community. It refers to *essential services* for the operation of the electrical system. In general, the ASs can be partitioned into:

- AS based on *capacity* (power): frequency control, load following, and reserves (with different response times).
- AS based on *energy*: energy balancing, loss compensation, other reserves.
- AS for *system management*: load balancing, services to improve the system dynamics, support to maintain system stability, congestion management, backup supply, and black-start capability.
- *Other* AS: voltage and reactive power support, data management services, metering and billing.

The inverters used for the grid interface of the generation from RES can potentially provide a number of additional services [47], such as reactive power compensation (better seen as *power conditioning* and waveform improvement in the presence of distorted waveforms and light flicker), voltage control (inside the capability curve limits), frequency control with addition of synthetic inertia (from some wind systems), and fault ride-through capability, due to the requirement of maintaining in operation the local generators as much as possible after a fault in the network.

In addition, AS may be provided by storage and EVs. Storage systems provide *load following* capabilities by smoothing the fluctuations due to the intermittent RES generation or to load variations. The storage charging and discharging has to be appropriately coordinated taking into account the time-dependent constraints on the storage capacity, ramping and autonomy. Efficiency and aging of the storage systems have to be considered as well. In the prospect of an increasing diffusion of the plug-in EVs, there is a potential for these vehicles to behave as moving storage. Moreover, if plug-in EVs are able to supply power at relatively fast rates, they can provide equivalent spinning reserves. The bi-directional energy flow in a plug-in EV is potentially useful also for providing balancing services.

9.2 Flexibility and Multi-energy Services

The *operational flexibility* has been defined in Ulbig and Andersson [118], in a context with resources and reserves, as the technical ability of a power system unit to modulate electrical power feed-in to the grid and/or power out-feed from the grid over time. More generally, the flexibility services can be seen in a wider way than ASs, because they involve also aspects not directly connected with the grid, such as direct load control at the demand side or interactions between different energy carriers in multi-energy systems [15]. However, also these interactions may have an indirect impact to provide flexibility at the grid connection point. Operational flexibility of ADNs has been addressed in Li et al. [62] by flexibility availability and flexibility provision.

On the demand side, flexibility can be addressed for *individual* loads, by considering the availability of the users to postpone the operation of an appliance without reducing their comfort, or for the *aggregate* load, by considering possible benefits from the common management of a portfolio of users, as well as possible limitations due to the collective behaviour of the users in some periods of time (e.g., poor availability of the aggregate users for demand reduction in the morning period, Sajjad et al. [95]), and the aggregate flexibility that may be offered by loads controlled by thermostats [38, 130], or which offer flexibility services by using other types of control [22].

In more general terms, flexibility can be assessed in *energy community districts* by using a stochastic model for demand response resources [35]. In this case, available flexibilities may come from *energy vector substitution*, enabled by the presence of an auxiliary gas boiler or a combined heat and power system, or electric heat pumps and storage (electrical or thermal), which provide wider room for flexible management of the energy mix. In addition, changes in the temperature inside the buildings and end-service curtailments can be exploited for increasing flexibility. In any case, flexibility has to be assessed by avoiding that the *thermal comfort* of the occupants is reduced below agreed or imposed limits.

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Retail Electricity Markets for Active Distribution Systems

Nitin Padmanabhan

Abstract The distribution systems operations (both economic and technical) are seeing a paradigm shift as a result of increasing deployment of distributed energy resources (DERs) and smart grid technologies. The next-generation retail electricity market will promote decentralization, efficiency, and competitiveness by accommodating existing and new entities through new business models and transactive approaches. However, these changes will bring several technical challenges to be addressed specifically in distribution systems. This Chapter aims to present a brief review of the state-of-the-art of retail electricity market, some recent developments in this area, and a comprehensive vision of the next-generation distribution system level electricity market by addressing the important characteristics, the challenges, the needs, and the relevant future research areas to be addressed.

1 Introduction

The electricity market deregulation had seen the initial developments since the United Kingdom opened a power pool in April 1990 [1]; however, in the U.S. electricity markets the competitive entities have been largely silent since the California electricity crisis around early 2000. Thereafter, since the 2010s, as a result of the increasing contributions of the smart grid technologies along with some innovative information technology business models, the power sector reforms and new market mechanism designs have been gaining significant attention [2]. However, it is noted that most research on the electricity market still focuses on the wholesale market, particularly enhancing the efficiency and transparency of the bidding process and integrating new participants such as the distributed energy resources (DERs) [3, 4]. The development of the retail electricity market on the other hand prefers to follow principles, like multi-options, peer-to-peer, sharing economy friendliness, negotiability, and so on.

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Many countries are pushing the reform of the electricity power sector very positively. For example, Chile pioneered the deregulation of the electric power industry in the 1980s [5]. The European Union had taken steps to liberalize its electricity sector in the 1980slate but the customers had the privilege to choose their electricity suppliers starting from 2000s [6]. China's power sector along with other Asian countries saw the restructuring and regulatory reforms by beginning of 2000 [7]. The electricity retailing in Japan was fully deregulated with fierce competition in April 2016 [8]. While in the U.S. retail electricity market, 14 states have already adequate retail competition with Texas, Illinois, and Ohio having 100%, 60% and 50% of their residential customers receiving service from electricity suppliers. However, its is noted that many customers in the U.S. still have very limited option to have direct participation in the existing retail electricity markets. In Ontario (Canada), the Independent Electricity System Operator (IESO) has initiated a pilot project for retail electricity market with support from the local distribution companies in late 2020 [9].

The introduction of deregulation has brought several new entities in the electricity market place, while on the other hand redefining the scope of activities of many of the existing players. Variations exist across market structures over how each entity is particularly defined and over what role it play in the system. A depiction of the structure of deregulation—bilateral/multilateral at wholesale and retail level is shown in Figs. 1 and 2, respectively.

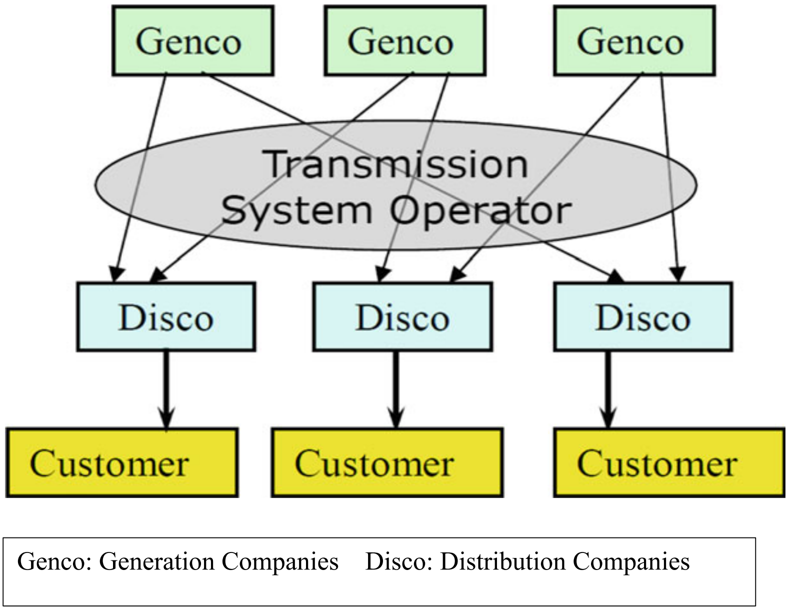

Fig. 1 Bilateral/multilateral transactions with wholesale competition

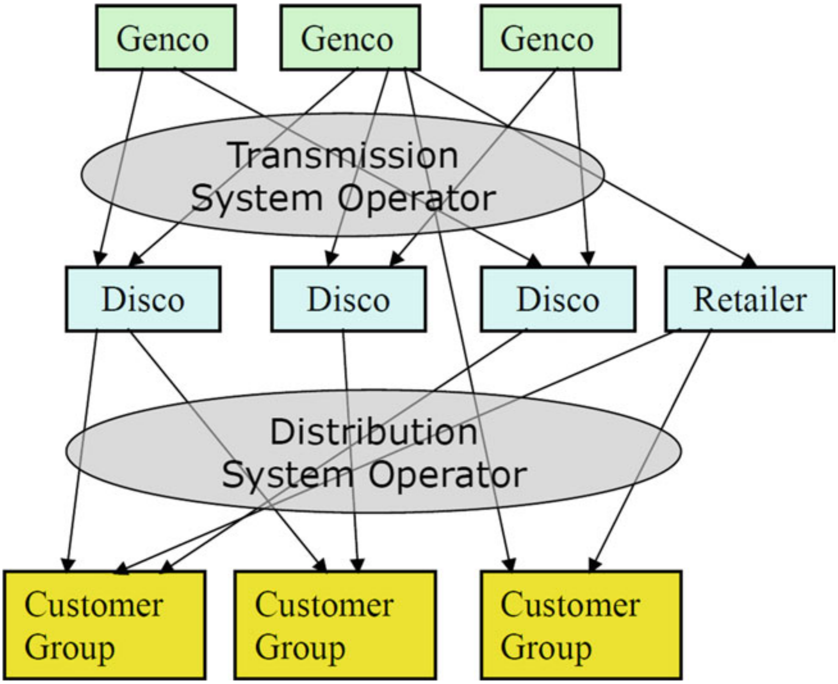

Fig. 2 Bilateral/multilateral transactions with wholesale and retail competition

One of the significant advancements in the distribution systems has been believed to be the development of customer-centric business models and well-designed demand side management (DSM) programs [10, 11]. With these developments, the next-generation retail electricity market will be a level playing field, where all customers have equal opportunity to play the role of active participants rather than pure passive price-taker [12, 13]. Furthermore, the recent development of the functionalities of the local distribution companies and the distribution system operator (DSO) has opened many new possibility for monitoring, coordinating and controlling short-term or real-time delivery of electricity at the distribution level. Especially with the further development of the concept of the DSO, deregulation of the electricity market has been spreading out from wholesale market design into retail market design, as noted from in Figs. 1 and 2. In the new paradigm for energy transactions, different customers or customer groups are free to choose their service provider, either a distribution company or utility company.

2 Retail Electricity Markets: Participants and Roles

The retail electricity market is the economic platform that facilitates the provision of electricity to retail customers. Traditionally, most retail customers worldwide were subjected to electricity rates defined by electric utilities and regulated by governmental entities. However, the liberalization of some retail electricity markets has promoted competition and diversification of services, enabling customers to choose from different services and suppliers. Liberalization made the retail electricity market more efficient by lowering the markup of retail prices over wholesale costs. In addition, the development of DER technologies enabled new types of retail tariffs and mechanisms for the integration of demand response (DR) and distributed generation (DG) into the distribution grid. In this Section, the different participants and their roles and features are explained, followed by the retail electricity market auction model.

The roles of retail market participants are significantly changing as smart grid technologies evolve and DERs spread in the distribution grid. The next-generation retail electricity market will see new entities and approaches, which will play important roles in the effective operation of transactive energy mechanisms and the provision of services to the distribution network. The main roles and responsibilities of the participants in the next-generation retail electricity market are briefly described below [14]:

2.1 DERs

The traditional way of generating, transmitting, and distributing electricity has been changing significantly as generating units become more distributed, efficient, and closer to consumption centers. The use of DERs, such as distributed photovoltaic (PV), energy storage systems (ESSs), and DR, combined with innovative smart grid technologies has been growing every year. DERs are not the most cost-effective option from a power system perspective, but many investments have been made worldwide in developing more affordable, flexible, and efficient solutions that enable greater adoption of these technologies at customer level, thus improving power system efficiency, reliability, flexibility, and helping several countries reach decarbonization targets.

As advanced metering infrastructures become more affordable, accessible, and spread in the distribution grid, more entities will take advantage of DERs, transforming conventional loads into smart loads, and conventional buildings into smart buildings and microgrids. Such technologies are provided with effective power management and control systems, and communication schemes that promote energy efficiency and allow direct interaction with external participants and systems. Thus, conventional passive customers will become active participants in the retail electricity market, by providing DERs in efficient and effective ways. Such active participants

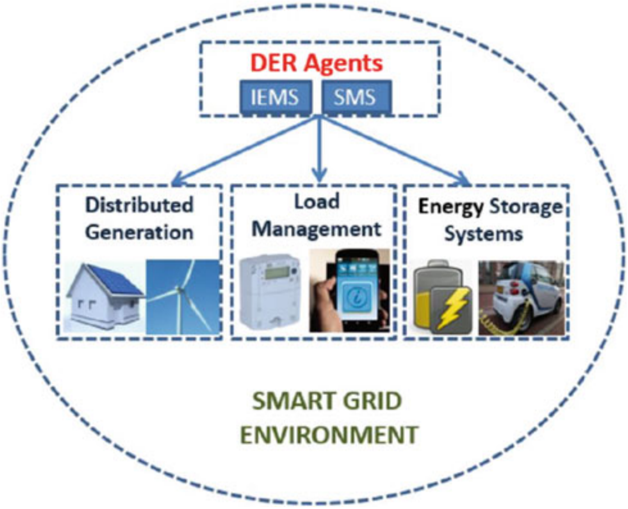

Fig. 3 DER participants in Smart Grids [15]

are defined as DER participants and their main technical capabilities are described as follows [14]:

1. DG: Small-scale production of electricity at distribution voltage levels. It can be based on variable renewable sources (e.g., PV systems), or systems that can be dispatched at any time (e.g., small gas turbine generators).

2. Load management (LM): Capability to receive and quickly respond to external signals to manage real-time electricity consumption, perform load shifting and scheduling, etc., through smart metering systems (SMSs), intelligent energy management systems (IEMSs), smart loads, etc.

3. Energy storage systems (ESSs): Capability to import, store, and export electricity to the grid via battery energy storage systems (BESSs), plug-in electric vehicles (PEVs) operating in the vehicle-to-grid (V2G) mode, and other energy storage technologies.

The management of DERs is performed through IEMSs and SMSs, whereby DER participants can receive and send information, set preferences, and control energy production, consumption, and storage in real-time. Figure 3 illustrates the concept of DER participants in the smart grid environment.

2.2 DR Providers

DSM is the planning and implementation of those utility activities designed to influence the customer's use of electricity in ways that will produce the desired changes in the utility's load shape, *i.e.*, changes in the pattern and magnitude of a utility's load

[4]. It comprises the whole range of management schemes linked with demand-side activities, and it can be classified into DR programs and Energy Efficiency programs.

Demand Response or DR is defined as "*changes in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized*" [4]. DR can be classified as:

Incentive based program (IBP): In this type of program, customer participation is recognized by providing incentives, since the utility can operate more economically and reliably. Some of the existing IBPs, such as direct load control (DLC), emergency DR, demand side bidding and buyback (DR auction markets) are briefly explained next [4].

1. DLC: The utility or system operator remotely turns off or changes the temperature set points of a customer's electrical equipment, such as air conditioner and water heater, on short notice, during critical periods. The customers are generally paid through an incentive mechanism in the form of electricity bill credits. Program participants are generally residential and small commercial customers. An example of DLC programs is the PeaksaverPLUS program, which is implemented in Ontario. In this program, residential customer's loads such as air conditioner and water heater are remotely controlled by the IESO [16].
2. Emergency DR Programs: Customers reduce their loads voluntarily when instructed by the ISO, and receive incentives based on a pre-specified rate offered by the utility. There is no penalty applied to the customers if they do not reduce the load when called for.
3. Demand Side Bidding (DR Auction Markets): These programs allow large customers to offer a certain amount of load reduction with an associated price in the wholesale electricity market auction. Once cleared in the auction, these are scheduled and dispatched in the same way as generators.

Price-Based Programs (PBP): Customers receive price signals for efficient and economic management of their loads. These DR programs encourage customers to alter their load pattern such that the system load profile is modified, and at the same time the customer's overall electricity cost is reduced. These include three main categories based on Time of use (TOU) rates, Critical peak pricing (CPP), and Real-time pricing (RTP) [4].

1. TOU Rates: These are pre-set tariff rates, depending on the time of the day and season of the year, in order to reduce the electricity use at certain time-periods.
2. CPP: It is a modified form of the TOU tariff where during critical peaks, prices are considerably higher than the average TOU rates. CPP reflects the system stress, and hence, even though these prices are pre-set, they are applied to customers on short notice, when required. An example of CPP program is the Industrial Conservation Initiative program, which is implemented in Ontario. In this program, industrial customer's loads are charged the Global Adjustment which is based on their load demand during the five coinciding peaks in the system [17].

3. RTP: Unlike TOU and CPP, RTP continuously varies and is not pre-set. This is related to the wholesale and retail electricity market, and encourages price responsiveness of customer in real-time markets.

2.3 LSEs

The LSEs consist of competitive retailers and utilities. The main difference between retailers and utilities is that utilities generally supply electricity to their customers and maintain power lines, transformers, substations, and other equipment in the distribution grid whereas retailers only resell electricity to their customers, having no ownership over any assets in the distribution grid. LSEs will continue to ensure the supply of energy at competitive prices and high-quality services to passive and active market participants, promote incentives for energy efficiency and DG, and bill retail customers for energy consumption and delivery charges.

2.4 Aggregators

For the sake of generality, aggregators and LSEs are described as separate entities since DER aggregation can be of two types: LSE aggregation and third-party aggregation. LSE aggregation refers to the capacity of LSEs to aggregate local DERs in its territory to support the needs of a local distribution grid or a transmission grid in cooperation with independent system operators (ISOs)/regional transmission operators (RTOs). On the other hand, third-party DER aggregation is performed by any entity other than LSEs and their individual customers, such as third-party investors.

2.5 DSOs

The DSOs are responsible for balancing supply and demand at the distribution level and close the gap between retail and wholesale markets. They will provide new functionalities to coordinate the participation of DER participants in the electricity markets (as market operators) and optimize technical operations in distribution grids (as grid operators). Working in the retail market operations, DSOs will balance supply and demand in the distribution grid, facilitate energy scheduling and settlements, coordinate the exchange of power with the wholesale market, and ensure the integrity and transparency of all transactions in the retail market. The common responsibilities of DSOs in both grid and market operations include the forecasting, planning, and integration of DERs as well as the social welfare maximization of all participants in their territory.

2.6 ISOs/RTOs

They are primarily responsible for the control and operation of transmission grids and wholesale markets, respectively. However, in the next-generation retail electricity market, such entities will work cooperatively with DSOs to ensure the transmission grid reliability by using DERs located in the distribution grid through transactive energy mechanisms.

3 Distribution Locational Marginal Price (DLMP) Based Retail Electricity Market: Framework & Auction Model

3.1 Framework

The DSO receives bids and offers from the various market participants. The loads submit the energy buy bids and the generators submit energy and spinning reserve offers. The structure of the demand bids and conventional generator offers are assumed to be in blocks of price-quantity pairs. With these inputs, the distribution system level retail (energy and spinning reserve) markets are simultaneously cleared using the novel and comprehensive joint optimization model, discussed in Sect. 3.2. It is to be noted that the model in Sect. 3.2 is a standard distribution level retail electricity market model considering generation offers and demand bids only. However, the model can be extended to consider the participation of ESS and DR providers. In such models, the ESS submit the charging bids the discharging offers for providing energy and spinning reserve service, similarly, the DR participants can provide energy curtailment and reserve offers in the market [18, 19]. The outcomes of the market settlement include the dispatch schedules, unit commitment (UC) decisions, and market prices (DLMPs). A retail electricity market framework is shown in Fig. 4.

3.2 Auction Model

The objective is to maximize the social welfare given as follows [18, 20]:

$$J = \sum_{k \in K} \sum_{i \in I} C^D_{i,k} P^D_{i,k} - \sum_{k \in K} \sum_{j \in J} \left(C^u_{j,k} U_{j,k} + C^d_{j,k} V_{j,k} + C^G_{j,k} P^G_{j,k} \right) \tag{1}$$

The first term in (1) represents the gross surplus of customers, the second term represents the total cost of gencos, which includes the start up cost, shut down cost and the energy cost. The model constraints are discussed next, and are based on [21].

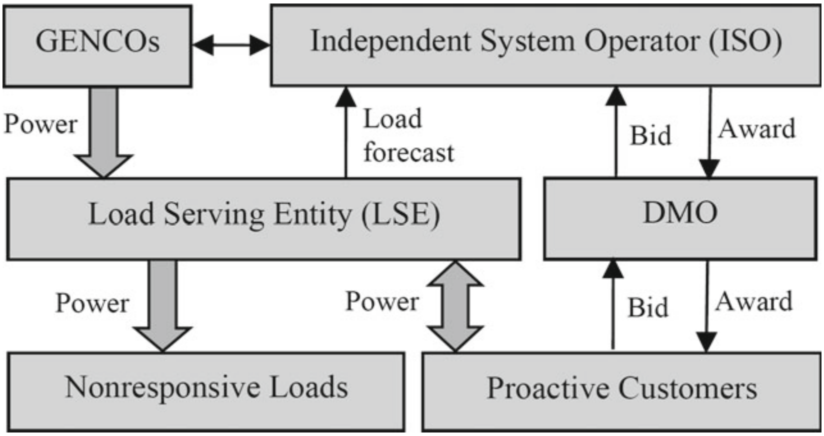

Fig. 4 Retail electricity market framework

Demand-supply Balance: These constraints ensure a balance between the supply and demand at each bus i at hour k.

$$\sum_{j \in E_j} P^G_{j,k} - P^D_{i,k} = \sum_{q \in I} \Big(B_{i,q}(\delta_{i,k} - \delta_{q,k}) \Big) \quad \forall k \in K, \forall i, q \in I \tag{2}$$

In constraints (2) the dc-optimal power flow (dc-opf) equations are used in place of ac power flow equations so as to reduce the computational burden. It is also to be noted that some DLMP-based market models include losses in the demand-supply balance.

Market Clearing Constraints: These constraints ensure that the cleared demand and generation quantities do not exceed their respective bid/offer quantities,

$$P^D_{i,k} \leq \overline{P}^D_{i,k} X_{i,k} \quad \forall k \in K, \forall i \in I \tag{3}$$

$$P^G_{j,k} \leq \overline{P}^G_{j,k} Y_{j,k} \quad \forall k \in K, \forall j \in J \tag{4}$$

Transmission Line Constraints: These constraints ensure that the line power flows on the transmission lines are within their limits.

$$P_{i,q,k} \leq \overline{PFlow}_{i,q} \quad \forall k \in K, \forall i, q \in I \tag{5}$$

where,

$$P_{i,q,k} = B_{i,q}(\delta_{i,k} - \delta_{q,k}) \quad \forall k \in K, \forall i, q \in I \tag{6}$$

Reserve Constraints: These constraint ensure that the spinning reserve requirement for the system is provided by the committed generators, as follows:

$$\sum_{j}(\bar{P}_j - P^G_{j,k})W_{j,k} \geq RESV \sum_{i} P^D_{i,k} \quad \forall k \in K \tag{7}$$

where, $RESV$ is a parameter decided by the DSO.

Generalized UC Constraints: These constraints include generation limits, ramp-up/down constraints, minimum-up/down time constraints and coordination constraints.

Generation Limits: The following constraints ensure that the output power of generator j at interval k is within its maximum and minimum limits.

$$\underline{P}_j W_{j,k} \leq P^G_{j,k} \leq \overline{P}_j W_{j,k} \quad \forall j \in J, \forall k \in K \tag{8}$$

Ramp-up/down constraints: The following constraints ensure that the ramp-up/down capability of the generator j at interval k is not violated,

$$P^G_{j,k} - P^G_{j,k-1} \leq RU_j \quad \forall j \in J, \forall k \geq 1 \tag{9}$$

$$P^G_{j,k-1} - P^G_{j,k} \leq RD_j \quad \forall j \in J, \forall k \geq 1 \tag{10}$$

Minimum Up/Down Time Constraints: The following constraints ensure that the generator j at interval k meets the minimum-up and down time, requirements [21].

$$\sum_{t=k-TU_j+1}^{k} U_{j,t} \;\leq\; W_{j,k} \quad \forall t \in [TU_j, K], \forall j \in J, \forall k \geq 1 \tag{11}$$

$$\sum_{t=k-TD_j+1}^{k} V_{j,t} \;\leq\; 1 - W_{j,k} \quad \forall t \in [TD_j, K], \forall j \in J, \forall k \geq 1 \tag{12}$$

Coordination Constraints: The following constraints ensure proper transition of UC states from 0 to 1 and vice-versa with unit start-up, shut-down decisions,

$$U_{j,k} - V_{j,k} = W_{j,k} - W_{j,k-1} \quad \forall j \in J, \forall k \geq 1 \tag{13}$$

$$U_{j,k} + V_{j,k} \leq 1 \quad \forall j \in J, k \tag{14}$$

4 Salient Characteristics of Future Retail Electricity Markets

The recent retail market developments described in the previous sections indicate that the current retail electricity market is evolving from a centralized and passive environment to a decentralized and interactive platform, where market participants can interact with each other and provide technical services to the electricity grid. This entails not only in new business models, but also in innovative regulatory paradigms and infrastructure upgrades. The salient characteristics of the future retail electricity markets are described as follows [14]:

4.1 Market and System System Optimization:

Market participants will be able to minimize costs, maximize revenues, and optimize the grid operation through timely, cost-effective, and safe transactive energy mechanisms that will promote the effective, reliable, and efficient integration of DERs for commercial and technical purposes. Furthermore, an efficient integration between retail and wholesale markets will allow DERs to be aggregated and effectively integrated into the wholesale market and the transmission system. The optimal management of DERs will facilitate the provision of affordable and fast-response ancillary services to distribution and transmission grids. The implementation of this paradigm would require high levels of real-time monitoring, protection, automation, and control to keep track, and large investments in enabling intelligent infrastructure (e.g., sensors, information systems, etc.).

4.2 Enhanced Flexibility

A flexible retail electricity market will be ready to accommodate new technologies and market entities by enhancing and expanding its infrastructure. Market participants will cope with uncertainties, such as electricity demand, electricity prices, and renewable energy generation through effective forecasting techniques and comprehensive decision-making strategies. In addition, a flexible retail electricity market will utilize its local resources to manage uncertainties, variations, and unforeseen events over various time horizons.

4.3 Customer Integration

A fully integrated retail electricity market is expected to maximize the social welfare of all market participants, accommodate a large number of diverse participants, and satisfy their needs and preferences in a competitive environment. Market platforms should be designed to allow the active participation and interaction of all participants and avoid market power and conflicts of interest by considering the strengths and limitations of each participant.

4.4 Sustainability

A sustainable retail electricity market will maximize the use of clean and renewable energy sources and promote energy efficiency initiatives through market mechanisms designed to reduce greenhouse gas emissions, mitigate load and network losses, and incentivize the use of environment-friendly technologies that will contribute to sustainability and energy efficiency.

5 Opportunities, Challenges, and Needs

In order to achieve the important characteristics described in Sect. 4, the present retail electricity market must be reformed to bring new opportunities for DERs integration as well as for properly address several challenges and needs. Some aspects are described as follows [15]:

5.1 New Business Models

As the number of DER participants increase in the distribution grid, comprehensive business models designed to accommodate, integrate, and allow the dynamic interaction of all retail electricity market participants will be needed. Such business models include clear rules and plans describing the market participants, their roles and interactions, products and services, as well as strategies to generate revenue, minimize costs, and maximize profits. The main elements and aspects of the new business models are described as follows:

5.1.1 Regulatory Modernization

The next-generation retail electricity market will depend massively on regulatory modernization in different jurisdictions. This includes market liberalization, decentralization as well as policies and incentives aimed to reduce the current dependency on centralized and pollutant power plants and incentivize the use and adoption of DERs. Today, in most countries, the concept of retail market liberalization and decentralization refers to the capacity of consumers to have freedom and independence to choose electricity suppliers and services according to their needs and preferences. Such a paradigm has promoted competition and cost reductions and increased innovation. However, in the context of DERs, liberalization and decentralization also include the provision of DG, LM, and ESSs for important energy services in a decentralized market framework. It is a long-term process that, to be successful, requires coordinated planning among governmental entities and all other involved sectors and participants. Furthermore, regulatory changes along with plans for investments in infrastructure and technology necessary to ensure all the characteristics described in Sect. 4 should take into account all possible economic and social benefits.

5.1.2 New Participants

The increasing adoption of smart grid technologies and DERs has brought several new participants in the distribution grid. Such participants include smart buildings, microgrids, ESSs, DR providers,and PEVs. However, their current participation in the retail electricity market is very limited since they are still under programs and tariffs imposed by electric utilities. Such programs and tariffs limit the active market participation and the provision of important energy services from DER participants, which can provide technical and economic benefits to the grid and to other market participants. The increasing number of DER participants will give rise to new entities to operate the distribution grid and facilitate market mechanisms in the retail level [22].

5.1.3 Transactive Energy Mechanisms:

The residential, industrial, and commercial sector account for a significant share of the system demand [7] and hence there exists ample opportunities for customers to provide DR services by modifying their loads. At the same time, there has been a significant increase in the residential ESS deployment in recent years. However, the participation of residential DR and ESS provisions for the flexibility services in wholesale electricity markets entails significant challenges, mainly due to the large number of customers and the negligible impact of each of them individually on the wholesale market. In this context, a transactive energy based operational framework for the LDC to efficiently utilize the flexibility of DR and ESS provisions at distribution level through aggregators is need of the hour. AN overview of the transactive energy framework is shown in Fig. 5.

Examples of transactive energy mechanisms include interactive bidding and offering platforms, and market clearing models capable to incorporate uncertainties from DG production, electricity demands, and wholesale market prices over different time horizons [23]. All transactive energy mechanisms should promote the information exchange among participants, facilitate the receipts and payments for energy services in real-time, and ensure price transparency. Thus, the real-time cost of power and ancillary services can be accessible to all market participants [24].

5.1.4 Competitiveness

The increase in DER use and adoption will stimulate competition in two ways. First, the incentives, subsidies, and other regulatory programs aimed to promote local

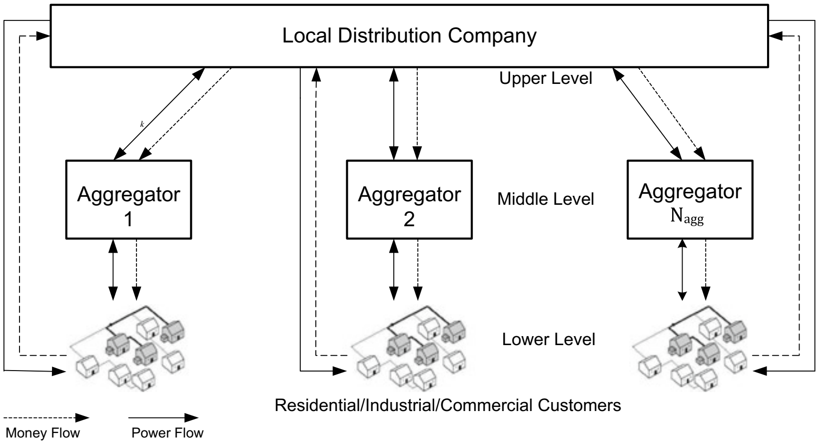

Fig. 5 Transactive energy framework

energy efficiency, flexibility, and sustainability will increase the competitiveness of DERs over centralized and non-renewable generation units. Without such regulatory programs, system operators are prone to use more centralized generation units since the widely use of DERs increases power system complexity and requires substantial infrastructure upgrades. Second, the creation of new business models and transactive energy mechanisms will stimulate retail market competition and, thus, promote lower electricity prices and better services. However, to ensure the social welfare maximization, the market rules and mechanisms should be clear, transparent, and fair to all market participants.

5.2 Innovative der Technologies

The massive adoption of DERs in the distribution grid will rely on innovative technologies aimed to increase efficiency, resilience, and flexibility to both technical and market operations in affordable ways. Existing technologies will be enhanced and expanded to provide additional functionalities. Some opportunities for enhancements and advances in DER technologies are described as follows:

5.2.1 DG Systems

In the last few years, DG systems have become more efficient and affordable. PV systems are currently the most used DG systems worldwide. Grid-tied PV systems are directly connected to the grid at all times and do not use storage systems. On the other hand, hybrid PV systems can operate in grid-tied form, charge batteries during the periods of low electricity prices, discharge batteries during the periods of high electricity prices, and even operate in the off-grid model. The development of innovative and clean DG system will promote a diversified portfolio of sustainable energy in the distribution grid. Furthermore, the power electronics of DG systems should be designed to provide high quality power supply, voltage regulation, and ancillary services in effective ways. Particularly, PV inverters should mitigate voltage rises, caused by reverse power flow from PV systems, through effective control strategies [25].

5.2.2 ESSs

The next-generation retail electricity market will rely on efficient and affordable energy storage technologies to manage a large share of intermittent resources. Furthermore, other existing ESSs such as flywheels and supercapacitors may also be improved and adapted to DER participants in the distribution grid.

5.2.3 PEVs

The recent advances in technologic, affordable, and customer-oriented PEV models boosted PEV sales in the last few years. The total U.S. PEV sales increased from fewer than 20,000 in 2009 to nearly 500,000 in 2022. PEVs can provide important DERs to the grid since they can act as loads and dispatchable ESSs. When not needed for transportation, PEVs can participate in DR programs and contribute to peak load reduction while being charged and can also operate in the V2G mode, when charged, to support the electricity grid needs such as energy dispatch, voltage regulation, and reactive power support [26]. In addition, PEVs can also operate in the vehicle-to-building mode under a grid voltage, and exchange power with charging stations and other PEVs.

5.2.4 Microgrids

DER proliferation and growing requirements from end users regarding reliability, resiliency, power quality, and efficiency have prompted a growing interest in both utility and customer-owned microgrids as a means to take advantage of some of the key benefits of DERs. While DER technology, analysis, standards, and relevant technical aspects required for microgrid deployment are evolving fast, existing regulatory frameworks are not ready to address the challenges associated with microgrid implementation. Aspects such as DER compensation, performance guarantees, liabilities, and participation of third-party providers in community or utility microgrids are areas that are still either undefined or not clearly defined, depending on the jurisdiction.

5.2.5 Smart Loads

Future low-voltage loads, such as electric vehicles, heating, ventilation, and air conditioning systems, lighting systems, and household appliances, should be designed to provide affordability, flexibility, energy efficiency, and easy communication with IEMSs, SMSs, and DSOs through adaptive and timely power control.

5.3 Grid Infrastructure and Operations

Presently, a large amount of DERs are behind-the-meter assets that are not directly available to grid operators due to limited distribution system awareness. These DERs result in making load forecasting and power system operations even more challenging. In this context, several advances in grid infrastructure and operations will be needed in the proposed vision of the next-generation retail electricity market to ensure the efficiency, reliability, and resiliency of distribution grids and support the needs of transmission grids through energy services coordinated by DSOs and transmission grid and wholesale market operators. Such advances are summarized into five aspects as follows:

5.3.1 Improved Control and Optimization Mechanism

The complexities associated with grid integration of DERs, transactive energy approaches, and the implementation of DSOs will challenge the existing control and optimization architectures in the electricity market. In particular, future DSOs will need to deal with a great number of DER participants and energy transactions in different buses of the distribution grid by producing adaptive control actions. Some of the technical aspects that should be considered in the decision-making strategies of DSOs include reactive supply and voltage control (Volt/Var control), self-healing actions, and many power flow constraints [27]. On the market operations, In general, all retail market participants should be able to collect, store, and analyze large sets of data through advanced architectures for data acquisition, transmission, storage, and processing. Big data analytics will play an important role for both technical and market operations in the distribution grid.

5.3.2 Strategic Grid Expansion Planning

The massive and widespread penetration of DERs in the distribution grid will bring more uncertainties and challenges to the transmission and distribution grid expansion planning strategies. The proper integration of DERs along with the development of transactive energy mechanisms may help defer investments on costly distribution and transmission grid assets. The REV strategy is a practical example of grid expansion planning considering DERs. This strategy focuses on the integration of DERs and nontraditional approaches, also referred to as non-wire alternatives (NWAs), into the planning of the distribution grid in the state of New York.

5.3.3 Forecasting

The uncertainties associated with the variability of short-term renewable energy production, energy consumption, energy storage levels, and electricity prices will challenge technical and market strategies in the distribution grid, thus requiring the development of advanced and accurate forecasting techniques to improve the decision-making strategies of retail market participants and allow the management of risks caused by unforeseen events [28]. New computational intelligence approaches capable of considering a vast number of uncertainties may be a potential solution towards this end.

5.3.4 Communications

Transactive energy mechanisms should be able to handle the vast amount of data coming from DER participants dispersed in the distribution grid and real-time information from wholesale markets and transmission grids. This will require advanced communication infrastructures as well as interconnectivity, interoperability, and scalability capabilities to allow real-time information exchange among retail market participants in different points of the distribution grid. Advanced wireless communication infrastructures with standard communication protocols will be essential to ensure information collection, dissemination, processing, and security. Energy Internet communication schemes may be a potential solution to allow effective communications and transactive energy mechanisms among market participants. EI, which is considered the evolution of smart grid, is an integrated grid of DERs, real-time monitoring, information sharing, and market transactions that provides energy packing and routing functions, similar to the Internet.

5.3.5 Cybersecurity

As the communication networks become more interconnected and interoperable, they become more vulnerable to deliberate attacks, such as those from disgruntled employees, espionage, and terrorists, as well as inadvertent compromises of the information systems due to natural disasters, equipment failures, and human errors. Such vulnerabilities might allow attackers to penetrate a network and destabilize the system in several ways [2]. In addition, in the event of an unauthorized disclosure and access to private and confidential data, market participants can orient their strategies to gain advantage illicitly and, thus, destabilize competitive energy trading mechanisms. Prevention should be the main goal, but preparation to respond and recover quickly should also be carefully planned. This will require advanced monitoring, sensing, and control mechanisms as well as standardized authentication and authorization strategies to ensure the system security and integrity. Blockchain and smart contracts may be a potential solution to facilitate auditable multiparty transactions based on prespecified rules between market participants and, thus, increase the trustworthiness, integrity, and resilience of energy transactions.

5.4 Distributed Grid Services

The next-generation retail electricity market will not only open economic transactions involving DERs, but also maximize the benefits of DERs to transmission and distribution grids through energy services designed to enhance and support the grid reliability and resilience. The main challenges and needs associated with the implementation of such services are described as follows:

5.4.1 Congestion and Losses Management

Presently, most electricity markets worldwide do not consider energy congestion and losses in distribution grids in the electricity price determination. However, the adoption of DLMP has been receiving increasing attention in the last few years as a potential solution to price congestion and losses in the distribution grid. The DLMPs can be decomposed into marginal costs for active power, reactive power, congestion, voltage support, and losses while considering the real value of DERs on each node of the distribution grid [29]. This will require powerful market clearing mechanisms capable of handling a large amount of decision variables while considering the imbalances and non-linearities of the distribution grid.

5.4.2 Markets for Ancillary Services

Ancillary services are essential energy services provided in addition to power generation to guarantee power system reliability, safety, and stability. In the present electricity market framework, such services are provided by large synchronous generators and coordinated by system operators in transmission grids via wholesale market operations. Several studies have shown potential ancillary services that can be provided by DERs through effective active and reactive power control of inverter-based DG, prompt load control, and proper management of ESSs, respectively [30]. However, the adoption of ancillary services provided by DERs should be accompanied by transactive energy mechanisms that facilitate the provision of those services locally to a distribution grid or aggregated to serve the needs of a transmission grid. Volt/VAR control is an example of ancillary service that may be provided to a local distribution grid by inverter-based DG. The next-generation retail electricity market should take advantage of the technical capabilities of DER participants and integrate effective transactive mechanisms for ancillary services. Thus, distribution and transmission grids may benefit from emerging DER participants to become more efficient and reliable.

5.4.3 Load Management

The existing price-based and incentive-based DR programs described in Sect. 2 do not explore all functionalities and capabilities provided by existing and emerging smart grid technologies to allow real-time load management as well as dynamic and effective interactions among DER participants and between DER participants and grid operators. Transactive energy mechanisms for load management will be extremely important in the next-generation retail electricity market as smart grid technologies continue to evolve and DER participants have their capabilities expanded to become active market participants and directly participate in real-time load management programs in effective ways.

6 Conclusions

The retail electricity market worldwide is changing due to the increasing integration of DERs in the distribution grid, the development of innovative smart grid technologies, and the necessity to ensure the reliability, resilience, and efficiency of transmission grids, and provide new services and functionalities to retail market participants. This Chapter presented an overview of the present retail electricity market describing the participants and their roles, the retail market framework and auction model. Then, some salient features of the future retail electricity market in the context of DERs has been presented. Finally, the opportunities, challenges, and need for DER integration for efficient and enhanced retail electricity markets been presented and discussed.

Appendix 1 - Abbreviations

BESS Battery Energy Storage System
CAISO California Independent System Operator
CPP Critical Peak Pricing
DER Distributed Energy Resource
DG Distributed generation
disco Distribution company
DLC Direct Load Control

DLMP Distribution Locational Marginal Price
DR Demand Response
DSM Demand-Side Management
DSO Distribution System Operator
ESS Energy Storage System
FERC Federal Energy Regulatory Commission
genco Generation company
IBP Incentive Based Program
IESO Independent Electricity System Operator
IEMSs Intelligent Energy Management Systems
ISO Independent System Operator
ISO-NE Independent System Operator New England
LM Load Management
LMP Locational Marginal Price
LSE Load Serving Entity
NWA Non-Wire Alternatives
NYISO New York Independent System Operator
OPF Optimal Power Flow
PBP Price Based Program
PEV Plug-in Electric Vehicle
PV Photo Voltaic
RTP Real Time Pricing
SMS Smart Metering Systems
SOC State of Charge
TOU Time of Use
UC Unit Commitment
V2G Vehicle-to-grid

Appendix 2 - Nomenclature

Sets & Indices

i, q Indices for the buses, $i \in I$.
j Index for the generators, $j \in J$.
k Indices for time (hour), $k \in K$.
E_i Set of generators connected to bus i.

Parameters

B	Element of susceptance matrix, p.u.
C^d, C^u	Start-up/shut-down cost of generator, \$.
C^D	Customer's demand bid price, \$/MWh.
C^G	Generator offer price for energy/spinning reserve, \$/MWh.
g	Conductance of transmission line, p.u..
$\overline{P}, \underline{P}$	Maximum/minimum limit on power output of generator, MW.
$\overline{P}^D$	Customer's demand bid quantity, MW.
$\overline{P}^G$	Generator offer quantity for energy, MW.
$\overline{PFlow}$	Maximum capacity of transmission line between buses, MW.
RU, RD	Ramp up/down limit of generator, MW/h.
TU, TD	Minimum up/down time of generator, hour.

Variables

P^D	Demand cleared, MW.
P^G	Generation offer cleared, MW.
P^{loss}	Power loss in the transmission line between buses i and q, MW.
U, V	Binary variable = 1, if generator starts/shut downs, and 0 otherwise.
W	Binary variable = 1, if generator is committed, and 0 otherwise.
X	Binary variable = 1, if demand bid is cleared, and 0 otherwise.
Y	Binary variable = 1, if generator offer is cleared, and 0 otherwise.
δ	Voltage angle of bus, radian.

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Practical Aspects of Active Distribution Networks

Active Demand Response Strategies for End-User Participation in Energy Services

Cláudia Abreu, David Rua, and João Peças Lopes

Abstract Electricity demand may vary significantly and consequently the generation side must be adapted to fully supply it. However, the increased penetration of variable renewable energy sources is changing the game by leading to an increase need of load response and load flexibility to face these changes from the generation side. Flexibility is highly related to the viability of Demand Response actions that can allow the participation of loads from buildings, clusters of communities, industry in market-driven energy services. Policymakers and energy stakeholders are beginning to prepare for a reality in which many consumers are also producers (prosumers) and operate with a significantly decentralized electricity grid. Also, the increased use of information and communication technologies is creating new opportunities for smarter control and load management schemes, interconnecting multiple demand-side stakeholders, where prosumers can leverage the potential for energy flexibility in demand-response programs. This chapter presents an overview of strategies to enable end-user participation in energy services, including building optimization schemes that provide load flexibility for the grid, as single users or as aggregated communities.

1 Demand Response in the EU and World Context

The energy system in all countries of the world has been in the last years in a constant state of transition. With the 2020 COVID-19 crisis, in addition to the immediate impact on health and implications for global economies, CO_2 emissions and

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electricity demand dropped to incomparable levels during the lockdown. For weeks, the shape of electricity demand was similar to a prolonged Sunday. It is expected that the impact of COVID-19 in energy demand would be more than seven times larger than the impact of the 2008 financial crisis on global energy demand [1]. Global CO_2 emissions are expected to decline by 8% as a result of the major disruptions activities brought by the pandemic. This reduction (year-to-year comparison), will be the largest ever recorded, twice as large as all other reductions since the end of World War II [2] Fig. 1.

In the 2020 atypical consumption scenario, renewables were the only source that were not affected by COVID-19 and presented growth in the electricity mix, driven by larger installed capacity and priority dispatch. Although, there are still some uncertainties about the future due to the expiry of incentives that is beginning to be noticeable in the forecast panorama. Sustained policy support is essential to enable strong growth in renewable energy beyond 2022. EU is particularly well-positioned to embrace renewable energies, especially wind and solar energy, thanks to its assertive policy of developing renewable energies. Yet, there is a long way to go to embrace the transition to wind and solar energy.

Aligned with the renewables growth's comes demand response options for residential, commercial, and industrial customers, that can provide flexible resources to meet specific renewable balance need. With electricity demand declining, the market for system flexibility will be reduced until demand is fully restored after the 2020 crisis.

Analysis from 2019 already showed that global demand response deployment is slowing down and there is a lot of effort needed to create flexible assets to meet 2050

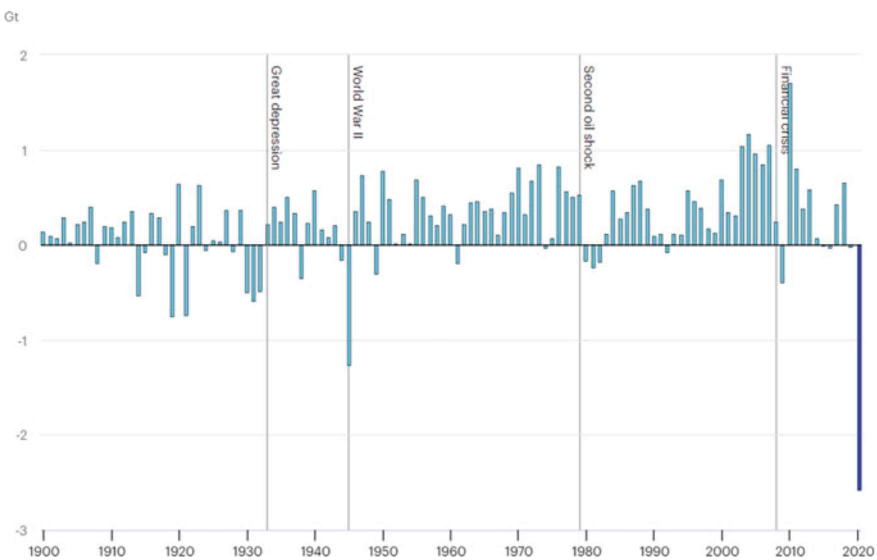

Fig. 1 Annual change in global energy-related CO_2 emissions, 1900–2020. *Source* IEA

goals. As for now, less than 2% of the global potential for demand-side flexibility is currently being utilized [3], so unlocking additional sources is essential. This is an opportunity for energy stakeholders to create value from new flexibility solutions in power markets. However, new opportunities usually add new complexities, and finding solutions that would suit all stakeholders has been a major focus of research in the energy sector. It is important to never lose sight of the fact that although there are many doubts about the future of the energy framework an answer remains unchanged as stated in Sioshansi [4]: "we know that even in the future, someone, somewhere, in some way will still be a consumer of electricity or a user of electricity-related assets or both. Business models will rise and fall, but the consumer will live on". It is important to note, that this evolution for an energy market where the focus will be on the consumer/prosumer can vary from country to country depending on several factors [4]. Retail prices, for instance, can differ for different reasons between nations and can highly affect the appearance of prosumers. Naturally, the higher they are, the more incentives consumers have to become prosumers. The role of policy and regulation on DERs is also crucial to allow and encourage custumers to invest in DERs. Finally, continuous innovation and technological advances allow, for instance, distributed solar revolution, making them more efficient and economically

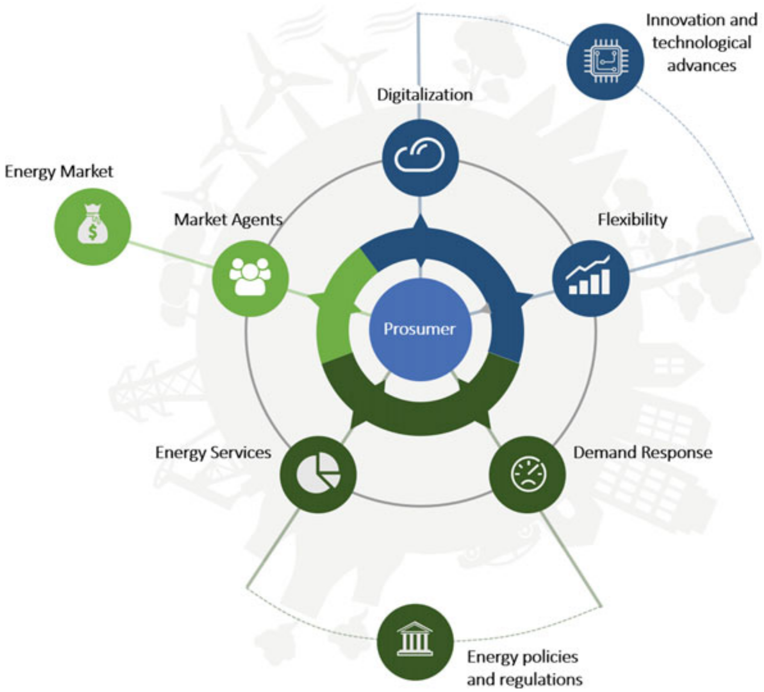

Fig. 2 Key factors that enable prosumer concept

viable over time. Thus, Fig. 2 focuses on some examples of key concepts that enable the prosumer concept and are the focus of this work.

1.1 Strategies and Services

In order to optimize the European climate policy framework, some actions have been taking place in the last decade. The Clean Energy Package initiated in 2014 developed a set of eight legislative acts on the energy performance of buildings, renewable energy, energy efficiency, governance, and electricity market design [5]. An essential element of the new electricity market design in the Clean Energy Package is the position of the consumer at the center of the energy transition. It is stated that the Member States must start to create legislation to allow consumers to participate in the market directly, or through aggregation. Customers can sell self-generated electricity, and they can choose to take part in flexibility and energy efficiency schemes. Also, provides for the possibility to establish the called citizen energy communities ('CECs') based on open and voluntary participation.

With the conclusion of the Clean Energy Package at the end of 2019, a new agreement was created as a successor. Green Deal, a roadmap for Europe becoming a climate-neutral continent by 2050, includes a better matching of the available technological and financial resources in line with the objectives and a broader perspective than the Clean Energy Package [6].

Regarding the energy performance of buildings, the EU has agreed with new rules to create economic opportunities in the construction industry and alleviate energy poverty. In the same way that the Member States need to start creating national policy measures to enable "prosumers" they also will now need to be prepared to achieve new objectives, such as: decarbonise buildings, facilitating more automation and control systems to make the building "smarter", E-mobility in buildings and combat energy poverty and reduce the household energy bills through renovation and improved energy performance of older buildings [7].

1.2 Main Regulatory Challenges and Limitations

In the last decades, European energy systems have faced significant changes driven by increased deployment of intermittent renewable generation to deal with the decarbonisation of the economy. One way of managing these changes and ensuring secure system operation is via the adoption of system flexibility, where demand response plays a key role.

DSOs can manage constraints in their networks with the activation of their flexible grid assets. Such actions are a default option and can be applied before or at the same time as considering market-based management. If a DSO cannot solve a problem with its own assets (e.g., topology changes, tap changers, voltage boosters, etc.)

it may need to invest in new assets. However, the use of flexibility for congestion management could be the better solution economically.

From a regulatory point of view, DSOs can access flexibility in Europe exploiting four manners:

- Rules-based approach—codes and rules, which impose detailed flexibility requirements;
- Connection Agreements—DSOs could reach arrangements with network users for the provision of flexibility;
- Network Tariffs—tariff structures may be designed to encourage network users to change their behavior for more efficient use of the distribution network;
- Market-based Procurement—DSOs can explicitly procure flexibility that benefits the grid services from the market. Flexibility can be procured via (bilateral) contracts or in a market, e.g., via a platform or other forms of interfaces, given there is enough liquidity and arrangements for the market-based procurement do not unduly distort markets and comply with unbundling rules.

Network users can, in theory, utilize 100% of its contracted volume or capacity whenever they want. However, in Low Voltage (LV) distribution grids, this may become a problem. LV networks are usually dimensioned with a certain simultaneous factor, taken into account that not all network users withdraw or operate their appliances at full power at their connection points at the same time. This grid planning philosophy of connect and forget is challenged by new consumptions devices (like heat pumps and electric vehicle charging) with different patterns characterized by greater power demand on one side, and RES with simultaneous infeed on the other, which are expected to exceed the network's capacity in both directions. A network user's rights to utilize its contracted volume usually do not differentiate between the two. Consequently, connection agreements by themselves provide no incentives for existing network users to adapt to the capacity currently available from the grid.

Network tariffs can provide incentives for efficient usage of the grid to network users and contribute towards limiting or postponing network investments and solving or avoiding congestion situations. The network users should be exposed to price signals that reflect that changes in their utilization of the grid affect future network costs. The tariff design should be targeted at reducing both the system peak and individual peaks. As an example, tariffs based on the peak capacity of the network user will lead to behavior where the peak is reduced as much as possible. In this way, the tariff structures affect the subsequent flexibility needed by the DSO. Advanced differentiation in time and location, for example through dynamic tariffs, may further incentivize network beneficial behavior. It must be noted, however, that the effectiveness of dynamic tariffs firstly depends on the actual existence of customer flexible demand response.

Market-based procurement is then the preferred option because the procurement of flexibility on a competitive basis would be efficient as long as markets are liquid, overall costs are lower than in alternative solutions, DSOs comply with unbundling rules and market misuse potential is acceptable.

Congestion management costs are classified as operational expenditures (OPEX), whereas network expansion costs are classified as capital expenditures (CAPEX). A DSO wishing to make improvements from an economic perspective would make the decision that is most attractive from the point of view of the revenue/remuneration regime. Some regulation schemes in Europe have a bias towards CAPEX solutions, e.g., due to an attractive rate of return on equity or a direct reflection of CAPEX in the price/revenue cap, whereas OPEX may occur in the revenue allowance with a certain lag, or even be treated separately in a variety of ways. Overall, a different regulatory treatment of OPEX and CAPEX leads to the lack of a level-playing-field in terms of the DSOs' choices of how to dimension their networks.

The market procurement procedure is the key process to appropriately signal the need for flexibility and acquire the necessary resources to engage in congestion management or voltage control in a cost-efficient manner. Network development plans are an important tool to elaborate on the first step and aim to help improve liquidity by providing information to potentially interested parties. If the market-based approach is deemed efficient several issues need to be assessed from the regulatory point of view, namely: product design, controllability, imbalance settlement, and market model. In what concerns the procurement procedure, the following important elements were also identified:

1. Flexibility demand: DSOs must signal and publish their need;
2. Request for tenders: should be as broad as possible; and
3. Product requirements: must be properly defined and preferably based on standards.

2 Digitalization for Demand Side Participation

The current and future generations are privileged to be living in a time where science and technology can assist everyone on a daily basis and automate things that would appear impossible two decades ago. And, like any other field, the energy sector is not getting behind.

Smart grids are a clear example of the integration of digital technologies in the energy sector, as they are about information exchange and making necessary data available to interested parties. Although there has already been a huge advance in the development and application of smart grids concept, there is still a long way to go. Effective smart grids should allow enhanced monitoring, automation, and control of the existing networks while ensuring that all involved stakeholders can interact: this will be made possible by a full digitalization of the power system.

Digitalization enables smart grids, houses, vehicles to provide new sources of demand-side flexibility to the energy system. With more renewable energy and enabling self-consumption by the community, the end result is a more efficient energy system, due to losses reduction associated with energy production and distribution [8].

The increased use of information and communication technologies (ICT) is setting new opportunities for more intelligent control and management schemes interconnecting several stakeholders in the electric industry as well as in the demand side where service providers and consumers (lately also known as prosumers) can leverage the potential of energy flexibility in demand response programs.

2.1 Distribution Grids Systems

The digitalization of the electric sector has been accomplished in several phases, mainly driven by operational requirements and existing technologies.

The first wave towards the transition to digitalization in distribution grid systems was ensured by the introduction of SCADA systems in the control and operation of the grid along with remotely operated devices and systems, such as breakers and reclosers. Also, the need to collect information from metered data from the consumption side, to reduce costs of manual labor and increase the collectible data (in size and regularity) as set the need to support remote metering or, as it is also known, as smart meters that allow the integration of grid control and automation features near the demand side.

The smart grid definition has paved the way for the second wave of digitalization and intelligence to be introduced in the grid domain to deal with the variability of the operating conditions in the grid due to the large-scale integration of renewable generation at different voltage levels, induced by energy policies worldwide (EU, US, China, etc.). The need to support distributed control strategies to deal with uncertainty has introduced concepts such as microgrids and virtual power plants, where the use of distributed energy resources (DER) has been exploited alongside load control strategies to ensure high system efficiency, reliability, and carbon footprint reduction of energy use.

The third wave, currently ongoing, is where predictability of electric systems operation, supported by widespread data collection of intelligent sensing systems and advanced control infrastructures, is being articulated with data-driven strategies to represent the operation of systems, which also include the generation and the demand side. The articulation of grid-related platforms with building energy management systems has created opportunities towards the adoption of energy and non-energy services, which can span across several domains as well as to accommodate several providers in the same domain. The flexibility of energy use is one of the resources most sought after as it can allow the participation of the demand-side on a set of different services (e.g., demand response, ancillary services, etc.).

The foreseeable next waves are bounded to be associated with interoperability and the ability to exchange information across several domains in a way that allows different services to be provided to consumers, namely the case where multiple providers of services may coexist in the same building domain (e.g., electric hot water, EV charging, PV integration).

2.2 Building Energy Management Systems

A growing number of simulation tools are currently available to improve understanding of the interaction of the building components that contribute to energy demand. It is already possible to create a ‘digital twin’ of the entire building with all its systems. Digital Twins enable an advanced approach to building management, through real-time decision making. These technologies not only deliver the current state of building subsystems but, through the collection of data, also provide a map of system trends to influence future management decisions.

One key element in the interaction among users and energy systems within a household is the Energy Management Systems (EMS), which can take several specialized designations: Home Energy Management System (HEMS), Building Energy Management Systems (BEMS), etc. The purpose of the EMS is to provide computational support towards the implementation of optimal energy actions to be carried out according to the optimization objectives, which can be multiple. In this sense, the EMS provides support also to data storage regarding the energy use related to several devices and systems within buildings. That data allows the creation of models that represent the operation of single devices, clusters, and ultimately the building itself.

The digitalization of buildings is set to provide a significant amount of information of existing devices and systems, including flexible loads and renewable generation, regarding their use and performance. This can be used to create predictive tools as well as data-driven modeling, able to circumvent the limitations induced by physical modeling, and allow the creation of flexible representations. Flexibility is a characteristic highly related to the viability of Demand Response (DR) actions that can allow the participation of buildings, clusters of communities in market-driven energy services.

The complexity of the optimization schemes, as well as the underlying modelling of flexible energy resources in building, can require significant computational effort, especially when dealing with several buildings, where multi-objective formulations may be required. Traditional optimization techniques and models have been employed in market products to provide price-based optimization for buildings but there is still ongoing research in delivering faster algorithms, based on sub-optimal formulations or employing metaheuristics, such as genetic algorithms and cross-entropy optimization.

The challenge in connecting all devices and systems lies in the multiple ICT solutions available and the implementation choices made by the different manufacturers and integrators.

2.3 Interoperability

Interoperability is a key aspect in the digitalization of the electric sector, including the demand side. Technology implementation is already capable of providing large and extensive datasets that need common ground to enable modular and easier access to service composition that allows exploiting the advantages of flexibility through the underlying devices and systems.

Interoperability is a fundamental requirement to enable uncompromised data exchange with different appliances and systems. This allows end-users and computational platforms, such as EMS, to be able to extract information from devices and systems regarding their characteristics, configurations and to be able to make decisions on the way they are used. End-users should be able to change their technology providers, without having to replace existing systems or become dependent on proprietary solutions with limited compatibility among manufacturers. This creates barriers to innovative management and control schemes and hinders the provision of competitive energy and non-energy services. This is seen by several entities, like the EC, as a limitation that needs to be addressed by several stakeholders.

Interoperability can be set at different levels, as portrayed below in the GWAC interoperability framework [9] where sematic interoperability is highlighted. Its importance is fundamental in the orchestration and knowledge inference that can improve automated logic procedures in M2M data exchange (Fig. 3).

Different interoperability approaches have been developed over time, however most of them with a specific focus. For instance:

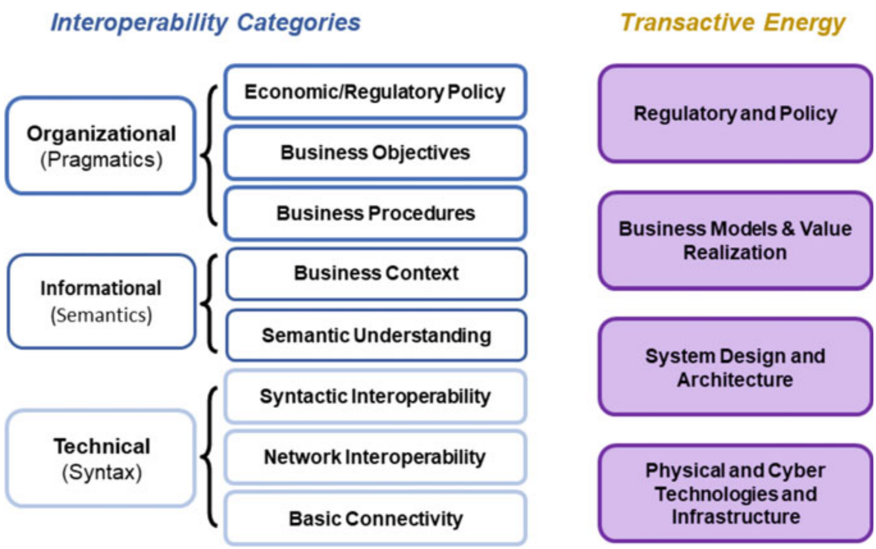

Fig. 3 GWAC interoperability [9]

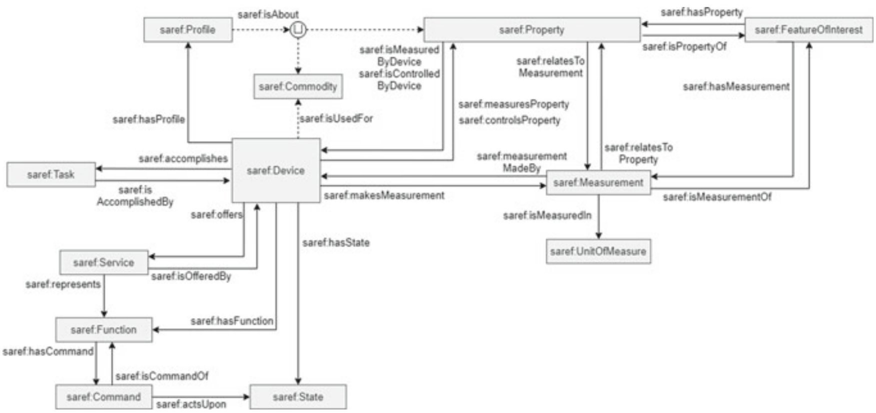

Fig. 4 Overview of SAREF. *Source* ETSI

- Common Information Model (CIM), was internationally standardized by the IEC [10] for Demand Response. However, this model has some limitations and contradictions and is over a decade old so was created based on centralized energy systems. Also, the CIM was designed in UML, so only represents relatively simple relationships and expressions.
- SPINE (Smart Premises Interoperable Neutral-message Exchange) [11] was developed by EEBUS and Energy@home for smart appliances representation and communication between applications and EMS to allow the use of device-related information towards the implementation of price-based optimization strategies.

EC made progress by launching a standardization initiative in collaboration with the European Telecommunications Standards Institute (ETSI) to create a shared semantic model of consensus to enable interoperability in the smart appliances domain. This resulted in the definition of the Smart Appliances REFerence ontology (SAREF) [11]. SAREF was created with the purpose of interconnecting data from different protocols and platforms, enabling communication between different in-home devices and systems. Aligned with the IoT concept, SAREF introduces the basis for a universal semantic representation as a common reference model, as highlighted in Fig. 4. It sets classes, properties, instances and namespaces of an ontology that facilitates the grouping of information and the semantic reasoning that allows inference of new knowledge.

Large scale pilots under Horizon 2020 are already in progress that targets smart homes and will allow companies to work together and test new business models. For instance, InterConnect [12] project is a clear example of different stakeholders working together to demonstrate a “real digital market environment over electrical systems with significant amounts of DSF, reducing operational and investment costs that will benefit energy end-users and help EU achieve its energy efficiency objectives”.

3 New Services and Business Models

Policymakers and energy stakeholders are starting to be prepared for a reality in which many consumers are also producers and operate with a significantly more decentralized electricity grid. This transformation is introducing new business opportunities that enhance the need of all participants (consumers, flexibility providers, producers, etc.) to work with the full range of stakeholders: transmission system operators, distribution system operators, Balance Responsible Party, aggregator, retailer [13].

Some studies [14] show that final users are willing to sell their surplus electricity to neighbors. This can enable the emergence of this new decentralized markets topology in which everyone would benefit, which would in turn decrease the threshold for acquisition of solar panels and systems.

Hence, there is an emergent need to rethink the electricity markets structure in a more prosumer-oriented way. In [15] are identified three possible models of prosumer-integrated markets: "peer-to-peer prosuming models, prosumer-to-grid integration (aggregators) and prosumer community groups".

3.1 Aggregators

Aggregators are a new type of energy model, more structured, where the prosumers are connected to a microgrid. If a microgrid is interconnected to the main grid, there is an incentive for prosumers to generate as much electricity as possible, because surplus generation could be sold to the main grid. If it is an island mode, prosuming services need to be optimized at the microgrid level and excess generation is an advantage only to the limit of storage and load shifting services availability. Some demand aggregator companies already offer electricity end-users the possibility to take part in DR activities using their load flexibility. These companies establish individual contracts with their customers, the end-users of electricity. Most implementations of DR programs are for large customers, in the residential sector, where aggregators could be a key enabler, the provision of demand-side flexibility is still at a pilot project level.

Thus, several actions must be executed to enable the use of bottom-up flexibility services. It is necessary the definition of a regulation concerning the role and responsibilities of the aggregator, allowing him to offer services to available market mechanisms. Independent aggregators or DSOs (evolved as active managers) need to be able to procure flexibility in DERs within the geographical area where they operate. The design of this market mechanism can be quite complex, especially for the coexistence of parties requesting flexibility for different purposes (market and grid-oriented use).

Of all the types of prosumer to grid market existing in the literature, the one that stands out the most is the concept of aggregating EV due to its storage capacity and easy prediction. For example, in [16] the concept of a "middleman company" aggregating a significant amount of EV is proposed in a mode of operation in which drivers communicate their driving needs to the aggregator, and the aggregator manages this information by creating a Central Virtual Energy (VPP).

Also, several studies can be mentioned regarding aggregators that use the load flexibility provided by the end-user through DR strategies with the aim to provide AS to the SO and also giving economic benefits to the end.

3.2 Peer-To-Peer Energy Markets

Peer-to-peer (P2P) is the ability of individual prosumers to share their excess energy with neighbors. These markets are inspired by the sharing economy concept that relies on numerous agents, some have suggested Airbnb and Uber models for the electricity grid, in which a peer-to-peer platform allows electricity producers and consumers to bid and directly sell and buy electricity and other services.

P2P makes it possible for individual consumers to trade electricity at a P2P marginal price that is cheaper than the time of use price and higher that feed-in tariffs, which provides advantages for both buyers and sellers perspectives.

Some literature [17] concluded that there are conditions to enable P2P markets in co-existence with existing market structures and future research should promote ways for P2P markets to be coupled with the existing wholesale and retail markets, allowing consumers to switch from one market to the other when it is most convenient.

P2P networks allow the management of the Blockchain technology that has gained much attention in recent years. Blockchains are shared and distributed data structures that can store digital transactions without using a central point of authority and are secured using cryptography. Some literature argues that blockchain can be the key factor to deploy a P2P market in the energy sector [18].

Blockchains can provide innovative trading platforms where prosumers and consumers can trade interchangeably their energy surplus or flexible demand on a P2P basis. One of the major benefits of this approach is reducing transmission losses and deferring expensive network upgrades. On the other hand, energy is still delivered through the physical grid, making the grid congestion under a P2P market between the grid operators a major concern [17]. However, P2P markets also present a new opportunity to rethink the use of common grid infrastructures and services, because P2P structures may allow the mapping of the energy exchanges (Fig. 5).

3.3 Communities

Energy communities are becoming an important phenomenon. This typology is more organized than peer-to-peer networks but less structured than prosumer-to-grid models. Energy Communities are characterized by varying degrees of involvement in

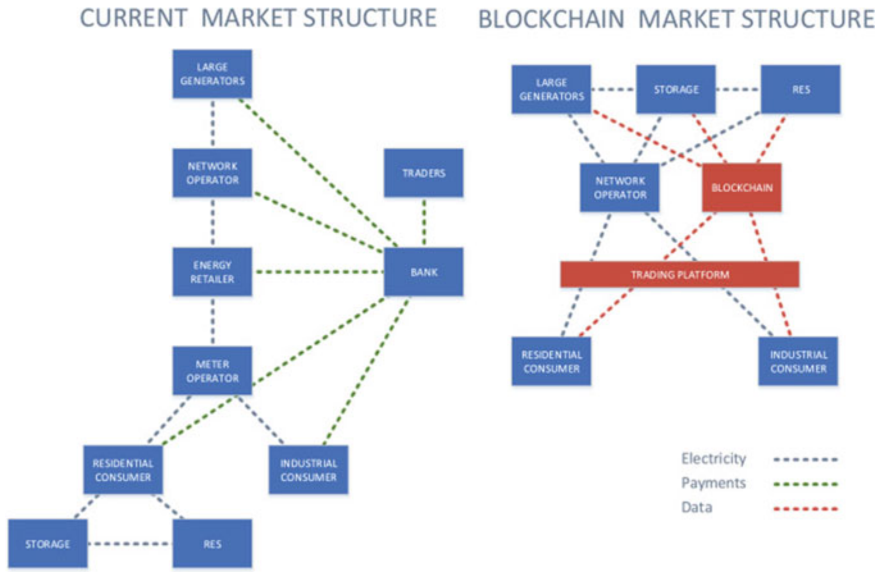

Fig. 5 Current market structure versus blockchain market structure [19]

decision-making and benefits sharing. The recently adopted Clean Energy Package set the foundation for energy communities under the EU legislative framework. Energy communities can be understood as a way to 'organize' collective energy actions around open, democratic participation and governance and the provision of benefits for the members or the local community [20].

By aggregating individual loads, communities can offer local flexibility services such as relieving network congestions and avoiding peak demands in electricity networks. Also, communities can also offer consumers more choices to participate in electricity markets, including for those on lower-income who can otherwise not afford to participate. However, a key challenge is how to ensure the cost-efficiency of energy communities once the local energy allocation can help decrease cost locally but can also increase system costs that would be paid equally by all customers.

Actually, with the increase of more DERs installed at the household and the community level, it makes sense to organize local energy collectively for economic and logistic reasons. With further facilitation from the smart grid development and the drive for energy independence, more local communities are expected to engage themselves to match their supply and demand locally. In fact, the local energy initiatives are emerging with varying numbers, success rate and strategies in Europe These existing local energy initiatives are the first steps to the development and implementation of Community Energy Storage (CES).

Many authors argue that CES will have an important role in creating a more efficient energy system.

4 Demand Side Flexibility

The first appearance of the Demand Side Management concept in the literature [21] stated that "demand-side management is the planning, implementation, and monitoring of those utility activities designed to influence custumer use of electricity in ways that will produce desired changes in the utility's load shape, i.e., changes in the time pattern and magnitude of a utility's load". So, back in the days, DSM was considered appellative from the technical point of view and made also economic sense, so electric utilities start applying simple measures to incentive efficiency in consumption. Currently, DSM actions taken either by electrical utilities or regulators and policymakers have both the goal of saving energy costs and provide energy flexibility. In a future system based on renewable energy generation which is mainly taking place in the distribution grid, locally available flexibility becomes more and more important.

Flexibility can be defined as the ability to increase or decrease the load over a given period in reaction to an external signal (price signal or activation) to provide the electricity system the possibility to respond to fluctuations of supply and demand while, at the same time, maintaining system reliability. The flexibility on the demand side, allows consumers to participate in a wider set of energy services via Home Energy Management Systems.

The HEMS concept started to appear by the time that models were being developed to better understand the dynamics of the evolving smart grid for electricity. At that time, HEMS emerged under the name of a gateway interface designated in some studies by Energy Box [22]. The initial idea for HEMS was the creation of a central unit located in the residential building, capable of being interoperable with SM infrastructure and perform an optimized control of behind-the-meter resources and consumption devices, in order to minimize the energy costs.

The recent advances in communication and modulation methodologies, as well as in the adaptive digital signal processing and error detection and correction, have allowed the development of sophisticated communication capabilities in many appliances. Currently, many commercial solutions can be found in the market for energy management of smart homes. However, many of these solutions are very expensive, are not able to integrate recent SM technologies and are often limited to support devices of a single vendor.

Keeping up with the advances in the communications methodologies, HEMS development currently strategies in the literature are not considering only traditional appliances anymore but also emerging ones, such as energy storage system, electric vehicle, etc. With the integration of all smart devices, an opportunity is provided for HEMS further reduce costs, mitigate peaks and overcome the variability of RES generation. However, if HEMS is not intelligently developed and regulated it can provoke serious damages, both on residents' comfort as in grid stability. For example, the loading and unloading of unmanaged EVs can exacerbate peak demand, causing potential overload. Therefore, smart control strategies regulated by HEMS play an important role in the smart home operation.

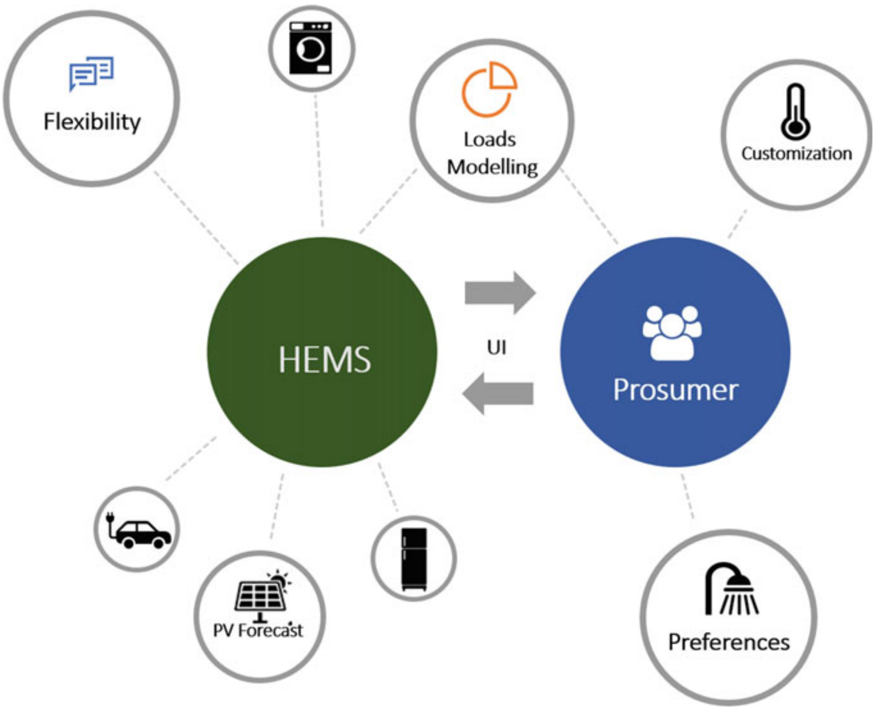

Fig. 6 HEMS and prosumer dependencies and interactions

Effective HEMS requires a preliminary analysis of household consumption, the characteristics and configurations of existing appliances, the physical characteristics of the overall space, as well as consumption habits represented in Fig. 6. This assessment is fundamental for understanding the overall behaviour of the devices, including inter-dependencies and interaction with other devices. This process can be done based on historical data retrieved from the household or based on default consumption patterns. However, to provide results with sufficient accuracy, especially when dealing with thermal variances, HEMS needs to be connected with sensors to monitor energy consumption or be equipped with suitable interfaces to allow the user to insert related information.

Hence, in the recent literature, there can be found new HEMS architecture proposals that are enhanced with functionalities that intend to maximize the end-user's participation by providing convenience functionalities, based on self/machine learning techniques and with advanced local analytics to determine more accurately the availability of existing energy resources, including the flexible loads. These functionalities can be divided into:

- Machine learning techniques to anticipate comfort preferences and the expected use of appliances as a complement and minimization of input information from the user side.

- Local analytics to enhance the PV integration to allow a more fine-grained maximization of the renewable resource integration.
- Dynamic UI that presents optimal and suboptimal solutions for the house operation and introduce a sensitivity analysis based on restrictions relaxation techniques.
- Computation of flexibility behind the meter that can be exchanged with the Grid and Market Platform to preserve data protection and anonymity.
- Multi-home/community operation integration to combine synergies from local homes to provide combined services to the market and grid.

4.1 DER and Flexible Load Modeling

Different energy models are used to estimate the energy use of potentially controllable appliances. Two different categories of appliances are usually considered in the literature—controllable and non-controllable loads. Controllable loads can be further distinguished between thermal and deferrable loads. Within deferrable loads, it is necessary to highlight electric vehicles. These loads can easily be controlled and represent a large percentage of a home's energy consumption.

Deferrable appliances can be distinguishable by operating on a predefined cycle with a known duration and power consumption. Note that the operation of these devices can be shifted along the planning horizon. Smart deferrable appliances can be remotely monitored and controlled by the HEMS while the manual ones are activated by the user upon request or through smart plugs. The deferrable device model can be based on three parameters: power (kW), duration (h) and a number of activations during the day. The number of time frames for the appliance is determined according to how many times the appliance is activated. For example, if the appliance operates only once, then there is the only one-time frame; if it operates four times, then four-time frames are considered. Each time frame can be defined as a time interval for the operation of the device. The best time for activation of the devices within the time intervals is decided by an optimisation method.

This simplified consumption model is enough for daily home energy management with a relatively low error. However, it must be assumed that the power of the device provided by the user as well as the duration is close to reality. Unfortunately, the average consumer does not usually have the necessary knowledge to properly understand what actions he/she needs to take to correct inefficiencies or make use of existing renewable energy resources, and reduce his energy bill just from changing some mobile home app configurations. It could be necessary a new layer of information that feeds the HEMS with meaningful information regarding the energy consumption dynamics. One example of such data analytics tool is a method entitled Non-Intrusive Load Monitoring (NILM) [23] which from the aggregate energy consumption data obtained from smart meters, can identify the existence and the energy consumption allocated to the main residential appliances or energy services.

Thermal device modeling, like electric water heater (EWH) or air conditioner (AC), is more complex than deferrable load modeling. In [24] Kupzog and Roesener described a thermal process of an AC based on comparison with a resistor–capacitor (RC) circuit. The objective of this approach consists of establishing relations between the electrical circuits and the thermal balance inside the room in which the AC device is operating. Similar differential equations are used to characterize other types of thermal loads, namely refrigerators (RFs) and EWH. In the case of refrigerators, the thermal model is equivalent to the AC representation. EWH models are very diverse; each one accounting for different constructive characteristics of this type of appliance. Hence, these device models require a significant amount of information about different aspects of the devices and consumption. Specific characteristics of electrical appliances and the installation environment are essential for an accurate model. These characteristics can be induced from sensors data or it is necessary to collect from the user, such as thermal capacities, thermal resistances/admittances, and nominal electrical power. Also, some inputs are needed regarding the consumption habits, such as the periods when the AC is running or the typical end-user's shower hot water usage (time and quantity).

However, the refrigerator models are rarely considered anymore in the literature since this appliance has tighter limits in terms of temperature and fast variations when powered having little impact on the cost minimization. Moreover, these devices consume less power when compared to other appliances and are currently being designed to be as efficient as possible.

The EV is usually included in the deferrable loads category because it also requires the same parameters to control. However, these parameters are not directly defined by the user but rather determined according to the user's pretended autonomy range. Hence, to create de EV mode the user needs to define two preferences: the pretended autonomy in km, and one unique timeframe for operation. The duration of the charging is always the same, and the number of activations is determined by the user's autonomy input.

Therefore, the number of charging periods needed to charge an EV depends on the type of home charger that is being used, and on the power consumed by the EV during the charge as well. The idea of these approaches is to divide the total duration of the charging in smaller fractions, so that it can be possible to shift the charging for low-priced periods or, if some power limit is considered, expand the range of options for the appliances' activation. In order to successfully apply this model, only one timeframe can be considered, being the previous established rules for one unique timeframe applied to the EV as well.

4.2 Buildings and Spaces

All buildings have thermal mass embedded in their constructions, which allows the storage of a certain amount of heat. Depending on the characteristics and variability of the thermal mass, it is possible to postpone heating or cooling for a certain period without compromising the thermal comfort of the building.

However, the development of high-fidelity energy models for building thermal environment is not an easy task. Most building energy systems are complex non-linear systems, which are strongly influenced by the climate conditions, physical characteristics, and occupants' schedulers [25]. Even more challenging, building power systems are usually not well measured or monitored. The sensors are installed only when they are needed for certain control actions and are generally less accurate than typical industrial applications. This increases the difficulty of applying the building energy model for the operation of buildings in real fields. Recently, there are new studies focusing on improving accuracy, as well as simplifying energy models to make them suitable for online control and optimization.

Regarding the thermal aspects of a building, many procedures have been adopted in order to optimize the thermodynamic behavior of a house, given some comfort requirements and a heating model. Until now, few attempts have been made to optimize home energy management considering the electrical and thermal constraints in a unique framework [26]. In this work, both the electrical and thermal aspects are solved concurrently within the same optimization algorithm. However, a suitable thermal model based on heat-pump usage has been considered in the framework. Despite being an interesting approach, it is not a valid solution for multi-layered buildings.

The equation of heat transfer through solids is linear and can be represented with the so-called electrical analogy when discretized in space. With this analogy, the conductivity of the materials is interpreted as electric conductivity and the thermal mass as electrical capacity. An example of a simulator using this electrical analogy was published by where the thermal behavior of a building heated with solar gains is modeled with a simple network of resistors and capacitors (RC-network), that represent conductivities and thermal masses of the building [27].

Modeling the layers independently makes the thermal model quite complex, so the main objective is to find a methodology that at the same time will reduce the number of elements in the thermal model that are needed to represent the thermal response and keep the overall accuracy of the complete model. For energy management purposes, the reduced model must be accurate under normal operating conditions of a building.

4.3 Optimization Strategies

One of the distinguishable features that a HEMS must provide is the capability of computing optimal (or suboptimal) energy use schedules that provide added value to the end-users. There are different optimization strategies that can be exploited through a HEMS and they largely depend on the criterion (or set of criteria) that might be established. Among the wide diversity of optimization criteria that can be associated with an energy management system, the cost is probably the most appealing as it focuses on finding a lower cost for energy use. If price discrimination follows an efficiency goal from a grid perspective, so will be participants in DR in general.

Several works have been carried out on detailing different types of models that can be used to optimize energy consumption inside a building or at the aggregator level. For instance, in [28, 29] the authors presented a multi-scale multistage stochastic optimization model for HEMS formulated as a model predictive control algorithm for cost minimization and peak-power reduction. The model includes plug-in hybrid electric vehicles (HEVs) charging, thermal dynamics, temperature measurement, and real-time pricing signals. The work in [30] describes an optimal and automatic residential electricity consumption scheduling framework that aims to achieve a trade-off between minimizing the payment and minimizing the waiting time for the operation of each household appliance based on the needs declared by users. In [31] Rahmani-andebili and Shen proposed a combination of LP with GA aiming to reduce the electricity consumption costs of a smart home. Their approach separates the discrete variables from the continuous variables by addressing the non-linearity of the problem with the GA (discrete) and boosting the search for the global optimum with LP (continuous).

Some research is already at the pilot tests level. InteGrid European project [32] developed and tested in different pilots a solution capable of storing the configuration and comfort preferences of users to produce optimal schedules of appliances (legacy and smart) for the next day. It is a highly customizable platform that incorporates functionalities from other existing systems as well as innovative ones related to the energy management purpose. The software modules were designed, implemented and embedded into a Raspberry PI 3 computation core to produce a cost-effective solution that is flexible and adaptable to different contexts.

An example of a possible scenario from a household operation is presented in the following figures. In Fig. 7 a baseline scenario with up to 96 periods each day is represented. Figure 8 considers the presence of dynamic tariffs to optimize household consumption.

However, the main goal of the optimization problem implemented in this solution consists in minimizing the total daily cost considering not only dynamic price tariffs, but also peak-power limit, deferrable appliances with different duration, power

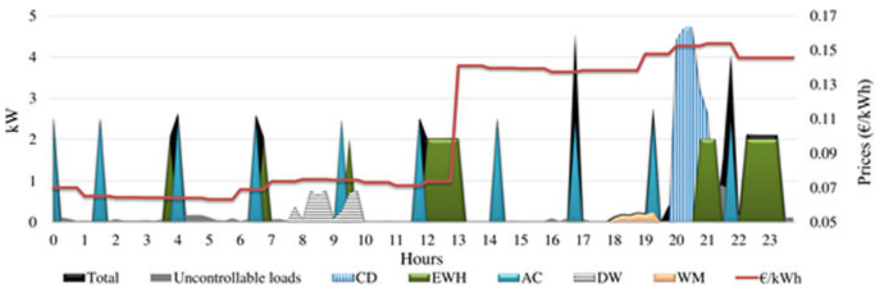

Fig. 7 Baseline scenario [33]

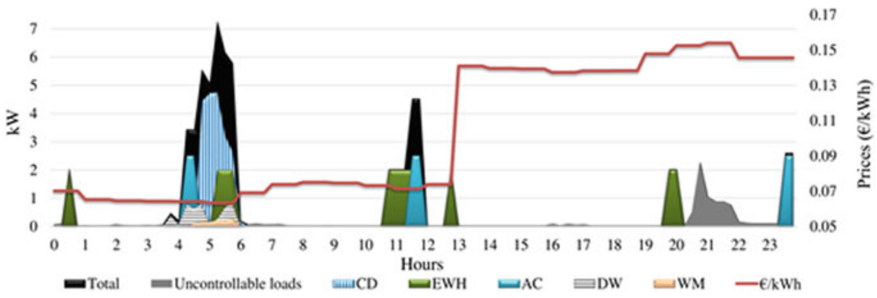

Fig. 8 Optimized scenario [33]

consumption, and a number of activations, models, and external data for thermal appliances, as well as technical limitations linked with the country's regulation [33].

4.4 *Flexibility Aggregation*

A simplification of a flexibility model that a domestic building can provide to the distribution system operator for the demand side is being used in the literature under the concept of a virtual battery [34]. He Hao considers a smart residential community, in which residents cede physical controls of their flexible loads to a community manager, who is responsible for forecasting the aggregate baseline load of the community and implement coordination and scheduling algorithms to manage the power consumption of flexible loads to avoid peak demand charge while respecting resource constraints. This framework is represented in Fig. 9.

Fig. 9 Schematic representation of the virtual battery coordination framework [34]

An adaptation of this model was used in InteGrid project [35]. In a Home Management Energy System, which on a daily basis optimize home devices, was implemented a virtual battery model that provides flexibility for ancillary services. The idea is to have a single virtual battery for each HEMS, which is the result of the aggregation of different individual virtual batteries, each one representing a flexible device available in the home domain. The DSO contracts flexibility services form domestic prosumers through the grid and market hub[1]. This flexibility is enabled by the home energy management system (HEMS) and aggregated by a flexibility operator. Both preventive and real-time operation are considered in this approach. Preventive define a series of control actions to "reserve" flexibility and prevent technical problems. In real-time the state of the grid is analyzed and if there are no significant deviations from the preventive management scenario, the pre-booked flexibility is activated, otherwise, the control is triggered to re-calculate the control actions necessary to manage the voltage deviation.

One advantage of this concept is to have a normalized structure, from the point of view of the system operator, that covers all the available flexible resources in the buildings without the operator having to know the type and characteristics of those resources.

To develop this perspective is considered that the charging of the battery occurs when a device is turned ON and starts consuming energy from the grid and the discharging when a device is turned OFF and stops consuming energy or is turned ON and can absorb energy from the grid. The amount of energy available in each HEMS is determined from a baseline (in this case, the optimized consumption profile for the day ahead) and defined according to two distinct directions:

- Upward flexibility (positive values)—The HEMS can charge the virtual battery by activating devices to consume energy—if State of Charge (SoC) is below the maximum limit. The variation of the SoC will depend on the amount of energy consumed by the device(s) activated.
- Downward flexibility (negative values)—The HEMS can discharge the virtual battery by absorbing energy from the grid or to stop the charging by deactivating devices—if SoC is above the minimum limit. The variation of the SoC will depend on the amount of energy absorbed by the device(s) activated or by the absence of consumption of the device(s) when deactivated.

Three devices with flexible behavior are usually considered for the flexibility in the home domain. Each one can be modelled as an individual battery, according to its technical limits and characteristics.

- Electric Water Heater (EWH)

The SoC of this device is determined based on the temperature profile that results from the schedule optimization. Considering that the maximum and minimum temperatures allowed correspond to a SoC of 100 and 0%, respectively, it is possible to obtain the SoC variation during the day using the max-min method for normalization. The

[1] InteGrid project concept.

setpoint temperature is used as the initial SoC and a safety gap is also considered to avoid the thermostat to reach its limits. The value for the safety gap should be proportional to the temperature variation of one activation. For each period, if the EWH is OFF and the current SoC plus the safety gap is below 100%, the upward flexibility is equal to the EWH rated power during the respective period—device available to consume energy. If the EWH is ON and the current SoC minus the safety gap is above 0%, the downward flexibility (negative value) is equal to the rated power during that period—device available to stop consuming energy.

- Electric Vehicle (EV)

In the case of the EV, the virtual battery limits are equal to the real limits of the battery. Therefore, the model requires the total battery capacity and SoC at the connection time, to determine the amount of energy needed to charge the EV. It is also required to have information about the connection and disconnection times, in order to determine the time that the device will be available to provide flexibility. Since the energy consumption of the EV varies during the charging, a maximum limit for charging must be defined for each period according to the power cap of the building. Finally, for each period during the connection time, if the EV charger is Off and the SoC its below its maximum, the upward flexibility will be equal to the maximum power that the EV can consume during that period. If the EV charger is On and there is sufficient energy to charge the EV in the next periods, the downward flexibility (negative value) in that period is equal to the current power consumption of the charging. Apart from an On–Off control, the vehicle charging can be controlled—the smart charging mode. For these cases, it is assumed that the EV does not have Vehicle-to-Grid (V2G) technology. When the EV operates in the so called V2G mode, it can inject power back into the grid, providing an extra degree of flexibility. From the grid perspective, this is the most interesting way of using EV capabilities given that, besides helping managing branches' congestion levels and voltage related problems in some problematic spots of the grid, EV have also the capability of providing peak power in order to make the energy demand more uniform along the day. If the EV in the V2G mode is managed at building or home level, it is said to operate under the vehicle to home (V2H) mode. In this case the EV battery can be used to provide extra positive and negative flexibilities at the building level and be used to control the peak power absorbed from the grid under control.

- Photovoltaic Inverter

Although the PV inverter has the battery and the PV panels associated, the inverter is not prepared to control these two elements separately. Therefore, in terms of flexibility, the only control available for this device is the PV curtailment. The limits for the SoC are the same as for the battery and the initial SoC is defined by the user. A higher initial SoC means that the battery will be charged sooner and consequently the energy injected into the grid by the PV inverter will increase. A higher amount of energy being injected into the grid means a higher amount of power that can be curtailed. Hence, the upward flexibility will be equal to the power being injected into the grid in each period—equivalent to activate a load in terms of power flow.

The downward flexibility was considered zero for now. However, if the PV power were already curtailed, the downward flexibility would be equal to that amount of PV power curtailed—that can be restored.

At the end, when all the devices are considered, the upwards and downwards flexibilities are summed up. If the total power exceeds the power cap defined in the HEMS, the flexibility of the devices is subtracted from the total amount in ascending order, according to the power provided for each device in each period.

5 Conclusions

The shift from consumer to prosumer is no longer just an idea, it is already a concept in motion. This scenario is becoming possible today with the convergence of energy management systems, DER, intelligent communications platforms and new regulatory frameworks. Remunerative programs are already being launched to encourage energy customers to adjust their consumption in response to pricing signals. This response generates potential flexibility from the consumer perspective, becoming the consumer itself an important player that has control of DERs, critical to helping balance the grid.

To achieve this energy model is urgent to start unlocking additional sources to fully utilize the global potential of demand-side flexibility.

The role of policy and regulation on DERs is crucial to allow and encourage custumers to invest in DERs. Continuous innovation and technological advances can make energy sources or communications infrastructures more efficient and economically viable over time. Information is also vital, energy management systems need to help the prosumers to best understand how to correctly participate and make the most of complex infrastructure and market.

This is an opportunity for energy stakeholders to create value from new flexibility solutions in power markets, that promise financial, operational, environmental, and societal benefits.

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Reliability Analysis of Active Distribution Systems

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Abstract This chapter discusses aspects related to the reliability analysis of active distribution systems. A general framework for the evaluation is provided, in which aspects related to the causes of events, event modeling, and system state analysis are highlighted, aiming at determining the effect of the response time of protective equipment, of the inclusion of modern automation and control infrastructure, and of the massive integration of distributed energy resources on the reliability of active distribution systems. The proposed framework allows estimating service driven (e.g. SAIFI, SAIDI), power quality driven (e.g. SARFI, SIARFI), and operational driven (e.g. SCCEI, SCFI) indicators, supporting a comprehensive analysis of the benefits associated with a large-scale integration of distributed energy resources supported by a distributed/multi-agent control as well as advanced protective solutions.

Acronyms

AENS	Average Energy Not Supplied
ASAI	Average System Availability Index
ASIDI	Average System Interruption Duration Index
ASIFI	Average System Interruption Frequency Index
ASUI	Average System Unavailability Index

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CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
CHP	Combined Heat and Power
ENS	Energy Not Supplied
MAIFI	Momentary System Average Interruption Frequency Index
MAIFIe	Momentary System Average Event Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
$SARFI_x$	System Average RMS Variation Frequency Index
SCADA	Supervisory Control and Data Acquisition
$SCCEI_x^n$	Short Circuit Current Expected Index
$SCFI_x^n$	Short Circuit Frequency Index
$SCPI_x^n$	Short Circuit Probability Index
$SIARFI_x$	System Instantaneous Average RMS Variation Frequency Index
$SMARFI_x$	System Momentary Average RMS Variation Frequency Index
$STARFI_x$	System Temporary Average RMS Variation Frequency Index

1 Introduction

With the proliferation of distributed energy resources and devices with enhanced communication and control capabilities, distribution systems are gradually allowing new key electricity services, including firm capacity and operating reserves, which can be used as an alternative to conventional network investments, enabling a more efficient operation of the network and a dynamic interaction with grid users [1]. This novel concept of active distribution systems is supported by flexible and intelligent distributed control mechanisms, enabling the implementation of innovative operation and control strategies [2], which can be exploited to increase the reliability of the network.

Differently from passive distribution systems, an active network can include a wide array of devices such as distributed generation, demand response, energy storage, intelligent protection schemes, and centralized and/or decentralized control strategies, which must be properly coordinated to support not only system but also local operation of distributed resources. Therefore, a smarter distribution network allows for several new possibilities, including wide area active control, adaptive protection, network management devices, real-time network simulation, advanced sensing and measurement, as a result of the distributed communication equipment [2]. This context brings new challenges to the design of network upgrades, particularly those related with an important criteria, which is the reliability of different alternatives and schemes.

The development of representative models for the behavior of the distributed energy resources and associated uncertainties is extremely important to obtain an accurate assessment of the reliability of active distribution system. Such models are embedded into reliability assessment techniques, which are the means to quantify the impact of the new devices and associated operation strategies usually through performance indicators. These indicators must embody a broad perspective, since all aspects previously referred alter not only the continuity of supply, but also power quality as whole. In this context, this chapter aims to present a framework for the reliability analysis of active distribution systems, allowing a quantitative evaluation of design alternatives, taking into account the aspects encapsulated within this new paradigm for distribution networks.

Accordingly, the chapter is organized as follows. In Sect. 2, a brief discussion over the state of the art is provided. A general framework for reliability analysis of active distribution systems is proposed and discussed in Sect. 3, alongside with examples of event transition modeling and performance indicators. In Sect. 4, simulation and illustrative results are presented to highlight the application of the general framework proposed for the reliability analysis of active distribution systems. Finally, in Sect. 5, an overview and final remarks of the chapter are presented.

2 State of the Art Discussion

Over the past few years, several works have been conducted to incorporate the novel paradigms related to active distribution systems such as, distributed generators, islanded operation, load shedding, self-healing analysis, cyber system availability, improved event and component modeling (e.g. adverse weather, dynamic stability, short circuit) and others, in the reliability analysis of these systems. As an example, the authors in [3] propose a method for evaluating the reliability of active distribution systems with multiple power sources using Monte Carlo simulation. The authors introduce the model of virtual power plant to represent microgrids with intermittent sources in order to minimize the computational burden of the Monte Carlo simulation. The authors of [4] propose a method to evaluate active distribution systems considering permanent and transitory failures. The model developed integrates short-term events, also with voltage sags and momentary interruptions, taking into account the duration of such events. A graph theory-based search algorithm is used to recognize the operation of protective devices and the presence of alternative supply.

An adequacy and security evaluation using a sequential Monte Carlo simulation for active distribution system is presented in [5]. A combined discrete-continuous simulation model approach is devised to verify the feasibility of islanded operation, using steady-state and dynamic analysis for assessing frequency and voltage stability of distributed generators. Similarly, a non-sequential Monte Carlo method is used in [6] to determine stable points of operation for distribution systems with distributed generation considering islanded operation. The stable island operation is represented by a complete model of synchronous machines for their voltage and speed regulators. The authors use classical and survival indices to evaluate distribution system reliability. In [7], a long-term impact assessment algorithm is presented to evaluate advanced under-frequency load shedding schemes on distribution systems with intentional islanding of distributed generation. The proposed approach is implemented using a sequential Monte Carlo simulation and a polynomial neural network to indicate when and how load shedding strategies can be used to support islanded operation.

In [8], a reliability analysis is carried out considering the integration of photovoltaic modules in distribution systems. The model considers not only radiation but also the degradation of the modules with time. Five new indices are proposed to quantify the benefits of islanded operation supported by photovoltaic modules. A reliability study of active distribution system with a mobile energy storage system is carried out in [9]. The analysis proposed uses an hybrid method based on analytical and Monte Carlo simulation techniques alongside with a bootstrapping to speed up the simulations. The authors emphasise that the mobile energy storage can supply a great portion of the load in islanded operation, improving the overall reliability of the distribution system.

In [10], an approach based on an event-tree methodology is presented to quantify the reliability of a specific automated distribution system, designated as the "low interruption system automated scheme". The assessments are carried out using an analytical approach considering grid elements and automated equipment failure. In [11], the authors propose an analytical approach for the reliability analysis of distribution systems considering smart monitoring devices. In this approach, these devices are used to monitor the health condition of on-load-tap-changers windings conservator tank, accessories, terminal status, along with failures due to adverse weather in lines and in protection equipment.

The authors in [12] propose a method to model lightning induced faults in distribution system reliability. In this work, direct strikes and induction faults are considered. A combined Monte Carlo and a analytical method are used to test the proposed method considering permanent and transitory failures. The effect of adverse weather in the distribution system reliability is analyzed in [13]. This work also considers the impact on the equipment lifetime due to weather, which, in turn, can affect preventive maintenance strategies. The work emphasises that weather induced degradation allows for a more adequate representation of the overall system behavior and must be taken into account in its reliability analysis.

In [14] is proposed a sensitivity approach for the reliability analysis of distribution systems using a fault incidence matrix. Apart from the failure and repair rates of feeders, a sensitivity analysis for new equipment installation is also proposed in order to improve customer related indices. An analysis of distribution transformer reliability due to the energy produced by rooftop photovoltaic modules is studied in [15]. A Monte Carlo simulation technique is used to represent scenarios in which the lifetime of transformers is degraded due to the reverse power flows, showing that the system reliability can be negatively affected using distributed generation without proper planning decisions.

In [16], a model focused on the evaluation of the cyber link with the distribution system is developed considering dynamic routing, delay, and communication errors. This model is used to determine whether a link is able to effectively transmit control messages. This work also presents an hybrid analytical and Monte Carlo simulation method to quantify the impact of cyber faults on the reliability of active distribution systems. The interdependence between the communication infrastructure and the physical system in reliability studies is shown in [17]. The authors claim that the decision support systems based on the availability of phasor measurement units communication links can facilitate the propagation of cyber failures into the physical system, affecting the performance in terms of energy delivery. In [18], a pseudo-sequential Monte Carlo simulation is used to investigate the reliability of active distribution systems considering communication networks. In this approach, the authors consider failures in the data transmission and communication elements in the evaluation of the physical system. Results with different communication availability levels are carried out to show the interdependence between the physical and the cyber communication levels of active distribution systems.

3 General Framework for Reliability Analysis of Active Distribution Systems

The term reliability has a broad meaning and usage in different engineering fields. Concerning distribution systems, this term is commonly refereed to as the overall ability of the system to perform its function, which is to continuously supply its costumers at a satisfactory quality level [19]. Most of the techniques available for the reliability analysis of distribution system are focused on its adequacy, which, in general, covers only the continuity of supply problem (availability). Nonetheless, the changes induced by the active distribution systems concept require suitable models and performance indicators due but not limited to the large variety of operational impacts produced by distributed energy resources, control philosophies, protective schemes, communication strategies, agent behaviors, and market structures.

The brief discussion over the state of the art has shown considerable research work on the reliability analysis of active distribution systems. These works have in common a similar goal: to provide an accurate representation of the phenomena of interest such that the results obtained are closer to the real system behavior, instrumentalizing decision makers with performance indicators which can be easily understood and used. Researchers have proposed different approaches and models, though only for one or few phenomena impacting active distribution systems reliability. Such individual models are addressed in each work according to specific goals, due to the complexity and computation burden inherent to the assessment. As such, a general analysis of an active distribution system in all of its perspectives is almost impractical due to the variety and complexity of models required for accurate system representation and simulation, rendering the great majority of reliability studies focused on a specific phenomenon of interest in academic or industrial fields.

Despite such limitations, a general framework for reliability analysis can still be abstracted. This framework should be sufficiently flexible to enable the simulation of events of interest, allowing an accurate assessment of its consequences and related operational actions, which, in turn, will impact active distribution system performance. A tentative general framework for reliability analysis is illustrated in Fig. 1, emphasizing the aspects that can be modelled and impact the reliability of active distribution systems. The framework is structured on the idea that a designer must identify the phenomena of interest and/or the sort of active solution/behaviors are envisioned to be assessed. Then, a set of system states must be established alongside the causes of events triggering state transitions and their corresponding consequences/related to the operational actions to be analysed. Finally, suitable performance indicators must be designed to capture the impact of the phenomena or active solution/behavior in the overall system reliability. Discrete-event stochastic models, discrete-event deterministic models and discrete-time deterministic models [20] are examples of evaluation techniques that can be used to represent state transitions, whilst a large variety of analysis tools can be applied to state evaluation. The act of designing an approach towards verifying the impact of a phenomena or active solution/behavior of interest on the reliability of an active distribution system is directly related to choosing adequate event transition models and analysis tools, weighting issues related to implementation feasibility and expected computational burden.

As an example, Fig. 1 illustrates a transition event related to the failure/repair cycle of components. A two-state Markov model can be utilized to represent the causes of transitions between the failure and the operation states of the components. Other sorts of models, such as the multi-state Markov model, can be utilized in more complex representations of the availability of installations and/or components. In the case of active distribution systems, a transition event can be due to, for example, faults (short circuits), miss operation of protections, maintenance actions and cyber failures. Faults are the most common cause of failures in distribution systems [21] and the most modelled in the literature. In fact, accurate modeling of the failure cause has a great impact on reliability evaluations for cases in which seasonal variations of weather have a direct impact on the equipment (e.g. hurricanes and snow on overhead lines) and also in regions with a dense vegetation and animals. Different models can be used to represent the availability and operation of equipment such as a recloser, which can deploy a series of attempts to extinguish a fault by opening and closing circuits, thus being decisive for fast recovery of supply in case of transitory failures. The same reasoning applies to any network device, including relays/sensors, controllers and communication equipment, in which each event can trigger or schedule other events.

Discrete events based on deterministic models are also emphasized in Fig. 1. These models have been applied to represent the behavior throughout the year of different customer types (e.g. urban, rural, industrial) as well as generation production profiles, usually connected to a resource representation in case of photovoltaic, wind generation, and hydro units. Market-related issues can be also be modelled as a discrete event, in which each agent of the grid might have an autonomous decision of how to behave depending on the market structure. Line and transformer capacity variations connected to a weather representation or sensing device operation states can influence the performance and trigger/schedule further events. Continuous-time models can be also utilized to represent events related to system dynamics (e.g. to evaluate islandings) or transients (e.g. to evaluate power quality issues).

Each of the state transition causes has direct and indirect consequences that can be followed by operational actions. These consequences and actions are evaluated

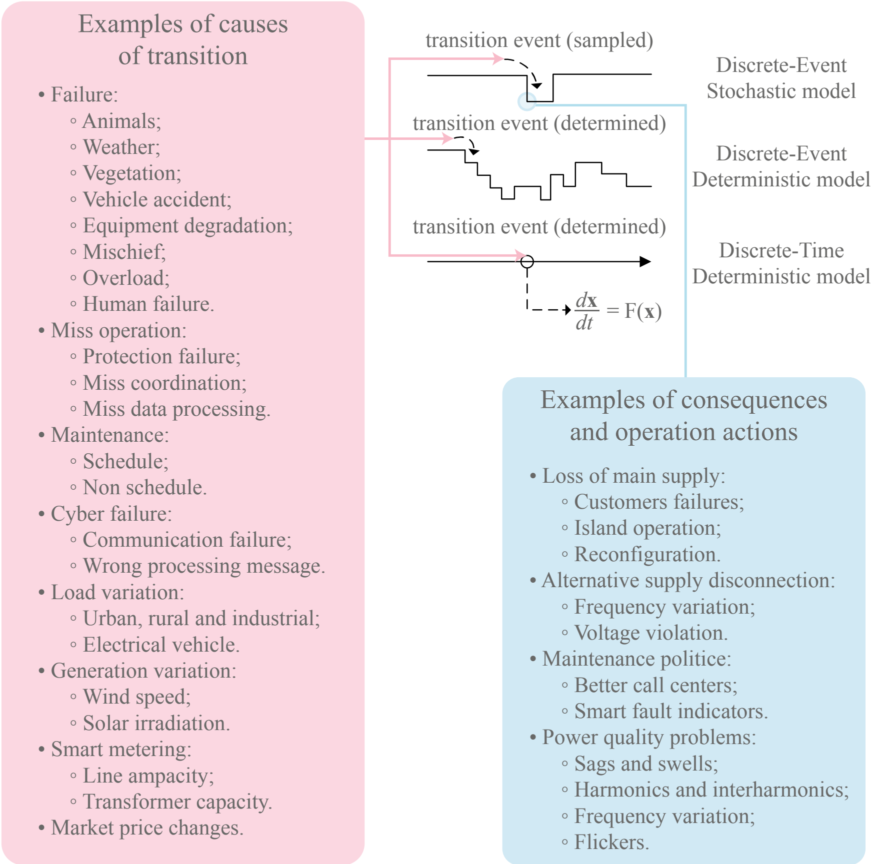


Fig. 1 General framework

through dedicated tools to feed test functions with instances, whose expectations or other statistical figures are utilized to obtain performance indicators. The operation of protection equipment, for instance, can disconnect a certain amount of customers from the network. If an inadequate protection coordination scheme is used, then more customers than required might be disconnected. However, if adequate distribution management systems are deployed, then a series of opening/closing actions can be devised (automatically or manually) to reconnect as much customers as possible until the failed equipment is repaired and/or replaced. Centralized and decentralized control schemes can be incorporated into the system representation to model actions based on Supervisory Control and Data Acquisition (SCADA) system and new decentralized approaches, such as those based on multi-agent solutions. If distributed generators are capable of supplying the disconnected load, then the technical feasibility of islanded operation may be evaluated through dynamic analysis to verify if there is enough voltage and/or frequency support, whilst exploiting generation/load shedding methodologies to disconnect as few customers as possible. During the fault period, models for corrective maintenance policies can be implemented to accurately represent crew work. The effects of intelligent sensing equipment, such as smart fault indicators, can be also verified. The use of smart metering can be represented to analyse power quality in real-time supporting preventive maintenance decisions to minimize customer interruption times.

Modeling such a wide range of aspects usually does not allow to compute performance indicators analytically. Accordingly, researchers have applied the Monte Carlo method and their variants to estimate performance indicators through sampling of states or state transitions. The Monte Carlo simulation technique can be classified in non-sequential, pseudo-sequential and sequential approaches, in which the latter is considered the most flexible one and it is the focus of this chapter. The sequential Monte Carlo simulation method relies on sampling state residence times, allowing to incorporate all aspects highlighted in Fig. 1. However, combined discrete-continuous simulation approaches [5, 7] are still rare in the literature of distribution system reliability analysis. A test function of a performance indice is modeled in the sequential Monte Carlo simulation as a random variable **G**, with an expectation estimated as follows:

$$E[\mathbf{G}] = \frac{1}{N}\sum_{y=1}^{N} G(y) \tag{1}$$

in which $G(y)$ is the value of the test function in year y, and N is the total number of years sampled.

The coefficient of variation β of the estimate of the performance indice can be computed as [22]

$$\beta = \frac{\sqrt{V[\mathbf{G}]/N}}{E[\mathbf{G}]} \tag{2}$$

in which

$$V[\mathbf{G}] = \frac{1}{N}\sum_{y=1}^{N} (E[\mathbf{G}] - G(y))^2 \tag{3}$$

The coefficient of variation is the main variable utilized to assert the convergence of the sequential Monte Carlo simulation.

3.1 Example of Event Transition Modeling

State transitions can be represented using a variety of models, as previously discussed. In active distribution systems, the variability of distributed energy resources, such as those related to energy sources, is of utmost importance to accurately estimate the value of the performance indice. Usually, the variability related to sources, such as wind, solar and small hydro generating units, is at least represented by means of

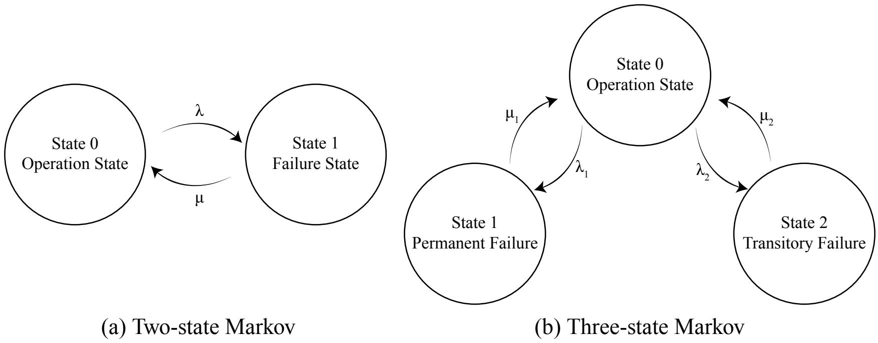


Fig. 2 Markov model representation

capacity time-dependent models, in which the maximum power capacity associated to states is multiplied by a time-dependent value taken from hourly wind, irradiance and water inflow series, respectively. Studies on the correlation among the resources of power generation can be performed in order to optimize the utilization of the primary resources and to provide further accuracy into the models. Regarding system demand, it can be modeled using deterministic levels for each point of consumption or a chronological representation that contains a load level for each hour of the year (8760 values). A function with improved resolution or a Markov model can also be used, depending on the application. Short- and long-term forecast uncertainties may be associated with the capacity series of generating units and customer loads.

Generally, the availability of installations and equipment in reliability analyses is at least modeled using a cycle of two recurrent states: the failure state and the operation state. In a sequential Monte Carlo simulation procedure, the component failure and repair cycles are typically represented using the two-state Markov model [23], as illustrated in Fig. 2a. The residence time in the operation (*up*) and failure (*down*) states are sampled using an exponential distribution function [24], with the corresponding failure and repair rates, as follows:

$$T^{up} = -\frac{1}{\lambda} \ln U \qquad T^{dw} = -\frac{1}{\mu} \ln U \tag{4}$$

in which T^{up} and T^{dw} are, respectively, the residence times in the operation and failure state, μ and λ are the repair and failure rate, respectively, and U is an uniformly distributed random number sampled within [0, 1]. The sequential Monte Carlo simulation method relies on (4) to sample states, reproducing the availability of the system components sequentially. This representation inherently assumes that a failure occurs after T^{up} is elapsed, causing the component to transit to the failure state, and vice-versa.

Notice that the application of the two-state Markov model collapses all aspects shown in the left-hand side of Fig. 1 in a simple model, depending only on two constant parameters per component: λ and μ. This might be seen as an oversimplification of the problem, but the approach is easily justifiable by the past unavailability data recorded by utilities. On the other hand, active distribution systems are envisioned to deliver large quantities of data for analysts, allowing the application of more accurate probability distributions.

As a simple example regarding the inclusion of additional features into the modeling process, let us consider the application of the three-state Markov model for a system element, as illustrated in Fig. 2b, with states defined as:

- State 0: it operates adequately;
- State 1: it does not operate adequately (sustained or permanent failure);
- State 2: it does not operate adequately (transitory failure).

By definition, the state transition parameters can be estimated as

$$\lambda_1 = \frac{NF_P}{T_0} \qquad \lambda_2 = \frac{NF_T}{T_0} \qquad \mu_1 = \frac{NR_P}{T_1} \qquad \mu_2 = \frac{NR_T}{T_2} \tag{5}$$

in which λ_1 and λ_2 are the permanent and transitory failure rates, respectively, NF_P and NF_T are the number of permanent and transitory failures, respectively, T_0 is the total time in the operation state, μ_1 and μ_2 are the permanent and transitory repair rates, NR_P and NR_T are the number of repairs after permanent and transitory failures, respectively, and T_1 and T_2 are the total time that the element has spent in the permanent and transitory failure states, respectively.

Now, let $P_0(t)$, $P_1(t)$ and $P_2(t)$ be the probability of a system element to be in state 0, 1 and 2, at time t, respectively. Let also dt be a time interval short enough such that the probability of occurrence of more than one failure event during dt is negligible. The state probabilities can be expressed as

$$P_0(t+dt) = P_0(t)(1 - \lambda_1 dt - \lambda_2 dt) + P_1(t)\mu_1 dt + P_2(t)\mu_2 dt \tag{6}$$

$$P_1(t+dt) = P_0(t)\lambda_1 dt + P_1(t)(1 - \mu_1 dt) \tag{7}$$

$$P_2(t+dt) = P_0(t)\lambda_2 dt + P_2(t)(1 - \mu_2 dt) \tag{8}$$

and, for $dt \to 0$, we have

$$P_0'(t) = -(\lambda_1 + \lambda_2)P_0(t) + \mu_1 P_1(t) + \mu_2 P_2(t) \tag{9}$$

$$P_1'(t) = \lambda_1 P_0(t) - \mu_1 P_1(t) \tag{10}$$

$$P_2'(t) = \lambda_2 P_0(t) - \mu_2 P_2(t) \tag{11}$$

The steady-state or limiting probabilities P_0, P_1 and P_2 can be evaluated by setting (9)–(11) to zero, as

Table 1 Data for the proposed three-state Markov example

State probability	Analytical approach	Monte Carlo approach	Difference (%)
P_0	9.999429e−1	9.999429e−1	0.000
P_1	5.707437e−5	5.705354e−5	0.036
P_2	1.521983e−8	1.522705e−8	0.047

$$0 = -(\lambda_1 + \lambda_2)P_0 + \mu_1 P_1 + \mu_2 P_2 \tag{12}$$

$$0 = \lambda_1 P_0 - \mu_1 P_1 \tag{13}$$

$$0 = \lambda_2 P_0 - \mu_2 P_2 \tag{14}$$

Since (12)–(14) is an underdetermined linear system, one of the equations may be replaced by the sum of the state probabilities, resulting in the set of equations

$$0 = -(\lambda_1 + \lambda_2)P_0 + \mu_1 P_1 + \mu_2 P_2 \tag{15}$$

$$0 = \lambda_1 P_0 - \mu_1 P_1 \tag{16}$$

$$1 = P_0 + P_1 + P_2 \tag{17}$$

This set of algebraic equations can be solved to obtain closed expressions for P_0, P_1 and P_2 as functions of state transition parameters. On the other hand, from a simulation point of view, the residence times in states 0, 1, 2 can be sampled using exponential distributions, as

$$T_0^{up} = -\frac{1}{\lambda}\ln U \qquad T_1^{dw} = -\frac{1}{\mu_1}\ln U \qquad T_2^{dw} = -\frac{1}{\mu_2}\ln U \tag{18}$$

in which λ is the sum of permanent and the transitory failure rates, and T_2^{dw} and T_1^{dw} are the residence times in the transitory and permanent failure states, respectively. Hence, state probabilities can be withdrawn from a sequential Monte Carlo simulation, in which each transition towards a failure state can be followed by a sampling procedure to verify if the next state will be a transitory or a permanent failure.

To illustrate the applicability of the modeling process, let us take as example the simulation of a single system element where λ_1, λ_2, $1/\mu_1$ and $1/\mu_2$ are equal to 0.1, 0.4 occ/year, 5.0 h and 1.2 s respectively. For this example, the sequential Monte Carlo simulation is utilized to sample state transitions using (18) and to estimate state probabilities using 100 million sampled years. Table 1 shows the probabilities estimated from the analytical technique, by solving (15)–(17), and from the Monte Carlo simulation. Both approaches provide equivalent results for all three states.

Notice that the exercise above highlights the simulation of a system element taking into account the separation of a failure state into permanent and transitory states. Due to the inherent nature of the event, the transitory state itself has negligible probability, as shown in Table 1. Nevertheless, one can establish performance indicators directly related to the transitory failure events by allowing these states to be explicitly represented within a Monte Carlo simulation. For instance, the impact of different settings and/or placements of protective equipment, such as a smart recloser with or without advanced control capabilities, on the performance of an active distribution system can be accurately simulated and evaluated. In such cases, system states must be evaluated using steady-state, dynamic and transient analysis, alongside with the availability of the communication infrastructure to assist fault isolation and system reconfiguration. Such analyzes allow estimating performance indices related not only to plain customer interruptions but also, for instance, short-duration voltage dynamics.

The three-state Markov model application illustrates the large variety of possibilities that can be found if more accurate event models are envisioned. Furthermore, it highlights that the modeling complexities and the consequences of the operational actions caused by such events can be included in the assessments, possibly requiring complex analysis tools depending on the phenomena and/or behaviors of interest.

3.2 Performance Indices

The performance of active distribution systems can be quantified through indicators, which aim to provide measures of the expected ability of a system to adequately supply its customers. The impact measured by the performance indices is utilized to verify if the aspects related to the inclusion of new equipment within the existing infrastructure, to dynamic phenomena and/or to other active behaviors is advantageous or disadvantageous to the overall performance of the system. In spite of the aspect under assessment, its corresponding transient and/or dynamic effect is prone to affect power quality. In this context, different categories of electromagnetic signatures have been proposed in the literature to provide requirements for characterizing the disturbances through measurements, as [25]:

- Transients: impulsive and oscillatory;
- Short-duration root-mean-square variations: instantaneous, momentary and temporary;
- Long duration root-mean-square variations: interruption, undervoltages, overvoltages and current overload;
- Imbalance: voltage and current;
- Waveform distortion: DC offset, harmonics, interharmonics, notching and noise;
- Voltage fluctuations;
- Power frequency variations.

Particularly, voltage variations can be classified according to Table 2, which defines the magnitude and duration of voltage disturbances [25].

The effects related or not to electromagnetic signatures can be accounted for via test functions and estimated in terms of performance indices. These include quantitative indicators aiming to measure the impact of the consequences and operational

Table 2 Categories and typical characteristics of voltage deviations

Categories	Duration (c, s or min)*	Voltage magnitude (pu)
Short-duration RMS variations		
(a) Instantaneous		
Sag	0.5–30 c	0.1–0.9 pu
Swell	0.5–30 c	1.1–1.8 pu
(b) Momentary		
Interruption	0.5 c–3 s	<0.1 pu
Sag	30 c–3 s	0.1–0.9 pu
Swell	30 c–3 s	1.1–1.4 pu
(c) Temporary		
Interruption	>3 s–1 min	<0.1 pu
Sag	>3 s–1 min	0.1–0.9 pu
Swell	> 3 s–1 min	1.1–1.2 pu
Long duration RMS variations		
Interruption (sustained)	>1 min	0.0 pu
Undervoltage	>1 min	0.8–0.9 pu
Overvoltage	>1 min	1.1–1.2 pu

*c—cycles, s—seconds and min—minutes

actions exemplified in Fig. 1. Examples of performance indices utilized in the literature are discussed in the following sections.

3.2.1 Adequacy Indicators

The reliability analysis of distribution systems is classically focused on the frequency and duration of interruptions. The corresponding indices take into account the number of customers and load affected during an outage, such as the well known indices SAIFI, SAIDI, CAIFI and CAIDI. The corresponding test functions used for these indices are presented bellow.

System Average Interruption Frequency Index (SAIFI): indicates how often the average customer experiences a sustained interruption over a year (occ/year).

$$G_{SAIFI}(y) = \frac{\text{number of customer interruptions in year } y}{\text{number of customers}} \tag{19}$$

System Average Interruption Duration Index (SAIDI): represents the total interruption duration for an average customer during a year (h/year).

$$G_{SAIDI}(y) = \frac{\text{customer interruption duration in year } y}{\text{number of customers}} \tag{20}$$

Customer Average Interruption Frequency Index (CAIFI): represents the average frequency of sustained interruptions for the customers experiencing sustained interruptions during a year (occ/year).

$$G_{CAIFI}(y) = \frac{\text{number of customer interruptions in year } y}{\text{number of distinct customers interrupted in year } y} \quad (21)$$

Customer Average Interruption Duration Index (CAIDI): represents the average time required to restore the service (h/occ).

$$G_{CAIDI}(y) = \frac{\text{customer interruption duration in year } y}{\text{number of customer interruptions in year } y} \quad (22)$$

Customer Total Average Interruption Duration Index (CTAIDI): indicates the total duration of interruption in a year that average customers who experienced an interruption were without power (h/year).

$$G_{CTAIDI}(y) = \frac{\text{customers interruption duration in year } y}{\text{number of distinct customers interrupted in year } y} \quad (23)$$

Average System Availability Index (ASAI): represents the probability or the fraction of time that a customer has received power during a year (pu or %).

$$G_{ASAI}(y) = \frac{\text{customer hours service availability in year } y}{\text{customers hours service demand (8760 h)}} \quad (24)$$

Average System Unavailability Index (ASUI): represents the probability or the fraction of time that a customer has not received power during a year (pu or %).

$$G_{ASUI}(y) = \frac{\text{customer hours service unavailability in year } y}{\text{customers hours service demand (8760 h)}} \quad (25)$$

Energy Not Supplied (ENS): describes the energy not supplied during a year (kWh/year).

$$G_{ENS}(y) = \text{total energy not supplied in year } y \quad (26)$$

Average Energy Not Supplied (AENS): represents the energy not supplied to an average customer during a year (kWh/cust.year).

$$G_{AENS}(y) = \frac{\text{total energy not supplied in year } y}{\text{number of customers}} \quad (27)$$

While most of the indicators are related to assessing customer interruptions, indicators for the load supplied can also be used [21]. These indicators might aid the decision making process within utilities since large loads can affect the utility revenues [19]. The load-based indicators are shown as follows.

Table 3 Interruption classification according to different norms

Norm	Terminology	Definition
IEEE 1159—recommended practice for monitoring Electric Power Quality (2009)	Sustained interruption	>1 min
	Momentary interruption	0.5 c–3 s
	Temporary interruption	3 s–1 min
IEEE 1250—guide to identifying and improving voltage quality in power system (2011)	Sustained interruption	>1 min
	Momentary interruption	0.5 c–3 s
	Temporary interruption	3 s - 1 min
EN 50160—voltage characteristics of electric supplied by public distribution network (2007)	Short interruption	<3 min
	Long interruption	>3 min
IEEE 1366 – Guide for Electrical Power Reliability Indices (2012)	Momentary interruption	<5 min
	Sustained interruption	>5 min
PRODIST Module 8 – Brazilian Electrical Energy Distribution Procedures at the National Electrical System (2020)	Momentary interruption	< 3 s
	Temporary interruption	3 s–3 min
	Sustained interruption	>3 min

Average System Interruption Frequency Index (ASIFI): based on load rather than customers affected. It indicates how often a load is interrupted during a year (occ/year).

$$G_{ASIFI}(y) = \frac{\text{total connected kVA of load interrupted in year } y}{\text{total connected kVA served}} \tag{28}$$

Average System Interruption Duration Index (ASIDI): based on load rather than customers affected. It represents the total interruption duration for a load during a year (h/year).

$$G_{ASIDI}(y) = \frac{\text{connected kVA duration of load interrupted in year } y}{\text{total connected kVA served}} \tag{29}$$

Notice that sustained interruption/load frequency and duration indices can be straightforwardly used in the assessment of active distribution systems, for instance, in the evaluation of islanded/load shedding strategies, reconfiguration/recomposition schemes and maintenance policies. In addition to these indices, momentary interruptions can be also taken into account. For this case, different standards specify different times to separate the concepts of sustained and momentary failures, as shown in Table 3 [25–29]. Examples of test functions for momentary interruption indices are shown in the followings:

Momentary Average Interruption Frequency Index (MAIFI): represents the mean number of momentary interruptions that a customer experiences during a year (occ/year).

$$G_{MAIFI}(y) = \frac{\text{number of cust. momentary interruptions in year } y}{\text{number of customers}} \tag{30}$$

Momentary Average Interruption Event Frequency Index (MAIFIe): represents the mean number of momentary interruption events that a customer experiences during a year (occ/year).

$$G_{MAIFIe}(y) = \frac{\text{number of cust. momentary interruption events in year } y}{\text{number of customers}} \tag{31}$$

Momentary interruptions in points of common coupling must be evaluated to assure proper behavior of different protective schemes. Other indices for the assessment of momentary and sustained interruptions are presented in [19, 29].

3.2.2 Power Quality Indicators

Due to the increased dynamism envisioned for active distribution systems alongside with the integration distributed energy resources and smart devices, all electromagnetic phenomena and its impact on power quality can be a source of concern. Particularly, the widespread of installations sensitive to short-duration interruptions or short-duration voltage variations have increased the interest in the indices related to this sort of disturbances. As example, four test functions to the evaluation of sag/swell events are presented herein [30].
System Average RMS Variation Frequency Index (SARFI_x): represents the mean number of RMS voltage variation events that occurs during a determinate period of time for a customer, with a voltage magnitude below $x\%$ for sags or above $x\%$ for swells (occ/year).

$$G_{SARFI_x}(y) = \frac{\text{number of cust. sags/swells bellow/above } x\% \text{ in year } y}{\text{number of customers}} \tag{32}$$

System Instantaneous Average RMS Variation Frequency Index (SIARFI_x): represents the mean number of RMS voltage variation events with magnitude bellow $x\%$ for sags and above $x\%$ for swells where the duration is between 0.5 cycles and 30 cycles (0.008–0.5 s 60 Hz) (occ/year).

$$G_{SIARFI_x}(y) = \frac{\text{n}^\circ \text{ of inst. cust. sags/swells bellow/above } x\% \text{ in year } y}{\text{number of customers}} \tag{33}$$

System Momentary Average RMS Variation Frequency Index (SMARFI_x): represents the mean number of RMS voltage variation events with magnitude bellow

$x\%$ for sags and above $x\%$ for swells where the duration is between 30 cycles and 3 s (occ/year).

$$G_{SMARFI_x}(y) = \frac{\text{n° of mom. cust. sags/swells bellow/above } x\% \text{ in year } y}{\text{number of customers}} \quad (34)$$

System Temporary Average RMS Variation Frequency Index (STARFI$_x$): represents the mean number of RMS voltage variation events with magnitude bellow $x\%$ for sags and above $x\%$ for swells where the duration is between 3 seconds and 1 min (occ/year).

$$G_{STARFI_x}(y) = \frac{\text{n° of temp. cust. sags/swells bellow/above } x\% \text{ in year } y}{\text{number of customers}} \quad (35)$$

Usually, SARFI$_x$ indices are used to estimate short-duration voltage variations, which indicate the frequency of voltage variations below or above the nominal level experienced by costumer $x\%$ [30, 31]. SARFI indices can be also accounted for according to the equipment compatibility curve. In [32], examples are presented and discussed for SARFI indices based on compatibility curves of the Computer Business Equipment Manufacturers Association (CBEMA), the Information Technology Industry Council (ITIC) and the Semiconductor Equipment and Materials International Group (SEMI).

Other definitions and indices for voltage sags can be found in [32]. As for the adequacy of distribution systems, different indices for power quality can be built to analyse different sorts of events [33].

3.2.3 Operational Indicators

Recently, there has been a increasing interest on assessing specific characteristics of active distribution system, such as islanded operation, distributed generation autonomy, energy costs, short circuit limits, and communication availability. Hence, additional indicators can be designed to highlight unique aspects important for utilities. As example, three test functions associated to short circuit events are presented as follows [34].

Short Circuit Current Expected Index (SCCEI$_x^n$): indicates the expected value of fault current amplitude through a given protective device n. The subscript x can be single-line-to-ground, double-line-to-ground, line-to-line, three-phase or three-phase-to-ground (A/occ).

$$G_{SCCEI_x^n}(y) = \frac{\text{sum of short circuit current amplitudes in year } y}{\text{number of events of a short circuit of type } x} \quad (36)$$

Short Circuit Frequency Index (SCFI$_x^n$): indicates the annual frequency of occurrence of short circuit type x that triggers protective device n (occ/year).

$$G_{SCFI_x^n}(y) = \frac{\text{number of short circuit events of type } x \text{ in year } y}{\text{number of simulated years}} \quad (37)$$

The frequency of each short circuit type may vary depending on the network topology of the distribution company.

Short Circuit Probability Index (SCPI_x^n): represents the probability of a short circuit current to cause the action of protective device n (pu or %).

$$G_{SCPI_x^n}(y) = \frac{\text{number of short circuit events of type } x \text{ in year } y}{\text{number of short circuit events}} \quad (38)$$

Notice that short circuit indices and their corresponding probability distributions can be used to help calibrating protective devices and to support maintenance decisions. Indices related to distributed generator outputs and islanded operation can be found in [8] and [35]. Also, in [35], economic related indices for distributed generation are proposed. In cyber physical distribution systems, the advanced information and control capabilities enabled by cyber systems can improve system operation, while, at the same time, increasing the risk of potential failures related with system control (delays, errors) and with the physical security of cyber systems and environmental safety. In order to evaluate the impact of a cyber failure (server, intelligent electronic devices, fiber optic links, switches) on the control capabilities of distributed generators, indices are proposed in [36].

4 Simulation and Illustrative Results

As discussed in Sect. 3, a complete analysis of an active distribution system is almost impractical due to the variety and complexity of models required to system representation and analysis. Nevertheless, applications devoted to specific phenomena of interest can be instanced from the general framework. In this sense, two applications are presented in this section. The first one is focused on an impact assessment of the distributed generation islanded operation with decentralized outage management. The second example is focused on the impact of protective equipment operation on the active distribution system reliability and short-duration voltage variations. The test systems and outcomes of the two illustrative applications are shown in the next subsections.

4.1 Impact of Distributed Generation Islanded Operation and Decentralized Outage Management

This section shows an illustrative example of the application of the framework presented in Sect. 3 by simulating and assessing the distributed generation islanded

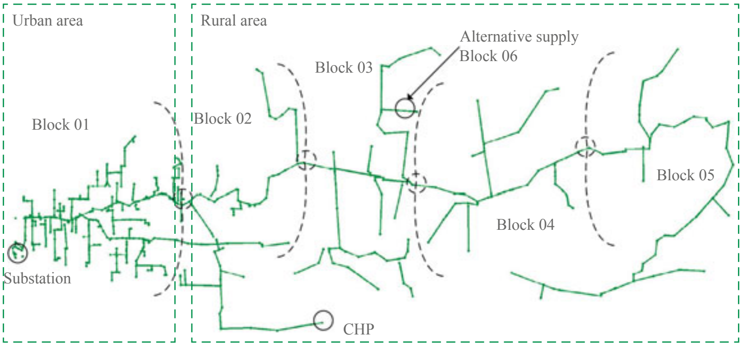


Fig. 3 CAX1-105 distribution feeder

operation with decentralized outage management on the expected reliability of a real distribution feeder from the South of Brazil, named CAX1-105 and exhibited in Fig. 3. The system is thoroughly described in [7] and covers a wide area of 166.33 km^2 providing electricity for 9780 customers (7895 customers in an urban, small, reliable, and well-serviced area; and 1865 customers in a rural, large, less reliable and ill-served area) with a peak load of 5.36 + j1.84 MVA and a Combined Heat and Power (CHP) unit of 1.2 MVA with islanded operation capabilities integrated in the rural area. Different active management approaches are assessed, as follows.

- Case A: islanded operation and decentralized outage management are not allowed;
- Case B: islanded operation is permitted, while decentralized outage management is not allowed;
- Case C: islanded operation is permitted, while decentralized outage management is not allowed. Furthermore, an electric vehicle charging station with droop control capabilities is considered in the rural area;
- Case D: Besides all features of Case C, a loading shedding scheme is used to support islanding processes, as in [7];
- Case E: all features of case D are considered, but a decentralized outage management system is used to support restoration of non-faulted zones through an alternative supply connection.

A multi-agent system is used to model the decentralized outage management solution. The system is coordinated by 6 agents, responsible for managing each network block, as indicated in Fig. 3. A CArtAgO framework is utilized to integrate the agent behavior into a Monte Carlo simulation. The block agent approach is described and discussed in [37]. In total, 650 years are sampled resulting in coefficients of variation less than 3% for all the chosen performance indices. The reliability results (i.e. performance indicators) for the cases are presented in Table 4.

The results of cases A and B show that the islanded operation procedures improved the performance of the system by increasing the availability of supply to the rural area. The system average interruption frequency has been improved on 184 occurrences over the 650 years of operation sampled for case B in comparison with case A. Within

Table 4 Adequacy indices for CAX1-105 distribution feeder

Indice	Cases				
	A	B	C	D	E
SAIFI (occ/year)	1.3852	1.3218	1.3112	1.2108	1.2108
SAIDI (h/year)	1.9003	1.8517	1.8442	1.7995	1.0938
CAIDI (h/occ)	1.3767	1.4009	1.4065	1.4861	0.9034
ASAI (pu)	0.9997	0.9998	0.9998	0.9998	0.9999
ENS (MWh/year)	9.0991	8.8576	8.8161	8.7308	5.6977
AENS (MWh/year.cust)	0.0009	0.0009	0.0009	0.0009	0.0006

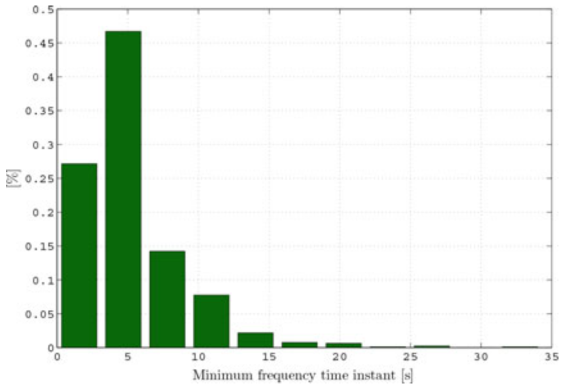


Fig. 4 Probability distribution of the time instant of the minimum islanding frequency of case B.

these state evaluations, 664 islandings have been attempted from which 31.63% have been successful and 68.37% have been unsuccessful.

Information related to the conditions of islanding operation are illustrated in Fig. 4, in which the under/over frequency relays have been disabled. The probability of the minimum frequency time instant after islanding is shown in Fig. 4, revealing that the minimum frequency has roughly a 95% of probability to occur between 0 and 10 s after islanding.

For case C, in which droop control strategies have been included into the electrical vehicle charging station, there are more successful islandings due to a smoother frequency behavior. The analysis of the results of case C indicates that the electrical vehicle droop control has been indeed able to aid the islanding process, leading to improvements on the system average interruption frequency, duration, and energy not supplied. In fact, among the 664 islanding attempts, 37.05% have been successful and 62.95% have been unsuccessful, which represents an increase of 36 islanding successful operations in comparison with case B.

For case D, a load shedding strategy is implemented using a neural network described in [7]. The outcomes show that the successful rate of islanding attempts can be considerably improved. In fact, 88.55% have been successful and only 11.45% have been unsuccessful, thereby representing an increase of 51.50% in the successful

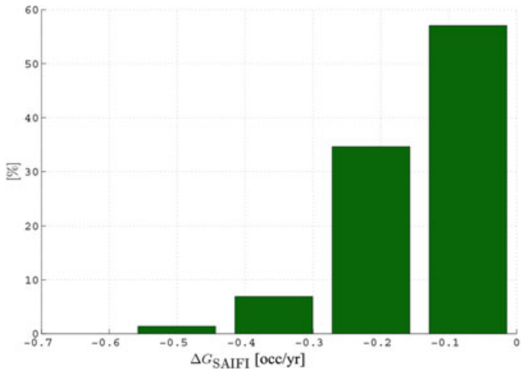


Fig. 5 Impact of load shedding strategies (case D) on the SAIFI of case C

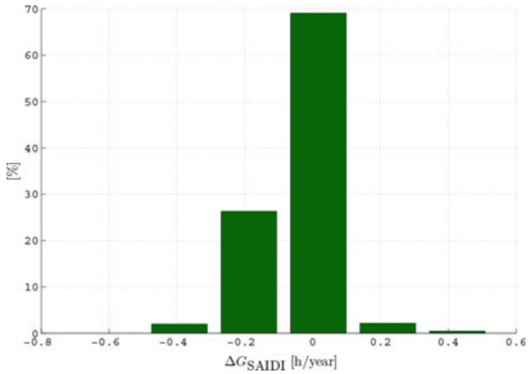


Fig. 6 Impact of load shedding strategies (case D) on the SAIDI of case C

rate of block islandings in comparison with case C. It is possible to observe that the advanced load shedding strategies have considerably reduced the system average interruption frequency as shown in Fig. 5. It is important to highlight that there are positive values in the estimated probability distributions of the SAIDI and ENS indicators due to the adoption of a load shedding, which have slightly increased the customer interruption duration and the energy not supplied in some the years sampled, as shown in Fig. 6 for SAIDI indice. In fact, the strategy deployed induced unnecessary and conservative load sheddings looking forward to achieve successful islandings with a security margin. This is not noticeable in the estimated probability distribution of SAIFI since its impact is at most 0.001738 (17/9780) occurrences per year.

For case (case E), outage management control is also considered, in this case to increase the reliability of the rural area with an alternative supply. It has been assumed a conservative/moderate hypothesis that the proposed decentralized control leads to a power restoration four times faster than the current power restoration procedure: power restoration of the CAX1-105 feeder, by using the sectionalizing switches to isolate components on outage and by controlling the tie switch to restore the service using the alternative supply. For this case, it is possible to verify asignificant

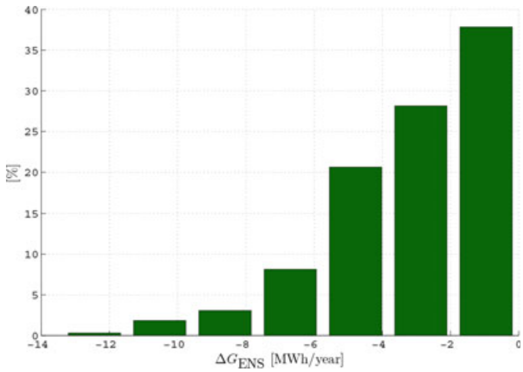
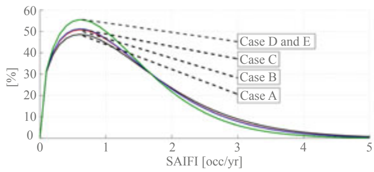
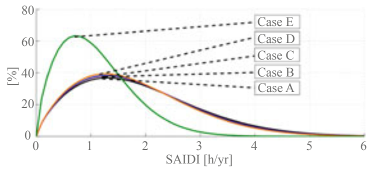


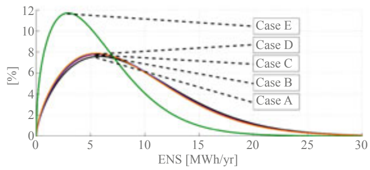
Fig. 7 Impact of outage management activities (case E) on the ENS of case D



(a) SAIFI



(b) SAIDI



(c) ENS

Fig. 8 Estimated Weibull probability density functions of the system performance indices

impact on the system average interruption duration and energy not supplied accounting reductions of 39.22% and 34.75% for each of these indices in comparison with case D, respectively. These benefits are also emphasized in the estimated probability distributions for the improvements on the SAIDI and ENS due to the outage management strategies, as shown in Fig. 7, which highlights improvements on the ENS indice in 83.69% of the years simulated.

For the sake of comparing the results achieved in cases A–E, Fig. 8 exhibits the estimated Weibull probability density functions (pdf) of the performance indices SAIFI, SAIDI and ENS achieved in all these cases. In this illustration, one can observe that case E stands as the most attractive case in terms of the performance indices. However, if the purpose of exploiting the architecture lies "only" on reducing the frequency of customer interruptions, case D is the most attractive one since it provides the same SAIFI results of case E without incurring on the outage management strategies. Clearly, several other/additional capabilities might be envisioned and evaluated (e.g. adverse condition alerting) aiming at improving even more the

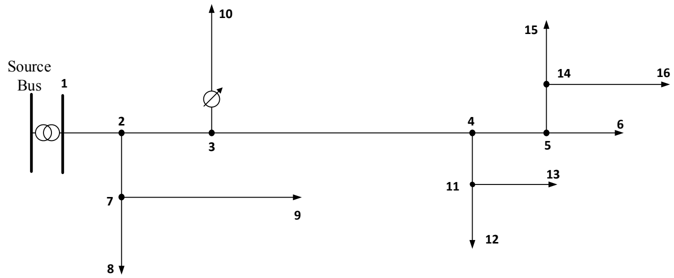


Fig. 9 UFSC 16 node test feeder

service provided by the utility through this feeder. Furthermore, aspects discussed in Sect. 3, such as fault causes, cyber failures, miss operation of equipment, power quality issues related to distributed generators and customer loads, among others, can be included within the simulation model to better represent the real operation of the system. However, it is important to highlight that the computational burden may increase significantly as more aspects of the active distribution system are incorporated into the simulation model.

4.2 Impact of Protective Equipment on Reliability and Short-Duration Voltage Variation Indices

A second illustrative example of the application of the framework proposed is presented in this section to highlight the impact of protective equipment operation on the reliability and short-duration voltage variation indices. The UFSC 16 Node Test Feeder is used for this evaluation. This test system has been created based on a feeder from the Southeast of Brazil [38]. Some modifications have been performed in the original configuration to showcase some singularities regarding the performance of unbalanced distribution systems. The single-line diagram of the UFSC 16 Node Test Feeder is shown in Fig. 9 [39].

This system has a regular overhead network geometry, a variety of configurations (distinct phasing, type of conductors, and number of phases), unbalanced loads and capacitor banks. The geometric configurations have been adapted from the IEEE 13 and 34 Node Test Feeders [40]. An equivalent transmission system is considered beyond the substation, which is modeled by a voltage source in series with an equivalent impedance. The distribution system supplies a total of 2152 customers (lumped at node points) distributed along the feeder. The grid data for the UFSC 16 Node Test Feeder can be found in [39].

Short circuits are one of the most known causes of failures of distribution system elements. To assess voltage variation phenomena that may arise due to short circuits, each failure is assumed to have a corresponding short circuit condition [39, 41]. In addition, fuse-saving protection schemes have been included in the feeder. Hence, when a single-line-to-ground fault occurs in a lateral, only the customers connected to the faulted phase will be disconnected. The recloser is able to identify the short circuit currents and disconnect the circuits using three-phase tripping actions and single-phase lockout.

In order to incorporate the previously described behavior, the state evaluation model is upgraded with short circuit and power flow analysis, which is embedded into the sequential Monte Carlo simulation. To accomplish that, a three-state Markov model, presented in Sect. 3.1, is utilized to represent the characteristics of transitory and permanent failures. Notice that alternative modelings for the protective equipment response to short circuits can be applied as in [42]. For the power flow and short circuit analysis, a three-phase modeling is utilized, with three-phase impedances and shunt admittances.

Some modifications are performed in the protective schemes in order to evaluate their impact in the adequacy and short-duration voltage variation indices. Five cases are considered in the study:

- Case A: only a circuit breaker with recloser relay at the beginning of the feeder is considered;
- Case B: circuit breaker with recloser relay at the substation and fuses in all seven laterals (branches 2-8, 7-9, 3-10, 4-12, 11-13, 5-15 and 14-16) are deployed;
- Case C: circuit breaker with recloser relay at the substation, fuses in all seven laterals and at the main trunk at branch 3-4 are utilized;
- Case D: besides the features of case C, two fault indicators are installed at branch 3-10 (serving a load center) and at branch 3-4 (main trunk);
- Case E: besides the features of case C, fault indicators are installed at all seven accounted laterals and branch 3-4.

The protective devices and substation equipment are considered to be 100% reliable. The permanent and transitory failure rates for the line segments are 0.5 and 1.0 occ/km/year, respectively. It is considered that the voltage regulator and the substation transformer have permanent and transitory failure rates of 0.03 occ/year and 0.06 occ/year, respectively. Mean repair times are assumed equal to four hours for main trunk and laterals in the first three cases [19]. Fault location time is assumed to consume 25% of total service restoration [43]. Hence, for the case D, it is considered that the fault location time is 25% reduced by adding two fault indicator sensors. For the case E, the fault location time is reduced from 1 h to 20 min (reducing 66.66% of the fault location time). For the analysis of reliability and short-duration voltage variation performance, 1000 annual samples have been used as stop criteria for the sequential Monte Carlo simulation. The convergence of the simulations has been based on the coefficient of variation of indices, which reached values less than 2.5%.

The reliability and short-duration voltage variation outcomes are presented in Table 5. In case A, in which only a circuit breaker with a recloser relay is considered at the substation, a great part of the customers experience a failure (either momentary or permanent) when a fault occurs. However, when a single-phase or a double-phase fault occurs, only the customers connected to the affected phases experience

Table 5 Adequacy and short-duration voltage variation indices for the UFSC 16 Node test feeder

Indice	Cases				
	A	B	C	D	E
SAIFI (occ/year)	10.2972	4.9053	2.7180	2.6771	2.6724
CAIFI (occ/year)	10.2972	4.9326	2.9752	2.9503	2.9339
SAIDI (h/year)	40.8181	19.5866	10.7759	9.8965	8.9604
CTAIDI (h/year)	40.8181	19.6852	11.7715	10.9018	9.8655
CAIDI (h/occ)	3.9640	3.9930	3.9656	3.6967	3.3530
ASAI (pu)	0.9953	0.9977	0.9987	0.9988	0.9989
ENS (MWh/year)	44.5610	21.1268	11.8658	10.8860	9.8768
AENS (kWh/year.cust)	20.6817	9.8173	5.5138	5.0586	4.5854
MAIFI (occ/year)	48.5298	53.9217	56.1089	55.5119	55.5386
$SARFI_{110}$ (occ/year)	2.4233	2.4236	2.4236	2.3765	2.3889
$SIARFI_{110}$ (occ/year)	0.6483	0.6483	0.6483	0.6428	0.6495
$SMARFI_{110}$ (occ/year)	1.5599	1.5602	1.5602	1.5247	1.5366
$STARFI_{110}$ (occ/year)	0.2152	0.2152	0.2152	0.2090	0.2027
$SARFI_{90}$ (occ/year)	19.7599	22.7148	24.5610	24.3339	24.4989
$SIARFI_{90}$ (occ/year)	7.1914	7.1776	7.1776	7.1246	7.1520
$SMARFI_{90}$ (occ/year)	10.2728	13.2354	15.0773	14.9263	14.9162
$STARFI_{90}$ (occ/year)	2.2956	2.3018	2.3061	2.2829	2.3307

sustained interruptions since single-phase lockout is assumed. In the single-phase lockout procedure, the load points have different failure occurrence frequency from each other, thus different SAIFI values. In the short-duration voltage variation indices, it is possible to notice that voltage sags are more prone to occur than swells.

For case B, one can verify that the installation of protective devices has improved the reliability of the system, as expected. The frequency and duration of permanent failures are roughly 50% of the values of these indices in case A. By analysing the momentary failure event indices, one can notice less sustained interruptions and more momentary interruptions since the system has more protective devices to clear permanent failures. A similar situation can be observed for the frequency of voltage sags, which increased from 19.76 to 22.71 occ/year while the frequency of voltage swells remained roughly the same.

In case C, the additional protective device is able to avoid interruptions in the load center at node 10, considerably impacting the reliability indices. Particularly, the ENS reduces 43.87% in comparison to case B. In terms of short-duration voltage variation performance, momentary voltage sags have increased, contrasting with the instantaneous and temporary voltage sags, which have not shown a significant variation in comparison with cases A and B. In case D, in which fault indicators are included in two branches, one can notice that the frequency indices (permanent and transitory) are close to the ones found in case C. Note that the positive impact can be verified on the indicators associated with the failure duration. For instance, a positive change on SAIDI and CAIDI indices is reached. On the other hand, in case E, the influence of the fault indicators on the interruption duration indices is highlighted as the SAIDI indice experiences a decrease of 16.80% in comparison to case C.

In general, the number of voltage sag events that compose the SARFI indice increases as the protective configuration of the test cases is changed. As a consequence, case C has 37.36% more voltage sags than case A, in which most occurrences are of momentary duration (between 30 cycles and 3 s). As for swell events, one can notice that changes in configuration do not interfered significantly in the accounting of events since, in the specific case of this system, voltage swells usually occur for faults at certain feeder laterals. In terms of the frequency of interruptions, case C, D and E, have the lowest values for SAIFI. It is interesting to evaluate that case A has a SAIFI of 10.30 occ/year and, as three-phase lockout operation is set for the recloser, the SAIFI becomes closer to 27.00 occ/year [44]. By assessing the SAIDI indices, one can notice that the use of fault indicators in case E decreases the indicator roughly in 2 h in comparison the same indicator in case C.

5 Final Remarks and Discussions

This chapter discusses aspects related to the reliability assessment of active distribution systems. To accomplish that, a general framework is proposed allowing to model and evaluate a wide-range of causes, consequences and operational actions that can influence the performance of active distribution systems.

In order to assess phenomena related to islanded operation, reliability and power quality, two applications of the framework proposed have been addressed. The first one focused on the evaluation of distributed generation islanded operation with decentralized outage management. The second example presents and discusses the impact of protective equipment on reliability and short-duration voltage variation in distribution systems. In each application, five simulation cases have been assessed, emphasizing the benefits of islanded operation, decentralized outage management, as well as different protective settings and configurations for the equipment.

Along the years, a variety of indices have been proposed to evaluate active distribution system operation, some of them presented herein. The literature review shows that researchers only use the most generic ones pointing out that the definition of indices concomitantly requires the performance analysis being carried out to be easily understood. At last, it is important to highlight that the computation burden associated with the assessments increases as more detailed characteristics of active distribution systems are modeled within the framework, rendering the design of comprehensive reliability analysis of active distribution systems a ever-growing challenging activity.

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The Role of Electric Vehicles in Smart Grids

Ebrahim Saeidi Dehaghani, Liana Cipcigan, and Sheldon S. Williamson

Abstract Transition to electric vehicles (EVs) is already under way. EVs have demonstrated to be the most fuel economic and emission free among other propulsion technologies. EVs can have a large impact on greenhouse gases (GHGs) reduction, increase in fuel economy, and higher fuel efficiency. The main idea behind this chapter is to analyse step-by-step energy efficiency, which is one of the key factors for technology acceptance. Penetration of EVs into the vehicle fleet affects load demand as well as electricity markets. Smart charging of EVs can remove a tremendous amount of stress from the continually evolving smart grid. Effect of home charging of EVs on electricity demand has been analyzed. More recently, EVs have been looked at as distributed sources of energy, whereby they could back up the power grid during critical high demand periods. With the help of an on-board battery pack, EVs can act as distributed generators and feedback energy to the grid. However, efficiency of energy conversion could become an issue in this power flow. Hence, in this chapter stage-by-stage efficiency of vehicle-to-grid (V2G) power flow has been evaluated.

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1 Impact of Different Domestic Electric Vehicle Charging Regimes on Quebec's Load Demand—Prediction for 2030

1.1 Introduction

Electric and plug-in hybrid electric vehicles (EVs/PHEVs) can have a large impact on greenhouse gases (GHGs) reduction, increase in fuel economy and higher fuel efficiency. EVs are propelled by the energy from electric power source, whereas PHEVs propelled by two energy sources as electricity and gasoline. Fig. 1 shows the layout of a pure battery-powered EV versus a PHEV.

The market penetration of battery electric and more electric vehicles (BEVs/MEVs) into a country's vehicle fleet is anticipated to increase the load demand at a national level. The severity of the charging impact on load demand will depend on charging regimes, EV uptake and owner's behavior. Therefore, smart charging of EVs is the need of the hour in order to remove stress from the grid. This section assesses the effect of home charging of EVs/PHEVs on electricity demand in the Province of Quebec, Canada. A number of case studies are developed to assess, how different charging regime and EV uptakes can change total load demand of Quebec in 2030. The number of light-duty vehicles and prediction of EVs/PHEVs penetration into vehicle fleet is drawn from different Canadian studies. Canada traffic distribution is developed from data acquired from INRIX Traffic Scorecard. The load demand for the year 2011 is used as a base load from Hydro Quebec and typical planning load estimates are used to project the load demand for the year 2030. It is shown that an uncontrolled charging regime would increase the load demand up to 12%, whereas controlled charging of EV batteries using TOU tariffs would lead to a have a tinny increase of up to 5% on load demand in summer time.

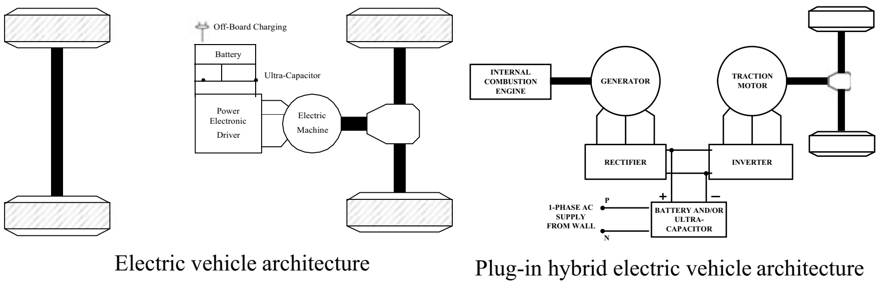


Fig. 1 Powertrain architectures of electric and plug-in hybrid electric vehicles

1.2 Related Works

Air quality and emissions will remain the major concern in our decade among different nations. In 2019, the oil and gas sector accounted for 191 Mt of CO_2 equivalent (Mt CO_2 eq) (26% of total emissions), followed closely by the transport sector, which emitted 186 Mt CO_2 eq (25%) [1]. Approximately 80% of the total bulk greenhouses gas emissions (CO_2, CH_4, and N_2O) are accounted to the secondary energy use sector in Canada, such as industrial, transportation, residential, agriculture, and commercial use [2]. Of those emissions, the transportation sector is the largest contributor of GHG emissions, representing ~30% of total GHGs in 2020. The Government of Canada has a target of total GHGs emission reduction by 17% by the year 2030. A fine progress is shown towards this target through a sector by sector approach. Federal approaches as well as action, which was taken by different provinces shows that Canada is at present half way towards the 2030 target [3].

EVs plug into the power system to charge their battery packs. BEVs are purely powered by electricity, while PHEVs using a combination of gasoline and electricity to propel the vehicle. A number of the new models of these vehicles from major automakers can be seen on the roads in Canada. It is obvious that, penetration of EVs/PHEVs and with help of smart grid, fossil fuel sources of energy can be displaced by electricity where dramatically reduce GHGs emissions. Provinces like Quebec and British Columbia use a large amount of clean electricity with a major fraction being from hydro. Clean electricity production will increase by 2030, with further new installations of renewable generation plants and closure of coal plants. A study at the University of Waterloo [4] shows that, EVs/PHEVs charging will not affect the load demand in the electricity grid, immediately.

The authors support that the system planners have 3-5 years' time to evaluate new vehicles penetration in Ontario's streets. It is likely that the adoption of EVs/PHEVs will be firstly realized in urban areas, which will impose congestions on the distribution grids assets loading and affect distribution feeders' voltage profiles. Considering EVs/PHEVs charging level and timing, a load equivalent to a new house can be added to the distribution system [5]. The implementation of smart EV battery charging methods, which will target charging during lower off-peak prices and encourage EV/PHEV owners to charge overnight out of peak hours, may help maintain the operation of distribution networks within their operating limits. The purpose of this study is to identify the impact of different domestic EV battery charging regimes on Quebec's load demand. It is anticipated that load demand can be affected by various characteristics such as: the number of EVs/PHEVs, the time frame and length of EVs/PHEVs battery charging and the power rating of the battery chargers. To ensure the accuracy of this research work, studies and methods of different sources are firstly reviewed and evaluated. A valley filling approach for EV battery charging was addressed in [6]. In this study, it is considered that 40% of distances are travels on EV mode with an average consumption 0.21 kWh/km. The findings of this study show that an increase of 18–40% in minimum load is anticipated with EV battery charging depending on different charging regimes.

A study from U.S. Oak Ridge National Laboratory [7] investigated the effect of EV utilization on the grid demand for different US regions in 2020 and 2030. The study focused on evening and night charging where in evening charging, half of the vehicles plugged in 5 pm, and the other half start to charge at 6 pm. Night charging is also divided in 2 groups as half of the vehicle start to charge at 10 pm, while the other half start charging at 11 pm. Three different charging levels of 1.4, 2 and 6 kW were considered. The results of the study show, that no additional generation would be necessary using the night charging regime, whereas in the case of evening charging regime at 6 kW rate, additional generation would be necessary to cover the EVs/PHEVs battery pack charging. A major European project called Mobile Energy Resources in Grid of Electricity (MERGE) investigated the effect of domestic EV charging on the national grid of six different European countries [8]. Dumb charging, where EV owners would charge their EVs charge as soon as they arrive home after their last trip and smart charging where EV battery charging would be controlled to minimize the impact on demand peaks using a valley filling control, was considered. The results of the study show that a dumb charging approach would increase the peak demand of all six countries under the study between 6 to 12%. The smart charging control would not increase the daily peak demand of any of the six European countries under the study.

The review of the above studies reveals the importance of considering the following factors in studying the effect of domestic battery charging on electricity demand at a national level: (i) EVs/PHEVs uptake level, (ii) battery charging occurrence and duration. The contribution of the present study is the assessment of the effect of EV/PHEV penetration in Quebec's load demand is forecasted through various penetration levels such as mild and aggressive uptakes. Firstly, the EV uptake for the year 2030 is estimated using governmental and international projections and then electric vehicle battery charging regimes are developed using data from a national survey. The term EV/PHEV or EV are used throughout this chapter to point at electric vehicles and plug-in hybrid electric vehicles, as both of them are treated in the same way from a power systems viewpoint.

1.3 Vehicles on the Roads in Canada and Quebec

Natural Resources Canada (NRCan) published the latest Canadian Vehicle Survey in 2009 [9]. This is a quarterly survey of activities in the area of vehicle transportation. The 2009 report dealt with road vehicle activities of the vehicles registered in Canada and provided the characteristics of the Canadian vehicle fleet and their fuel consumption as well as a comparison between the number of vehicles in 2000 and 2009. According to the study, Ontario and Quebec had 58.7% of the total Canadian fleet in 2009, with 7.4 million vehicles in Ontario and 4.7 million vehicles in Quebec. It is also reported that in 2009, 96.3% of the 20,511,161 vehicles in Canada were light vehicles. Medium and heavy trucks accounted for 2.1% and 1.5%, respectively. For this reason, focus in this study is on the light vehicle sector in general

Table 1 Number of cars in Canada and Quebec

Region	No. of cars: 2000	No. of cars: 2009	Compound annual growth rate	Estimated No. of Cars: 2030
CANADA	17,217,143	20,511,161	1.9%	28,695,114
QUEBEC	3,856,820	4,679,516		6,546,642

Table 2 Number of light vehicles in Canada and Quebec

Region	No. of Veh.: 2000	No. of Veh.: 2009	Compound annual growth rate	Est. No. of Veh.: 2030
CANADA	12,034,782	14,706,502	1.9%	20,574,396
QUEBEC	2,695,917	3,355,213		4,693,925

Tables 1 and 2 provide results from the survey. Assumption on compound annual growth rate prediction for 2030 is taken based on light vehicle growth rate between year 2000 and 2009 and translated to 2030. Table 1 shows the total number of vehicles in Canada and Quebec. Table 2 shows the total number of light vehicles in Canada and Quebec. In this study, light vehicles assumed to be as light cars, SUVs and station wagons.

The Canadian Vehicle Survey [9] reports that:

- There is a steady annual average increase of 0.8% in light vehicle kilometers driven.
- The growth of light vehicles between is on an average 2–3% per year.
- Light vehicles are driven on an average 17,000 to 20,000 km per year.
- Vehicle ownership typically increases by 7–8% per year.

1.4 Study Analysis and Assumptions

According to the Quebec Action Plan, charging stations must be located in places that vehicle parked long enough to charge their battery pack. These places can be home, work or shopping malls and restaurants. It is estimated that around 80% of charging load will be in either home or work place where vehicle parked in a long time during the day. EVs will most likely be used and developed first in urban areas. So, the best place to charge these vehicles are at residential parking and garages. A survey [10] that has been done by Hydro-Quebec in 2009 shows, that 94% of Quebecers who own or intending to buy a vehicle already have a parking space in their homes. 89% of these people have access to Level-1 charging point in their parking. Although with quick technology development, fast charging stations can be seen soon in strategic location. This study will consider, 1-phase, 120V, 15A connection will be the main domestic charge rating of Quebec in 2030. The Depth of discharge (DOD) considered

Table 3 Main assumptions of the study

Assumptions		References
EV charger efficiency	87	21
EV battery charging efficiency	85	24
EV charger rated power (KW)	1.8	32
Average battery capacities (kWh)		
BEV	24	33
PHEV	4	33
Usable battery capacity	80% on nominal rate	24

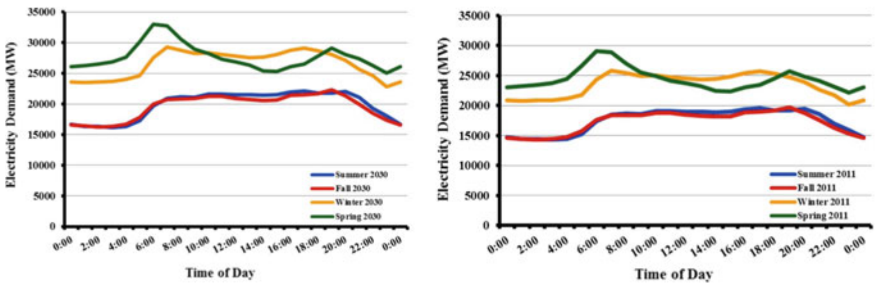


Fig. 2 Quebec electricity demand for 4 seasons: Actual (right) and 2030 projection (left)

in this study is 80%. Therefore, it is assumed that batteries are initially at 20% state of charge (SOC), and then they are being fully charged (Table 3).

The load demand for the year 2011 and the expected annual growth have been provided by Hydro-Quebec. The load profiles of 15th day of the first month of each season are used in this study for analysis of typical days. In "état d'avancement 2011, du plan d'approvisionnement 2011-2020" [11], Quebec annual electricity demand for 2011 indicated as 184.5 TWh. Plan also predicted annual electricity growth rate is 0.7% for 2011-2020. By calculating this rate for 2011- 2020 period and transpose it to 2021-2030 period, estimated annual electricity demand of Quebec in 2030 would be 209 TWh. Fig. 2 shows the electricity demand of the assumed typical days of 2011 and 2030 for Quebec.

1.5 EV Charging Regimes in Quebec

The impact of EVs/PHEVs on load demand from the model, considers different variables such as: Quebec population, vehicle growth, electricity price forecast and EV/PHEV efficiency through development of the technology. The model will consider the number of EVs/PHEVs and their energy consumption rate. The EV/PHEV load demand forecast is not a certain procedure. Changes in any of major variables and assumptions will affect new technology adoption and may lead to modify the prediction especially in the next 10 years. The new technology acceptance will depend on many factors such as: technology improvement especially in battery production, consumer acceptance and charge station infrastructure. EV/PHEV charging is developed using two major charging regimes. Uncontrolled as well as dual tariff (price driven and smart charging base) regimes are considered for this study. The additional load demand from EV/PHEV charging on Quebec load demand is incorporated for electricity grid preparation and safe electricity production margin purposes.

1.6 Uncontrolled Charging Regime

In this regime, EV owners start charging their vehicle as soon as they arrive home. The charging periods of EVs depend on the daily traffic pattern of the region. The daily traffic pattern of Canada is used for Quebec, which is acquired from INRIX Traffic Scorecard [12]. A study on assessing vehicle mobility behavior shows, that vehicles are parked at home in about 20-22 hours on average per day [13]. Therefore, the total driving time will be one hour per day. According to a study that presents traffic statistics for Canada [14], Canadian commuters took an average of 30 minutes with all modes of transportation to go to work in metropolitan areas that have population of more than one million. 30 minutes travel time is used in this study as reference of an average time for a daily trip with car; it is considered that every trip that occurs within specific hour, commuters can start charging in the following hour. Figure 3 shows the traffic pattern of Quebec in 24 hours.

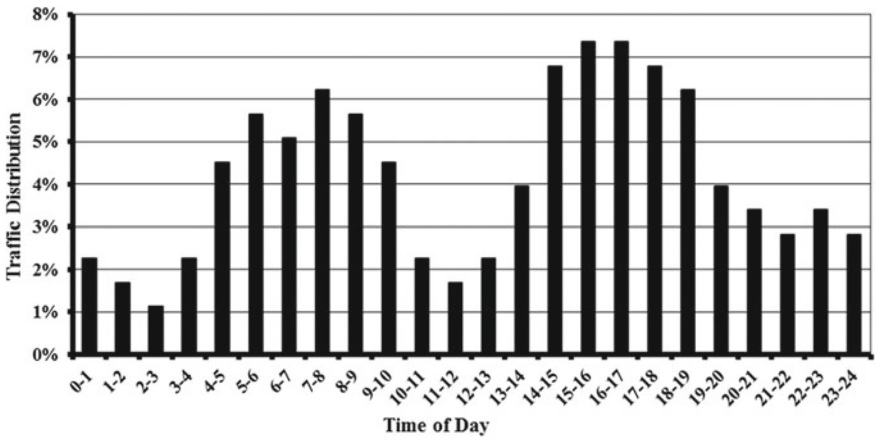


Fig. 3 Quebec's traffic distribution in 24 h

EVs/PHEVs are different from dispatchable loads, such as pump storage stations in their primary function. These loads can be named as flexible loads used as vehicle that has own simplicity and constrains. The required daily energy is directly proportional to total daily trip distance.

$$E_d = N \times d \times f \quad (1)$$

Here:
E_d : Total daily vehicles energy requirement,
N: Number of vehicles,
d: Average travelled distance by vehicle and
f: Average energy consumption KWh/km.

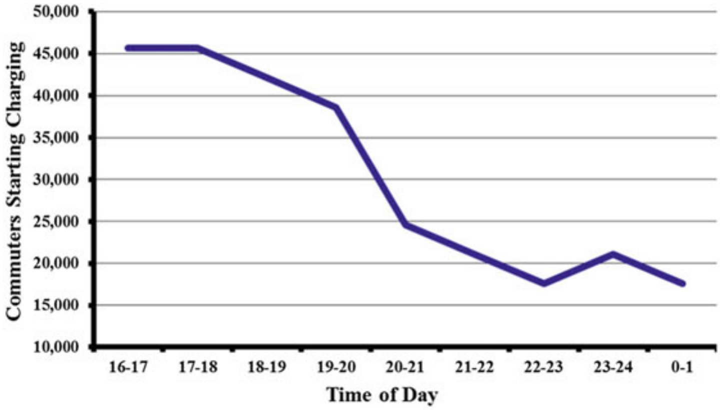
Number of vehicles for mild penetration is 328,575 and 2,276,554 for aggressive penetration. Average distance travelled by light vehicles is around 45 kilometers per day and average energy consumption is 0.2 KWh/km [15]. Therefore, the average daily vehicles energy consumption for EV low uptake is 2.9 GWh and for EV high uptake is 20.4 GWh. In Quebec, with Level-1 charging facility, PHEV batteries would become fully charged from fully discharge level, in an average of 7 hours and EV batteries charging time can be 12 hours in an average. Quebec EV charge distribution is also shown in Figure 4 for mild (above figure) and aggressive EV penetration. Note that in this study, 4 PM considered starting time to charge EVs.

1.7 Controlled Charging Regime

Quebec's electricity tariff is based on the amount of consumption in 24 hrs. 5.32 ¢/kWh is the price for the first 30 kWh of consumption and 7.51 ¢/kWh will be charged for the remaining energy usage. Target in dual tariff regime is to move EV charge to overnight. In the 2006-2015 Quebec Energy Strategy, government wanted Hydro-Quebec to employ the new rates model based on season and time of use for residential customers [16].

"Time it right" rate project was run in 2010 in four cities in Quebec [17]. Target in this project was to set a new rate structure, which could help customers to manage their electricity bill better. In this project, off peak period starts at 10 pm and finish at 6 am of the next morning. By changing in rate structure and with using smart meters, dual tariff regime can be applied to Quebec EV charging. It is assumed that, EV owners who arrived home before 10 pm start to change their vehicle at 10 pm, and those who arrived home between 10 and 11 pm start charge their vehicles at 11 pm.

To have an assessment on the impact of dual tariff regime on EV charging, hourly electricity price that Hydro-Quebec used in its electricity transmission to neighboring provinces in Canada and US, is considered in this study. Since, there is no dual tariff on Quebec electricity tariffs; electricity transmission price to out of province customers is used as a tool to evaluate the impact of this EV charging regime on load demand.



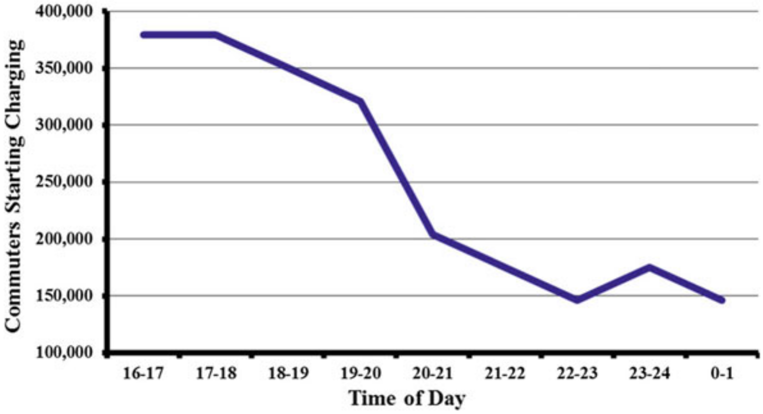


Fig. 4 Quebec's EV charge distribution for EV low uptake (top) and EV high uptake (bottom) for uncontrolled scenario

EV charging regime could have a major role on load demand. Penetration of EVs can have benefits if specific vehicle charging implemented. In general, by employing controlled regime, utilization of the existing power system can be maximized. By implementing a particular charging method, and move EV charging to overnight, thermal generation can be minimized and inflexible generation such as renewable energies in particular wind energy can be facilitated. With this smart strategy, emission and total system cost are also reduced. But, with uncontrolled charging regime these benefits may not arise and load demand, total system cost and emission will increase [15].

1.8 Study Results and Effects of Charging Patterns

The effect of EV market penetration on Quebec's load demand is assessed using four different seasonal load profiles for both uncontrolled and controlled charging regimes. Figure 5 shows two days duration load demand for each season in uncontrolled charging regime for year 2030. The peak load is found to increase in all seasons for low and high EV uptakes. The time that commuters would return home coincides with the peak demand. However, it is interesting to observe that new peak demand times occur for summer and winter. Figure 4 also shows, peak increase is relevant to the time that commuters arrive home and start charging vehicles. In result, increase in peak demand, peak demand time shift for different seasons and times.

Table 4 shows the peak demand without EVs, the peak demand with a low EV uptake and the peak demand with a high EV uptake using an uncontrolled charging regime. The percentage in peak increase and new peak time in uncontrolled charging regime for different seasons of year 2030 are also provided.

Figure 5 and Table 4 show that using an uncontrolled charging regime in Quebec for 2030:

- For a low EV uptake, the peak demand is increased up to 1.4%. The demand peak time is shifted in summer and winter seasons into the evening.
- For a high EV uptake, the peak demand is increased up to 11.57%. The demand peak time is shifted in summer and winter seasons into the evening.

Figure 6 shows two days duration load demand for each season using a controlled charging regime for year 2030. The peak load is found to increase in all seasons for low and high EV uptakes. However, this scenario is considerable in high EV uptake. Demand peak increased in all seasons with more stress in summer and fall. Peak is also shifted from afternoon and morning to evening in summer and fall. Load demand profile is also developed for controlled charging regime. For this charging regime, an algorithm is used that allows a vehicle that arrived home before 10 PM, start charging at 10 PM. Vehicles arrives home between 10 and 11 PM must wait until 11 PM. Therefore, their charge will start at 11 PM. In this regime charge profile is developed with regular rate for after 10 PM charging. Using this controlled charging regime, it is found that the major fraction of EV battery charging would occur overnight. Giving this charging strategy with off- peak energy use by delaying of home charging after 10 PM can optimize the use of low cost energy at off-peak period. With use of this strategy, renewable energy generation can fit into the generation market and can be consumed directly with the help of overnight EV charging.

Table 5 shows the peak demand without EVs, the peak demand with a low EV uptake and the peak demand with a high EV uptake using a controlled charging regime. The controlled charging offset the charging time of owners, as shown in Table 5, in order to restrict any new charging from occurring between peak times.

Figure 6 and Table 5 show that using a controlled charging regime in Quebec for 2030:

- For a low EV uptake, the peak demand is maintained in both figure and time.

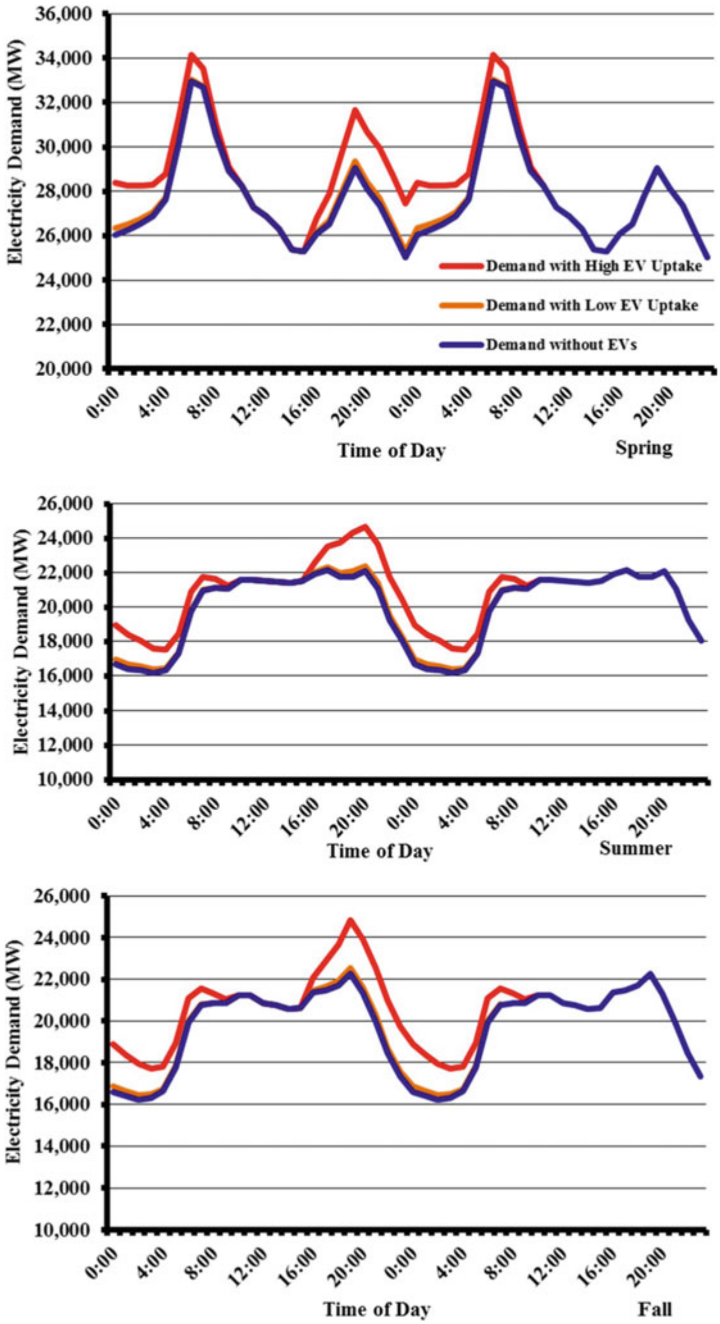


Fig. 5 Quebec's predicted energy demand in 2030 for uncontrolled scenario

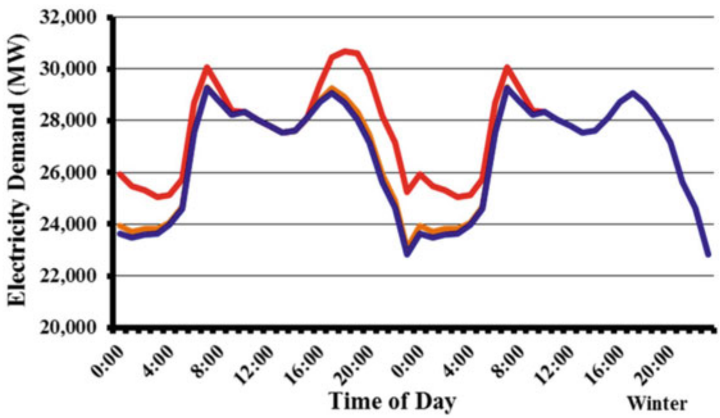


Fig. 5 (continued)

Table 4 Peak increase and new peak time as a result of EV penetration in uncontrolled scenario

Season	Demand without EV	Peak Time	Demand with Low EV Uptake	New Demand Peak Time	Peak Increase (%)
Spring	32,970.30	6–7 AM	33,052.46	6–7 AM	0.25
Summer	22,137.69	5–6 PM	22,382.55	8–9 PM	1.11
Fall	22,250.99	7–8 PM	22,560.67	7–8 PM	1.39
Winter	29,272.19	7–8 AM	29,313.27	6–7 PM	0.14
Season	Demand without EV	Peak Time	Demand with High EV Uptake	New Demand Peak Time	Peak Increase (%)
Spring	32,970.30	6–7 AM	34,124.05	6–7 AM	3.50
Summer	22,137.69	5–6 PM	24,670.23	8–9 PM	11.44
Fall	22,250.99	7–8 PM	24,825.24	7–8 PM	11.57
Winter	29,272.19	7–8 AM	30,665.79	6–7 PM	4.76

- For a high EV uptake, the peak demand is increased up to 4.21%. The demand peak time is shifted only for the summer season into the evening.

The advantage of this controlled charging regime over the uncontrolled charging regime is the application of valley filling. The ability of the controlled charging regime to mitigate the impact on peak demand increase and time shift has been demonstrated.

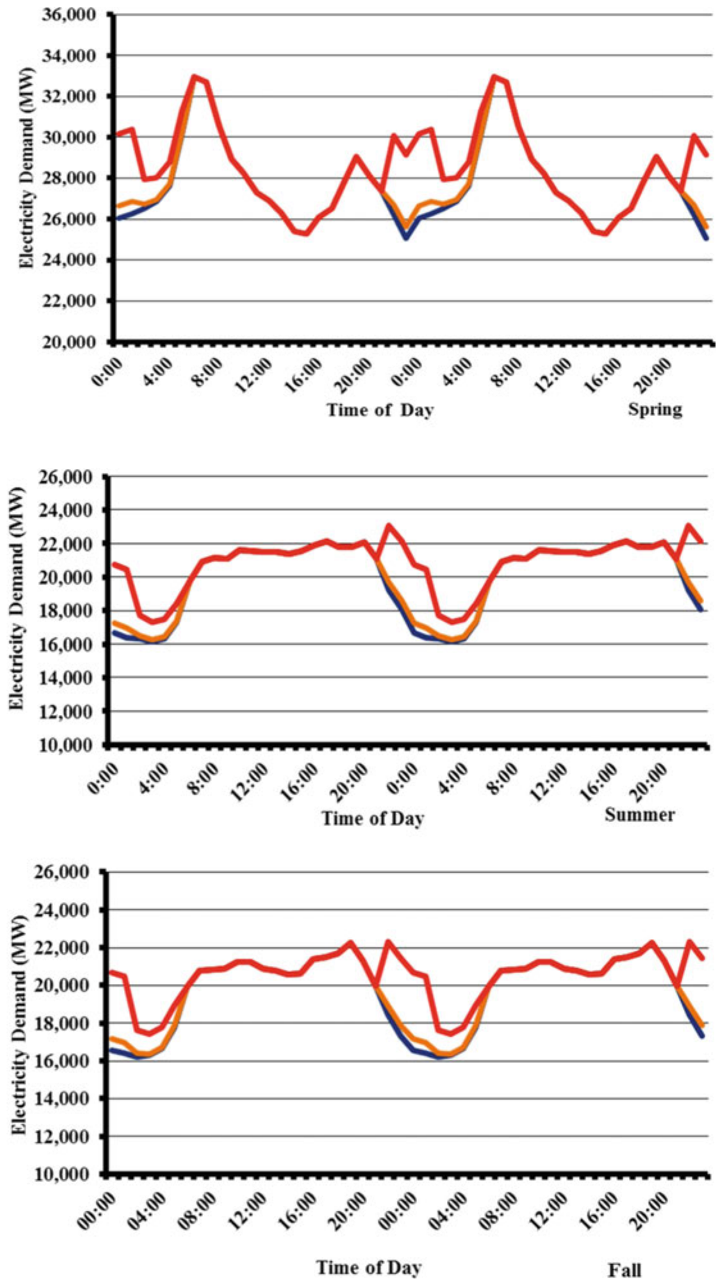


Fig. 6 Quebec's predicted energy demand in 2030 for controlled scenario

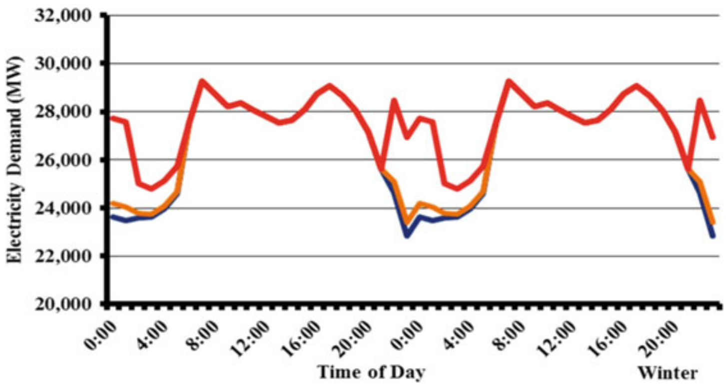


Fig. 6 (continued)

Table 5 Peak increase and new peak time as a result of EV penetration in controlled scenario

Season	Demand without EV	Peak Time	Demand with Low EV Uptake	New Demand Peak Time	Peak Increase (%)
Spring	32,970.30	6–7 AM	32,970.30	6–7 AM	0
Summer	22,137.69	5–6 PM	22,137.69	5–6 PM	0
Fall	22,250.99	7–8 PM	22,250.99	7–8 PM	0
Winter	29,272.19	7–8 AM	29,272.19	7–8 AM	0
Season	Demand without EV	Peak Time	Demand with High EV Uptake	New Demand Peak Time	Peak Increase (%)
Spring	32,970.30	6–7 AM	32,970.30	6–7 AM	0
Summer	22,137.69	5–6 PM	23,068.93	12 midnight to 1 AM	4.21
Fall	22,250.99	7–8 PM	22,295.09	7–8 PM	0.20
Winter	29,272.19	7–8 AM	29,272.19	6–7 PM	0

1.9 Comparison with United Kingdom (UK) Study

This study has been compared with the results from a UK project, which analyzes the impacts that EV domestic charging may create on the national electricity demand [18]. The purpose of the study was also to identify the impact of different home charging regimes on UK load demand. The UK study considered 13A, single-phase, 240V connection as the main domestic charging rate in the UK in 2030 [19]. In this study, the batteries of BEVs and PHEVs considered to become fully charged from full discharge in 15h and 4h respectively. Figure 7 shows the impact of EV domestic charging for three seasons and for different uptake levels in uncontrolled scenario.

In the dual tariff regime, the EVs assumed to start the charging process at night. There are different price rates and off-peak times in the UK, according to each energy

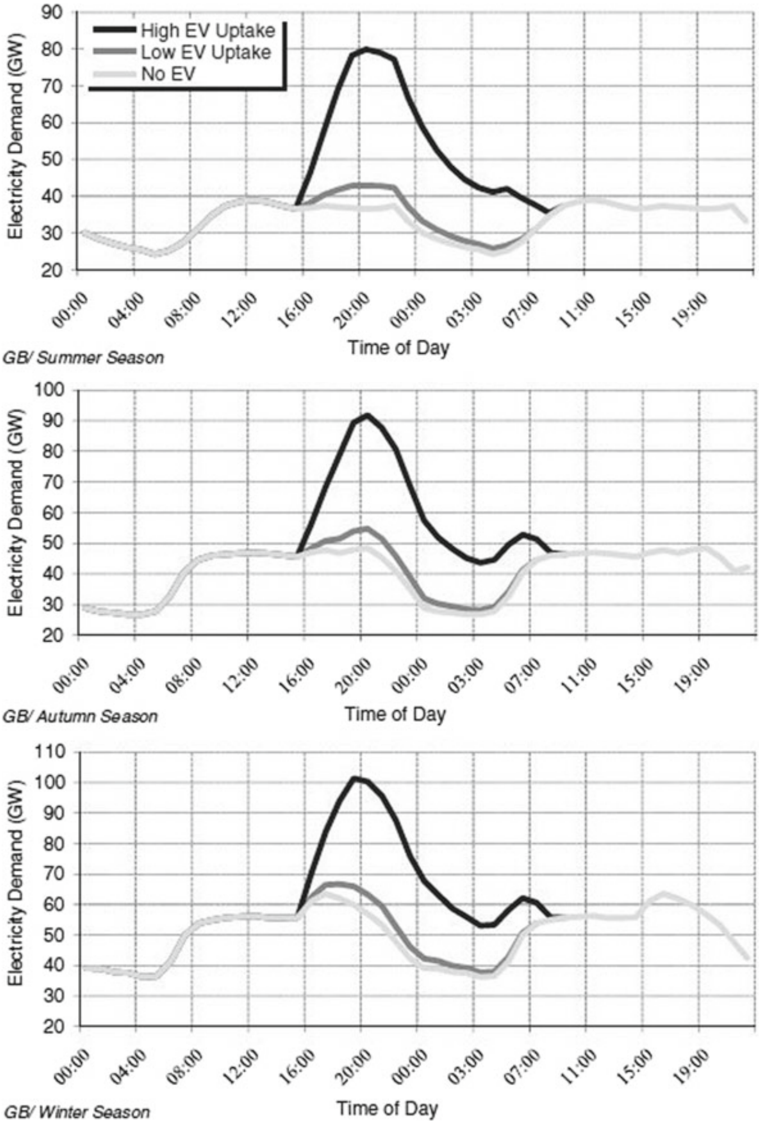


Fig. 7 Predicted energy demand for uncontrolled charging in 2030 [19]

supplier. For this study, it was assumed that the off-peak charges start at 11 PM and finish at 7 AM of the next day [20]. This period is also considered the off-peak time in 2030. EVs that return before 23:00 will wait until this time then start the charging process. EVs arrive between 11 PM and 12 midnight; will begin charging the batteries at 12 midnight. The predicted load demand for the dual tariff regime is presented in Figure 8.

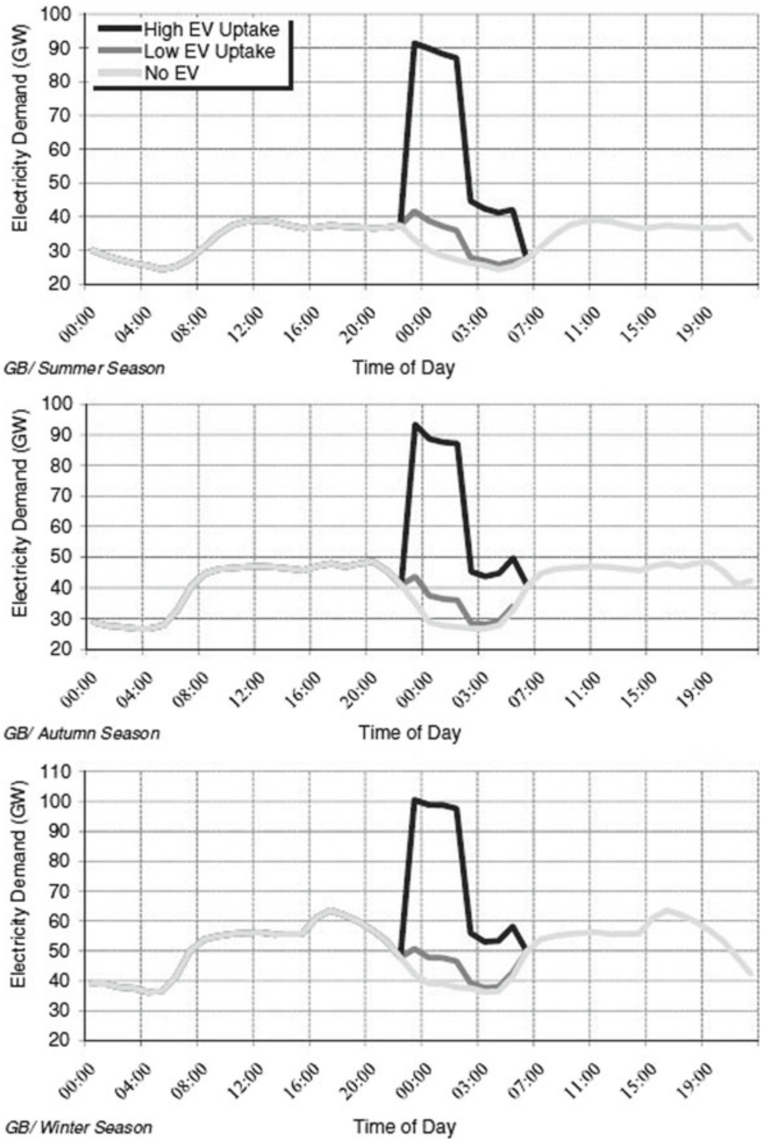


Fig. 8 Predicted energy demand for dual tariff charging in 2030

The peak increase and time displacements by season for the low EV uptake case are illustrated in Table 6 for both uncontrolled and dual tariff charging regimes.

It was found that even the low EV uptake level, will increase the peak of the electricity demand in 2030. The uncontrolled EV charging was found to increase the winter day peak demand by 3.2 GW (5%). However, with a dual tariff control strategy, the winter day peak demand will not change. In conclusion, it was found that

Table 6 Peak increase and time displacement by season for uncontrolled and dual tariff regimes as a result of EV charging and low uptake

Charging Scenario		Uncontrolled charging		Dual Tariff charging	
Season	Actual Peak Time	Peak increase (GW)	Projected peak time (2030)	Peak increase (GW)	Projected peak time (2030)
Spring	6 PM to 7 PM	5.770 (11.4%)	7 PM to 8 PM	0	6 PM to 7 PM
Summer	12 noon to 1 PM	3.94 (10.1%)	8 PM to 9 PM	2.653 (6.8%)	11 PM to 12 midnight
Autumn	8 PM to 9 PM	6.315 (13%)	8 PM to 9 PM	0	8 PM to 9 PM
Winter	5 PM to 6 PM	3.160 (5%)	6 PM to 7 PM	0	5 PM to 6 PM

the peak day demand will increase slightly with low EV uptake, in the uncontrolled scenario. However, in dual tariff regime peak increase can successfully eliminate for the most cases. For the high uptake scenario, it was found that more smart control algorithms must be applied to manage the EV charging requests without increasing future electricity demand in the UK.

1.10 Summary

In this study, the effect of EV home charging on Quebec's load demand was examined. Two EV home charging strategies are developed, as uncontrolled and controlled (dual tariff) regimes. In the uncontrolled scenario, there is no time limit on EV charging. Charging starts as soon as vehicle gets home. Results showed demand peak is increased in four seasons for mild and aggressive EV penetration in Quebec and UK. The maximum increase is in the Fall, with 11.57% between 19:00 and 20:00 for Quebec. In the UK case, 13% is the maximum increase occurred between 20:00 and 21:00. Comparative results between the two studies was presented for the uncontrolled scenario. In Quebec, peak time is shifted to evening for summer, fall, and winter. This peak shift is not in interest of distribution companies, as it will put extra stress on the network. Therefore, expensive electricity must be generated to supply the extra load. In the UK case, all load shifts are in the afternoon and evening with more stress between 20:00 and 21:00 in fall season (Table 7).

In the controlled scenario, certain limitations are applied to EV charging. EVs are not allowed to charge at any time they want. Results showed that in both cases, there is no extra load in spring and winter. Less than 0.5% increase for Quebec in fall and less than 7% increase for both cases in summer, which is shifted to late evening for both cases. Table 8 shows the results of comparison between two studies in controlled scenario.

Table 7 Comparison in peak increase and new peak time between QC and the UK for the uncontrolled scenario

Season	QC Peak Time	QC Peak Increase (%)	QC New Demand Peak Time	UK Peak Time	UK Peak Increase (%)	UK New Demand Peak Time
Spring	6:00–7:00	3.50	6–7 AM	6–7 PM	11.4	7–8 PM
Summer	17:00–18:00	11.44	8–9 PM	12 noon to 1 PM	10.1	8–9 PM
Fall	19:00–20:00	11.57	7–8 PM	8–9 PM	13	8–9 PM
Winter	7:00–8:00	4.76	6–7 PM	5–6 PM	5	6–7 PM

Table 8 Comparison in peak increase and new peak time between QC and the UK for the controlled scenario

Season	QC Peak Time	QC Peak Increase (%)	QC New Demand Peak Time	UK Peak Time	UK Peak Increase (%)	UK New Demand Peak Time
Spring	6–7 AM	0	6–7 AM	6–7 PM	0	6–7 PM
Summer	5–6 PM	4.21	8–9 PM	12 noon to 1 PM	6.8%	11 PM to 12 midnight
Fall	7–8 PM	0.20	7–8 PM	8–9 PM	0	8–9 PM
Winter	7–8 AM	0	6–7 PM	5–6 PM	0	5–6 PM

The results of both studies show that, neither in Quebec nor in the UK, uncontrolled charge scenario would be an adequate solution for EV home charging. These increases in electricity demand will affect the cost of generation in high peak time. Therefore, electricity market prices will be affected and consumers must pay more for their consumption. As a result, controlled charging seems to be a smart solution for EV home charging in the future.

2 Vehicle-to-Grid (V2G) POWER FLOWS: Inefficiencies, Potential Barriers, and Possible Research Directions

EVs are equipped with a drivetrain that is completely electric powered, with a large on- board battery pack. More recently, apart from charging applications, it has been proposed that EVs could also provide back-up power to grid during critical high demand periods, using the on-board battery, in the form of vehicle-to-grid (V2G) power flow [21–25]. With the help of an on-board battery pack, EVs can act as distributed generators and feedback energy to the AC grid. V2G connection has acquired much attention and interest amongst power system engineers and numerous business models have been proposed. While interconnecting EVs with the grid for reverse V2G power flow seems to be a lucrative business model, the question to be raised from a pure electrical engineering standpoint is, that how efficient (or inefficient) is the process of interconnecting the EV to the grid. Power electronic converters need to take care of energy conversion stages. This raises some critical conversion efficiency issues as well as protection and security concerns. Modeling of operating condition for V2G power flow and detailed loss (or efficiency) will be proposed in this chapter, in order to depict realistic system efficiency. Possible solutions through interconnecting renewable energy systems, advanced power conversion designs, and virtual power plant concepts will be discussed. Furthermore, possible research topics in the areas of advanced power electronic conversion for V2G applications will be highlighted. Thus, this chapter will point out the myths and concrete realities of connecting future EVs to the existing grid or homes.

2.1 Power Demand and Vehicle-To-Grid Overview

Load demand on the grid is high in certain seasons. In summer, there are appliances that can put up more stress in the electricity grid. An example can be air conditioners that can be used in different sectors. On the other hand, electricity demand is not constant throughout a typical day. Figure 9 shows a typical 24 hour load profile during a day for commercial, industrial, and residential loads [25]. Several models have been described to reduce stress from grid in high demand times. Vehicle-to-Grid (V2G) is considered as a possible solution to stabilize the power network and to smoothen the load curve. It is claimed that EVs can be considered as load and distributed storage [26]. Future V2G connection of EVs or PHEVs is considered as a lucrative solution to stabilize the existing AC grid.

In addition, V2G proposes smoothening out stressful load demands within the grid, especially in time slots when grid power is expensive, and to provide ancillary service. V2G power flow will be established when a connection is made, such that the energy is transferred from the vehicle to electricity grid. Figure 10 shows a schematic diagram of V2G connection.

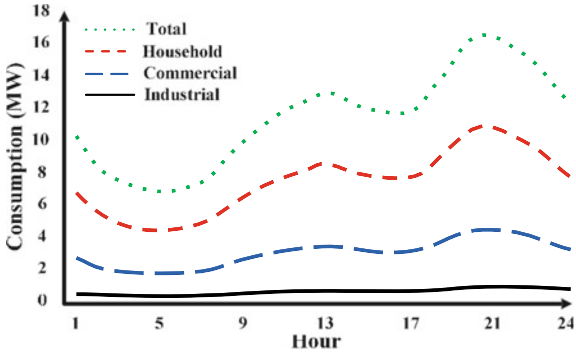


Fig. 9 Typical 24-h load profile

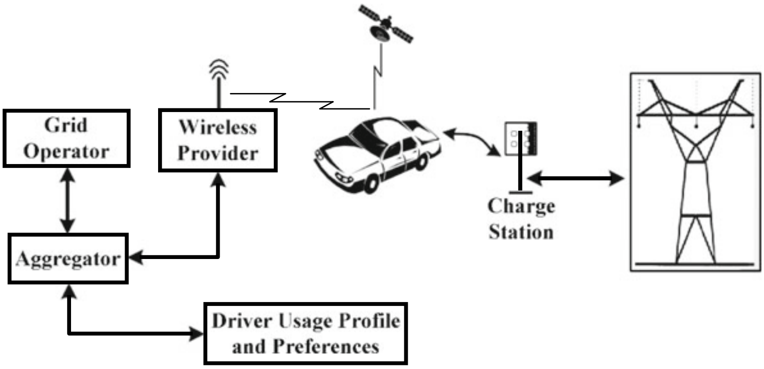


Fig. 10 Schematic diagram of V2G connection

Following are the imperative elements to implement V2G successfully: 1) multiple power electronic converter stages, so that energy can flow from EV to grid, 2) bi-directional charging unit that can either be on-board or off-board, 3) accurate, certified metering, on-board the vehicle, to track energy flow, and 4) means of communication between grid and EV. Based on the vehicle type, there are three main V2G systems proposed.

2.2 Battery Electric Vehicles (BEVS)

Drive train in BEVs is completely electrified and battery is the main source of energy to drive the vehicle. The battery pack will plug-in and charge, whenever needed from the grid, and when there is a shortage power in electricity grid, the process will be reversed, and the EV discharges its stored energy to the grid.

2.3 Plug-In Hybrid Electric Vehicles (PHEVS)

The battery pack is used only for short or medium distances in PHEVs. The ICE is on-board, to provide additional power through a generator, for driving beyond the battery range. For V2G applications, either the battery or the engine as motor-generator, can supply power to the grid. The battery pack in PHEVs is designed for traveling short distances and cannot feedback much energy to the grid. Hence, powering the grid from a PHEV will rely on the ICE, which can be used as an alternator.

2.4 Plug-In Fuel Cell Hybrid Electric Vehicles (PFC-HEVS)

These vehicles are powered using recyclable hydrogen. The hydrogen may be sourced from water (electrolysis) or reformed from hydrocarbons. In addition to using hydrogen as a fuel, these vehicles have the capacity to plug-in to the grid and charge its battery (and regenerate hydrogen on- board). The stored energy in the battery pack can be used for propulsion or for V2G applications.

2.5 Major V2G Difficulties and Issues

Vehicle fleet integration with the power grid has two critical technical areas. Grid-to-vehicle (G2V) capability is already proven and PHEVs as well as EVs can be now charged from the grid EVs/PHEVs act as new loads to the grid. Thus, restructured load curves must be reconsidered. Vehicle-to-grid (V2G) is a perception that is being proposed vehemently by power system researchers, claiming that it could stabilize the power grid. V2G claims to provide benefits for the power grid, the vehicle owners, the government, as well as the environment.

Since an EV would be parked for about 20-22 hours per day on an average [27], there exists an opportunity to feedback power to the grid with a large number of battery EVs. Surely, this seems a very lucrative proposal. The proposal claims that the EVs can be charged during low power demand and reverse energy flow can be achieved during high load demand. Unfortunately, the proposed idea suffers from fundamental energy conversion problems, which makes it unlikely for viable processing on a large scale; at least, in the near future. The following sub-sections highlight the concerns that make the V2G concept questionable.

2.6 Battery Degradation and Protection Against Power System Fault Damage

Using rechargeable batteries to power the grid will increase its number of charge and discharge cycles, which will unquestionably end up in probably having to replace the EV battery sooner than usual (compared to only using the battery pack for driving purposes and charging it when idle). As is well known in EV energy storage literature, the number of charge/discharge cycles contributes heavily towards the lifetime of rechargeable lithium-ion (Li-ion) and nickel-metal hydride (Ni-MH) batteries [27, 28]. The lifetime of batteries is not unlimited; this is the major concern with EV commercialization. Using an EV battery pack to perform long term V2G will decrease the battery capacity (or drastic change in SOC) over its lifetime [27–29]. Studies show that V2G is a technically feasible option to balance electricity load with the generation in the future. The energy that can be fed back to the grid per vehicle can be calculated as [27]:

$$W = (E_S \times DOD - (d_1 + d_2) \times R_{eS} \times E_{kn}) \times 5_{con} \tag{2}$$

DOD: Depth of discharge;
E_S: Battery capacity;
d_1: Number of kilometers that car was driven during a day;
d_2: Extended drive range to not limit flexibility of drive;
E_{kN}: Per kilometer energy consumption;
5_{con}: Charge/discharge Efficiency;
R_{eS}: Electricity driving share of vehicle.

Studies show that EV owners can benefit from V2G from few hundred to several hundred dollars per month. However, a study in the German market shows positive control and feeding back electricity are not going to be a trusted option, due to the not-so-cost-effective degradation of battery packs. Battery degradation must be considered in order to estimate decreasing battery lifespan as a result of powering grid with V2G. DOD_{V2G} is the depth-of-discharge (DOD) as a result of V2G [27]. With the assumption that the battery pack is completely charged before each dispatch, DOD_{V2G} can be calculated as:

$$DOD_{V2G} = \frac{P_{veh} \times Nin\left\{t_{Dicp}; 24.R_{d-c}\right\}}{E_c} \tag{3}$$

t_{Dicp}: Dispatch time;
R_{d-c}: Dispatch probability (%).

The other important parameter is the number of charge/discharge cycles over the entire battery lifespan (C_{Sife}):

$$C_{Sife} = 1331 \times DOD^{-1.8248} \tag{4}$$

It should be noted that battery life will be reduced disproportionally to the depth of discharge [27, 28]. A greater rate of energy delivery can be obtained when depth of discharge is shallow in a cycle, compared to a deep discharge over the lifespan of the battery. This means that at the end of the day's driving, if the battery is at 55% DOD, it is better to plug it in and charge it, rather than discharge the remaining capacity to the grid. Also, another study claimed that, in order to assure the mobility of the vehicle, the EV can participate in V2G service only if the SOC is higher than 60%. With this assumption, there is not much energy that can be fed back to the grid from the on-board battery pack. To back up these statements, a mutual relationship between battery DOD and total number of cycles over a lifespan is shown in Fig. 11 [27].

In addition, it should be noted that the environmental benefits of V2G are also not promising. By using the vehicle as a distributed generator (DG), the battery pack will lose its lifespan and will need to be replaced more frequently. Again, as is well documented in EV literature, it is well known that the overall process of battery

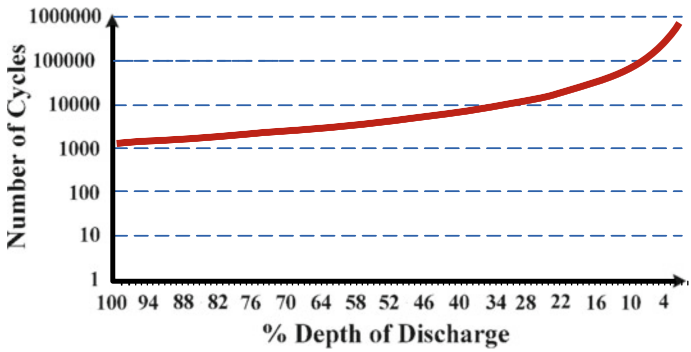


Fig. 11 Mutual relationship between DOD and cycle lifespan

manufacturing is a not an efficient process. Apart from that fact, recycling of old or completely exploited batteries is a major environmental concern, which needs to be seriously considered before practicing V2G services.

Another problem while considering EV battery pack connection to grid is battery protection circuitry. It is obvious that grid operators cannot support protection of millions of EV battery packs coming online at the same time. The utility companies cannot guarantee the occurrence of a fault.

Hence, they obviously cannot guarantee the safety of the EV owners' battery packs. Hence, this issue cannot be ignored, before practicing V2G.

2.7 Grid Control Issues

During V2G, every EV acts as a generator, and in the mass market, millions of tiny generators will be connected to the power grid. Controlling these small EV distributed generators independently is another problem that needs to be addressed. It should be noted that by using ordinary EV-grid interface devices cannot resolve issues arising as a result of integration of EVs to the distribution grid. The grid operator needs to know the status, availability, and willingness of these EV generators at all times, as to which one is suitable for drawing energy from a specific battery pack. Issues such as voltage drop, as a result of EV charging, decrease the charging rate locally. Voltage drop control methods could be used to manage and control these interfaces [28]. However, this would not be acceptable, when it comes to higher level control, such as control and management of congestion in the branches or participating EVs to electricity market sharing.

2.8 *Energy Conversion Losses; Efficiency Issues Related to Well-To-Grid, Grid-To- Vehicle, and Reverse Power Flow*

It is obvious that there exist losses each time energy is stored, converted, or transmitted. In a PHEV, the amount of losses vary, which can be very large, such as losses in the ICE, or smaller losses, such as those in power electronic devices and electric drives. In a PHEV-grid or EV-grid interconnection, it is obvious that, when energy goes through the various stages of storage, conversion, regulation, and transmission, each stage contributes to losses. Thus, the result is that the actual energy available for work is considerably low. Figure 12 shows losses in the process of energy transmission and conversion, specifically for V2G practice.

Using a theoretical (back-of-envelope) efficiency analysis, it is clear that efficiency of the process of generating and transmitting electricity (source-to-electric outlet; STO efficiency) is about 50-52% [29]. For EV charging, this energy must go through a charger, which has approximate efficiency of about 94%. This energy has to be stored in the EV battery, which has an efficiency of approximately 80% [29, 30]. Thus, the efficiency of stored energy (5_E) is calculated as:

$$5_E = 5_{ST0} \times 5_{Charge} \times 5_{Batt} \quad (5)$$

Thus, $5_E = (0.52) \times (0.94) \times (0.8) \cong 0.39$.

Approximately 60% of energy is lost in different stages of generation, transmission, and conversion to charge an EV battery pack. Furthermore, V2G process claims that energy flow can be reversed, and stored energy can be fed back to the grid. The

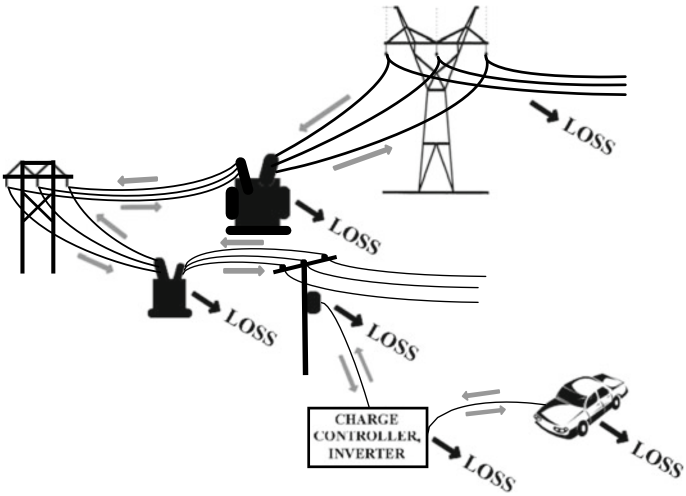


Fig. 12 Energy transmission and conversion losses

proposed V2G idea is to use the distribution grid, which has an approximate efficiency of 92% [30]. Thus, the theoretical back-of-envelope efficiency of V2G can be calculated as:

$$5_{\mathrm{V2G}} = 5_{\mathrm{E}} \times 5_{\mathrm{Charge}} \times 5_{\mathrm{Grid}} \tag{6}$$

Therefore,

$$5_{\mathrm{V2G}} = (0.39) \times (0.94) \times (0.92) \cong 0.34$$

This is relatively low. This efficiency number certainly cannot be considered appropriate to back up the power grid using EVs and PHEVs.

2.9 V2G Reliability and EV Owner Behaviour

The V2G concept assumes that the EV is a reliable and available source of energy that can be available as reserve during peak load shaving. Hence, it should be noted that mobile behavior of EV owners could seriously affect the reliability of these EV distributed generators. Assuming that the power demand is high and there exists a sufficient number of EVs connected to the grid. Also, let us assume that there is enough energy to feed back into the grid. However, depending on driving behavior, EV battery charge availability varies during distinctive times and days of the week. In fact, mobility behavior of owners is obviously different on weekdays compared to weekends. If a large number of EVs are not able to feed energy or if owners simply do not intended to feed the grid, it could cause an unexpected shortage to the grid. From a pure efficiency standpoint, not only the number of connected EVs to the grid is important, but also the location of their connection. Even though these EVs act as DGs, if a group of EVs are connected at some point in the system, and demand is high on another side of the system, energy must be transmitted to the critical demand side, and transmission losses needs to be accounted for.

It is obvious that, from an owner's perspective, driving is the primary purpose of the EV; not V2G. Furthermore, because of the aforementioned reasons, the EV cannot be treated as a reliable source to deliver the exact amount of energy demanded by the grid in real time. Thus, to begin with, using V2G seems like using an unrestricted and cheap resource to help the grid overcome high demands. However, the fact is that, by using V2G, both the grid as well as the EV requires an enormous amount of upgrades to be built into their respective systems. Even then, such a restructuring of the grid and EV/PHEV charge/discharge system would prove to be an exceptionally uneconomical task.

2.10 V2G Efficiency Solutions and Potential Research Directions

In the electricity grid, generation capacity is grouped in different categories. The four main categories are: (1) Peak power, (2) spinning reserve, (3) regulation services, and (4) renewable sources and energy storage systems. Spinning reserve and regulation services are assumed as ancillary services to support the grid. Renewable energy will have a prodigious positive impact on the electricity network. One main concern about renewable energy sources, such as photovoltaic and wind is that, there is no guarantee to acquire energy whenever required. The volatility as a result of renewable energy resources to the grid must be compensated with reinforcement of the power grid, virtual power plant structure, demand control management, energy management, and energy storage systems.

One of the main candidates to help the reliability of the power grid is a virtual power plant (VPP). VPP structure is an accumulation of DGs, energy storage systems, as well as loads that can be controlled locally. The entire system can be controlled by a central control entity; it works as a unique power plant. VPP not only deals with the supply side, but it also helps manage the demand and ensure grid reliability through demand response in real time. Figure 13 shows a virtual power plant structure.

The control aspect of VPP can be divided into three different categories: direct, hierarchical, and distributed system. Decision-making in direct control concept is centralized control, whereas distributed control concept is based completely on decentralized decision-making. The hierarchical control lies between the other two methods that have some level of distributed decision-making. Responsibility of the control center in VPP is to coordinate between available resources in an optimal

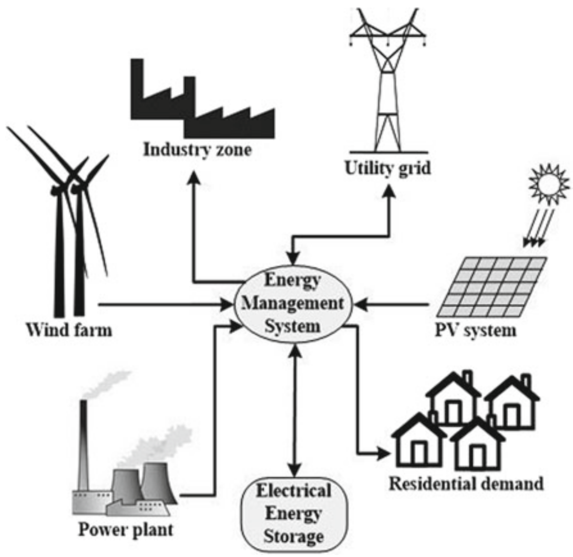


Fig. 13 Virtual power plant structure

way and present them to the market as a single entity. Information and communication technology solutions enable the control center of VPP to manage resources within the system to near real time. Operation of a group of individual resources can be managed by some entities. EV charging facilities may be represented by charge point managers (CPM), within the framework of VPPs. Number of connected EVs to the grid, their power consumption at each time, state of charge of their individual battery packs, and controlling the charging period can be done by VPP control center, based on reviewing the aggregation of all gathered information.

Furthermore, power generation and load profiling can be forecasted in VPP. Power generation and consumption can be scheduled in the VPP control center. Any error in this forecasted schedule can be corrected in real-time operation. By means of a metering system, data can be provided to VPP control center, to monitor the behavior of power generation and load consumption. It is obvious that a demand side management (DSM) system can easily shift the charging period of EVs shifted to low-demand times. In addition, if EV owners insist on charging their vehicles during high load demand period, multiple price bidding can be scheduled. In VPP, different sources of power generation are available. Renewable energy can be one of the important resources in VPP. Since the power production of renewable energy resources cannot be forecasted, it can be considered as ancillary services to the power generation market. Hence, a means of reliable storage system is required to store the energy, and inject it into the grid, whenever required. Local scale battery systems offer very high efficiency and reliable energy for short durations, and can be used as distribution generation in virtual power plants. Energy will be stored during high power production and can be used during high demand, without having complex and overwhelming control systems [31].

2.11 Summary

This chapter discussed the important issue of V2G inefficiency, from a well-to-wheels efficiency standpoint. Most critically, the energy conversion efficiency suffers, due to the multiple conversion stages, when attempting to connect an EV to the electricity grid. Efficiency of energy conversion is a major issue in reverse power flow, while discharging an EV battery to the grid (vehicle-to-grid). Hence, vehicle-to-grid (V2G) power flow requires a detailed stage-by-stage efficiency analysis, to evaluate practical feasibility. This chapter introduced the critical issues in connecting battery-powered EVs to the electricity grid. The chapter highlighted the important inefficiencies of V2G connection, especially from the point of view of power electronics converter energy conversion stages, and suggested some research directions for the near future, in order to possibly make V2G a practical reality.

More specifically, this chapter highlighted the grid control issues, battery degradation issues, and the critical problem of V2G inefficiency with regards to power electronic conversion stages. Hence, the virtual power plant (VPP) is suggested as a possible and likely solution solely for EV charging purposes. EV charging can be performed most efficiently by matching available battery energy with load demand. By shifting EV charging loads to low demand times, the load peak as a result of EV charging can be shaved. Individual regulation needs to be adapted instead of asking EV owners to feed energy back to the grid. This way the owner can charge their EVs during a suitable low demand time, in order not to put any stress on the grid. With these regulations, utilities can make sure owners' charging behavior will not add up consumption to the grid during high demand times.

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Battery Energy Storage Systems for Applications in Distribution Grids

Fabrizio Sossan and Fernando Alvarado

Abstract Battery Energy Storage Systems (BESSs) have become practical and effective ways of managing electricity needs in many situations. This chapter describes BESS applications in electricity distribution grids, whether at the user-end or at the distribution substation level. Nowadays, BESS use various lithium-based technologies. BESS systems rely on three layers of control: (1) the power converter firmware layer that manages grid synchronization and charges and discharges the battery, (2) the battery management system manages the cell stacks, to ensure that cells are evenly charged and discharged and operate within their design limits, and (3) the energy management system layer that operates at a high level to charge and discharge the battery to attain higher level objectives. These objectives can include obvious and simple uses of a BESS for time arbitrage (save energy when excess energy is available to deliver it back at a later time), and it can be also used to implement far more complex objectives, including the use of batteries to match production or consumption schedules, frequency regulation, eliminate distribution line overloads, provide voltage regulation and control and reserves for possible power outages. This chapter describes the general characteristics of all BESS systems and gives details of a mathematical model that can be used to implement the operation of a BESS. Several examples of applications unique to BESS systems in distribution network are illustrated, including actual operation of a BESS to implement a "dispatchable feeder" to a load, the use of a BESS to minimize the cost of imported electricity, and the use of a BESS system to maximize the utilization of a solar array that operates an intermittent load.

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1 Battery Energy Storage Systems

1.1 Introduction

Storage batteries are devices that convert electricity into storable chemical energy and convert it back to electricity for later use. In power system applications, battery energy storage systems (BESSs) were mostly considered so far in islanded micro-grids (e.g., [1]), where the lack of a connection to a public grid and the need to import fuel for conventional generation makes it convenient to store surplus electricity from local renewables to use during generation shortfalls. However, increased safety and reduced prices of lithium battery technologies (e.g., [2]) have made it possible for lithium-ion BESSs to be considered for applications in grid-connected contexts. BESSs are modular and appealing for both behind- the-meter applications (such as peak-shaving and PV self-consumption) and grid operators as a non-wire alternative to traditional grid reinforcement for grid congestions and voltage control. Additionally, BESSs have faster ramping rates than conventional generation, so they are better suited to provide quick regulation, for which there will be an increased need in the future. An example of BESS is shown in Fig. 1.

The objective of this chapter is to give an overview of lithium-ion BESSs and illustrate the main notions for effective energy management. The rest of this section describes the main components and characteristics of BESSs. Section 2 describes an extensible framework for energy management, with a number of applications described in detail. Finally, Sect. 3 presents the main elements for the operation of a multi-objective real-time energy management system.

(a) (b)

Fig. 1 Outdoor **a** and indoor **b** view of the 560 kWh/720 kVA lithium-titanate BESS installed at EPFL's campus, in Lausanne (Switzerland). Copyright by Alain Herzog/EPFL

1.2 Specifications of a BESS

Two main specifications of a BESSs are its energy capacity (in kWh) and its power converter rating (in kVA). The energy capacity is defined as the total energy that the system can provide, starting from a 100% state-of-charge, at a given constant discharge current. Since power losses increase with current, the available energy decreases with larger charging/discharging power. The power converter rating for a BESS defines the maximum operating power of the system.

The power converter rating of a BESS is related to the battery cells' maximum current capability. The charging/discharging current of a battery cell is expressed in terms of its C-rate, which is defined as the current in ampere (A) over the cell energy capacity in ampere-hour (Ah). Power-rating-to-energy-capacity ratios of commercially available BESS are generally between 0.75 and 2. The efficiency of a battery cell is the energy released during discharging divided by the energy stored during charging. The efficiency of lithium-ion batteries is very high, usually above 95%. High efficiency, together with high specific power, high energy density, and low self-discharging rates, have made lithium-ion the mainstream of today's battery technology.

1.3 Components and Software Layers

Components The main components of a grid-connected BESS are the battery, the AC/DC power converter (or inverter), and grid connection equipment (switchgear, and transformer if connected to an MV grid). Figure 2 provides an example.

The battery consists primarily of cells, whose number, nominal capacity and voltage determine the total energy capacity of the system. The energy capacity of a single battery cell is usually a few hundred watts at nominal voltage, depending on the specific chemistry and cell packaging. Cells are arranged in series to form a module, and modules into a string. Parallel strings form the DC bus, connected to the power converter through contactors. The modules include a thermal management system

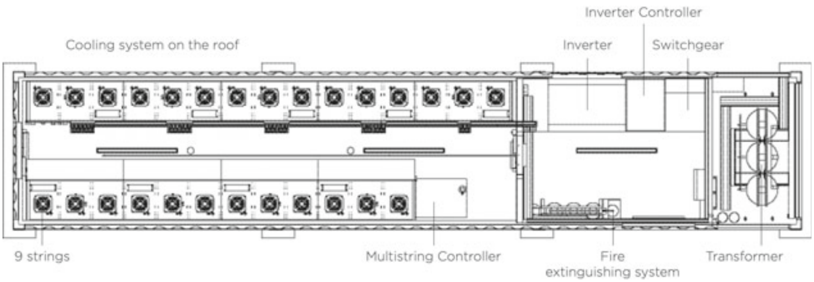

Fig. 2 The main components of a containerized BESS (courtesy of Leclanche.com)

to ensure suitable and uniform cells' temperature and prevent premature aging. All cells' current and voltage are monitored. Cells implement voltage balancing circuitry. Mainstream chemistries for lithium cells include NMC (nickel manganese cobalt oxide) and LFP (iron phosphate) for anode materials, and graphite and lithium-titanate for the cathode [3]. Lithium-titanate achieves higher cycling endurance, but it is more expensive and with lower energy density.

The power converter adapts the DC voltage of the battery to the AC voltage of the power grid. Power converters are four quadrants, meaning that they can provide both negative and positive active and reactive power within the limit imposed by their kVA rating. For large BESSs (above tens of kW), the converter is 3-phase, whereas, for small systems (up to few tens of kW), it is typically single-phase, as for residential solutions, where only 1 phase or 2 phases are normally available. MW-class BESSs may have multiple power converters in parallel. In case of connection to low-voltage grids, the power converter is typically directly connected to the grid; in medium-voltage grids, a step-up transformer is generally used. A breaker with under- and over-voltage protections enables to disconnect from the grid. The power converter typically implements active over-current protections. Fuses on the DC bus and modules act as additional protection in case of faults. The power converter also includes current and voltage meters on both the AC and DC side.

Large BESSs are usually installed in ad-hoc containerized solutions. Figures 1 and 2 illustrate typical BESS containers. These containers include a fire-extinguishing and HVAC (heating, ventilation, and air conditioning) systems. HVAC ensures suitable air temperature in the container and correct operations of the cells' primal thermal management system. Indoor temperature is kept in a prescribed range (e.g., 10–30 °C) by activating the heating and air conditioning system as needed. The ventilation is generally kept active at all times. For example, the rating of the air conditioning and heating unit of the system in Fig. 1 represents a 5 kW load when in operation. Additional auxiliary components of containerized BESSs are lighting and sensors on electrical cabinet doors. A dedicated transformer supplies power the auxiliary services.

Software layers There are three main software layers in a BESS (Fig. 3): the firmware of the power converter, the battery management system (BMS), and the energy management system (EMS). The first two layers handle the low-level communication with all BESS's components and ensure their correct operation. These two layers, briefly described in the rest of this subsection, are generally implemented by the manufacturers of all commercially available systems. The third layer is the *application* layer that determines when and how the BESS should charge (or discharge) according to the operator and application requirements.

Many BESSs (especially small-size residential systems) usually come already with pre-built EMS for specific applications (e.g., PV self-consumption). However, even in these cases, some level of customization is often desirable. In many other other (usually larger) applications, it is necessary to design an entire EMS layer in order to meet the requirements for the application in questions. The EMS layer can be

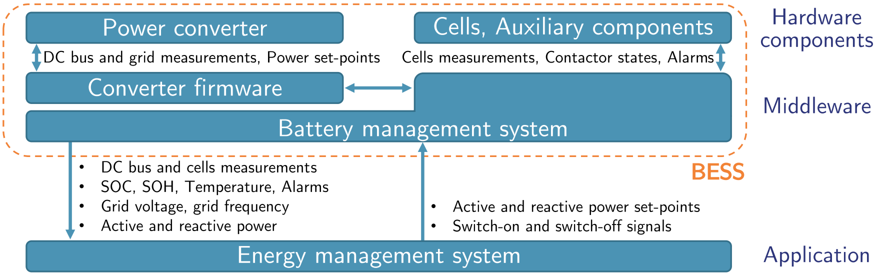

Fig. 3 Software layers of a BESS, and information exchange between the BMS and the EMS layers. Real-time applications requiring fast response (e.g., tens of milliseconds) may need dedicated deterministic communication with the power converter

used to optimize operations and to increase performance. EMSs layers are covered in detail in the next section.

The power converter firmware controls the activation of the switching devices (e.g., IGBTs) to keep them synchronized with the grid and supply the active and reactive power set-points requested by the operator. The firmware is implemented in specialized hardware capable of real-time computation and with digital and analog input/output, such as digital signal processors (DSPs).

The BMS ensures correct and safe operations of the cell stack, including thermal management, voltage balance across the cells, monitoring of cells' current and voltage levels, prevention of overloading, avoiding completely draining a battery, and monitoring all auxiliary systems. It estimates the state-of-charge (SOC) and state-of-health (SOH) of the battery. Based on the voltage levels of the battery cells, the BMS also determines the maximum charging and discharging power that the BESS can provide. In turn-key BESSs, the BMS offers an abstraction layer of the underlying hardware resources so that the operator does not have to, for example, directly communicate with the power converter to implement power set-points or query each single battery module to retrieve their state or read alarms.

All BESS's functionality is made available by the BMS through a communication interface. Examples of key available functions include switching the system on and off, verifying the status of the BESS and auxiliaries, querying real-time measurements, and sending requests of active and reactive power set-points to be implemented. The feasibility of the requested active power set-points (that depends on the BESS status) is typically ensured by the BMS before being implemented. BMS implementations need to interface with both hardware (at module and cell levels) and upper-level software; they are typically implemented on multiple platforms, such as DSPs and industrial computers.

An important aspect related to communication and control is the refresh interval at which the BESS implements new power set-points. The refresh interval depends on the communication latency and the processing time. A communication interface commonly available in commercial BESS is Modbus over TCP-IP. In this case, refresh intervals are in the order of magnitude of hundreds of milliseconds. This refresh interval is generally sufficient for primary frequency regulation, demand peak-shaving, and all energy-oriented applications such as energy arbitrage and PV self-consumption. Applications that require tens-of-milliseconds refresh intervals (e.g., inertia support and grid forming algorithms for power converter) should be implemented with deterministic communication protocols, or in the converter firmware to achieve minimum latency.

1.4 Designing BESS Applications: Planning, Scheduling, and Real-Time Operations

There are three distinct phases associated with designing BESS applications: planning, scheduling, and real-time control.

Planning aims at determining the energy capacity and power rating of the system. The energy capacity and the power rating of a BESS are selected according to the services it is intended to provide, considering realistic operative scenarios and time correlation of the control actions. Modeling time correlation is critical because the state-of-energy of a BESS depends on the charging/discharging history, and time coupling among control set-points affects the total energy need. Time correlation can be captured with time series scenarios. For certain applications, such as grid congestion management and voltage control, the location of the BESS is also a variable of the problem. Locations can be predetermined or it can be limited to a restricted set of options based on their suitability to host a BESS (space requirements, safety, access to a grid connection point). The location decision can also determine whether the BESS is located in front of or behind a meter, of whether the BESS is to be located at a substation or along a feeder.

The scheduling phase determines a charging/discharging schedule for the next operation time frame (e.g., next day). The objective is ensuring that the BESS has enough energy to provide the subscribed services. The scheduling problem is covered in Sect. 2.

Finally, the real-time phase refers to computing the BESS's real and reactive power set-points so that the prescribed services are delivered as desired. Pre-computed schedule rely on forecasts and are subject to forecast errors. To adjust to changing conditions, the real-time phase can also include a rescheduling stage that refines the schedule based on real-time measurements and resolved uncertainties. The real-time phase is discussed in Sect. 3.

1.5 Mathematical Models to Support Decision-Making

The appropriate BESS model for a specific application depends on the underlying time constants. This subsection describes the typical modeling requirements for

BESSs for scheduling and near real-time decision-making. Power converters' simulation models for shorter (electromechanical and electromagnetic) transients is beyond this chapter's scope and not covered.

Models for scheduling applications Scheduling applications typically target hours- and day-ahead horizons. It is of interest to capture the state-of-energy dynamics and converter's power limitations because they determine the capability of BESSs to provide the desired services to the grid in an efficient and effective manner. The state-of-energy of a BESS, SOE, is the amount of its stored energy. In general, the available energy that one can extract from (or stored into) a BESS depends on the C-rate and cell temperature. However, for C-rates and temperatures encountered in typical BESS operations, these dependencies can be neglected, and the state-of-energy can be approximated as:

$$\mathrm{SOE}_{t+1} = \mathrm{SOE}_t + T_s \cdot \left(\eta [B_t]^+ - \frac{1}{\eta}[B_t]^-\right), \tag{1}$$

where SOE_t and SOE_{t+1} are the state-of-energy at the next and current time interval (in kWh), η is the charging/discharging efficiency, T_s is the sampling interval (in hours), B_t is the piecewise constant positive (negative) BESS charging (discharging, respectively) power (in kW), and $[\cdot]^+$, $[\cdot]^-$ denote the positive and negative part of the argument.

The approximated efficiency η can be estimated from measurements. For lithium-ion BESS, η is typically high, often larger than 90% depending on the operating power levels. Self-discharge is typically small for lithium-ion BESS and not included in (1). The state-of-energy divided by the BESS nominal capacity defines the state-of-charge (SOC).

The notion of efficiency in (1) does not account for the BESS auxiliaries' power demand. This additional demand includes the one of auxiliary systems always active (ventilation and IT equipment), and air conditioning and heating. Air conditioning and heating units are activated only when the temperature in the container is outside a prescribed range. Depending on the climate, this power demand can be relevant. A detailed analysis of the consumption of auxiliaries and its impact of the round-trip efficiency is provided in [4]. The no-load losses of the power transformer can be aggregated in the efficiency-based model (1).

When the BESS scheduling problem is associated with an optimal power flow, an alternative to the efficiency-based model in (1) is augmenting the grid topology with a resistive transmission line between the BESS and the grid connection point, as proposed in [5], allowing one to remove from (1) the (non-linear) sign operators for a more tractable formulation.

The BESS active power, B_t, is generally supplied by a four-quadrant power converter. Under nominal voltage conditions at the DC bus and at the grid connection point, the power's converter limitation can be modeled as:

$$B_t^2 + Q_t^2 \leq S^2 \tag{2}$$

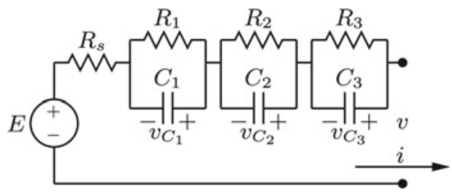

Fig. 4 A third-order equivalent circuit model for the battery DC voltage as a function of the charging/discharging current

where Q_t (in kVAr) is the supplied reactive power and S is the apparent power rating (in kVA) of the power converter. Equation (2), a circle with radius S in the real/reactive power plane, is called the "capability curve" of the power converter. As long as the power converter's DC bus is supplied, the converter can provide reactive power to the grid with negligible internal losses thanks to its high efficiency. As long as enough energy is available in the battery, the converter's capability curve determines the charging/discharging power limit of the BESS. When the BESS is near a fully charged or a completely discharged state, the BMS applies stricter power constraints than (2) to avoid violations of DC current and DC voltage limits. These limits are normally communicated by the BMS.

The model in (2) is valid under nominal voltage conditions of the DC bus and grid connection point. In real-life, both these voltages vary as a function of operating conditions and impact on the power converter's capability curve. The work in [6] tackles this aspect and models the dynamic capability curves of BESS converters.

Models for near real-time simulation and control A battery is not an ideal voltage source, and its terminal voltage varies as a function of the current it delivers. Voltage dynamics can be represented with an equivalent circuit model, which trades detailed modeling of the electrochemical reactions for increased tractability. Single battery cell equivalent circuit models can then be extended to represent the behavior of a multi-cell battery. Figure 4 shows a three-timeconstant (third order) equivalent circuit model that can be used to represent the behavior of a multi-cell battery array. Its parameters depend on the battery SOC, temperature and C-rate. They can be estimated from BESS's DC voltage and current measurements for given operating conditions [7, 8].

The three time-constant model captures voltage dynamics in the order of hundreds of milliseconds to tens of minutes. If sub-second dynamics of the The third RC branch of the circuit used to capture transients of few seconds or more can be omitted when sampling measurements at slower intervals.

The third RC branch of the circuit is useful to capture transients of few seconds and can be omitted when sampling measurements at higher intervals. Voltage dynamic models are useful to compute voltage and current constraints on the DC bus, and in dynamic simulations to model the interactions with power converters.

1.6 Service Life and Degradation

Degradation of the cell electrochemistry is a complex non-linear phenomenon that determines energy capacity fading and increased internal cell resistance, limiting the cell power. Aging processes are classified into calendar aging, which depends on time, and cycle aging, which depends on use. Both accelerate at higher cell temperatures. Commercial BESSs are typically guaranteed for a calendar service life of 15–20 years. The number of cycles that a cell can perform is larger for lower depth-of-discharge (DOD) and C-rates. Cycle aging can be determined empirically by cycling a cell or in combination with models, see, e.g., [9]. Cycle aging depends on many variables, including use history and C-rate, stateof-health, state-of-charge, cell temperature, and battery chemistry. NMC cells can typically perform 4000–5000 cycles at 90% DOD at 1 C, whereas lithium-titanate cells can perform more than 15,000 cycles.

When addressing degradation in BESS application designs, one should consider the battery technology in use and the number of cycles it is capable of. For example, with long-endurance lithium-titanate cells, calendar aging may be the dominating aging factor depending on the number of cycles per day. As cycling degradation in batteries is partially explained by mechanical loading due to lithium intercalation, rain flow counting algorithms, typically used to model fatigue of mechanical components, have been proposed to model it (although no experimental proof that this is justified has been provided so far [9]) and included in aging aware decision-making, as in [10]. Constraints to reduce cycle aging that require fewer modeling assumptions are implementing conservative state-of-energy limits to reduce the DOD or limiting the energy throughput to a maximum value per day, see, e.g., [11].

2 Scheduling the Operations of a BESS

2.1 The Role of Scheduling

Unlike conventional power plants that may have large stocks of fuels and can potentially produce electricity for a long time, the BESS's capability of supplying a load depends on its stored energy and is generally small. Proper energy management is critical to ensure that the BESS has a correct state of energy to provide the subscribed services reliably.

The design of suitable energy management starts from defining the services that the BESS operator wishes to provide. Examples are demand peak-shaving, PV self-consumption, and grid control. A number of these services will be presented and discussed throughout this chapter. Once the application requirements are identified, they are embedded in a suitable operation timeline, called the dispatch plan. As we will see, the dispatch plan also accounts for the need to recharge or discharge the BESS. For example, a nearly empty battery should be recharged if it will have to

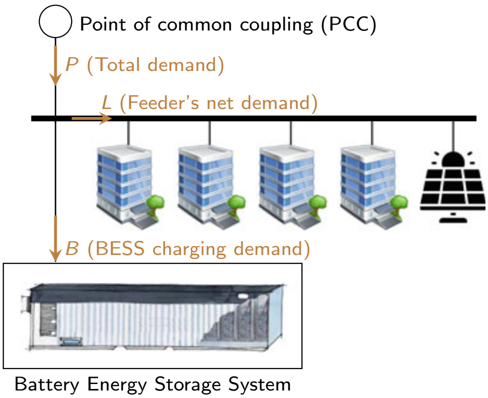

Fig. 5 A point of common coupling with a BESS and prosumers

inject power, and this need can be incorporated into the dispatch plan. As it will be discussed later, computing the dispatch plan requires taking into account suitable forecasts of the services to provide in order to ensure proper energy management and provide a hedge against uncertainty.

To compute a dispatch plan, we will resort to a suitably defined optimization model. Optimization problems are a handy framework to accommodate this need because their formulation follows from intuitive notions (such as "minimize the total cost of operations") and is generally interpretable. The resulting optimization problem can be solved, if properly formulated, with off-the-shelf software libraries in standard computers.

2.2 Dispatching Heterogeneous Resources

Dispatch plan Consider the example in Fig. 5, showing a point of common coupling (PCC) interfacing heterogeneous resources. The heterogeneous resources are a BESS and stiff (non-controllable) conventional demand from commercial buildings with rooftop PV installations. The total real (active) power demand at the PCC is denoted by P, the net demand from the feeder by L, and the BESS's charging power by B. The power flow at the PCC is subject to a maximum value representing the level of maximum power contracted with the electric utility (peak-shaving).[1] Power losses are here assumed negligible, and grid constraints are not considered.

The objective is to determine a dispatch plan at the PCC that the operator can track in real-time by adjusting the BESS's power injections. For this application, the only design property of the dispatch plan is to implement a schedule for peak-shaving. Later in this chapter, we will illustrate other possible dispatch plan objectives.

[1] In combination with the total reactive power at the PCC, this constraint can be used to model the apparent power rating of the substation transformer.

A dispatch plan is denoted by the sequence $\widehat{P}_t$, where $t = 0, 1, \ldots, T-1$ refers the time interval. For this application example, a time resolution of 5 min is considered.The dispatch plan assumes a 24 h interval, thus $T = 288$. The dispatch plan for the setup in Fig. 5 is formally given by

$$\hat{P}_t = \hat{L}_t + F_t^o, \quad t = 0, \ldots, T-1 \tag{3}$$

where $\widehat{L}_t$ denotes point predictions (i.e., forecasts) of the feeder net demand and F_t^o is the so-called offset profile. The offset profile, whose computation is described next, accounts for the amount of BESS energy necessary to restore an adequate level of flexibility in the battery during operations. If for example, at the end of a dispatching interval, the BESS residual charge is close to the upper (or lower) bound, the offset plan biases the dispatch plan positively (or negatively), so causing the BESS to discharge (or charge) and bringing the state-of-energy to a suitable level of flexibility. Embedding the charging/discharging demand into the dispatch plain in this way avoids the need to implement a separate charging/discharging process process for longer-term operation of a BESS.

The offset profile is determined by an optimization problem, as discussed next. The first proposed formulated follows directly from the state-of-energy model of the BESS discussed in the former section. As this formulation results in a nonconvex optimization problem, a convex re-formulation will also be discussed.

Determining the offset profile The BESS is controlled to ensure that the real power flow at the PCC tracks the dispatch plan. Its real power injections at a given time interval can be written as the difference between the dispatch plan and the net demand realization, l_t, which is unknown at this stage. This reads as

$$B_t = \hat{P}_t - L_t = F_t + \hat{L}_t - l_t \tag{4}$$

where (3) has been used to rewrite the dispatch plan. Assuming that predictions of the upper and lower bounds of the net demand realization, denoted by $l_t^{\uparrow}$ and $l_t^{\downarrow}$, are available from prediction intervals, the worst-case imbalances that the BESS needs to compensate are:

$$\hat{B}_t^{\uparrow} = F_t + \hat{L}_t - l_t^{\uparrow} = F_t - \epsilon_t^{\uparrow} \tag{5}$$

$$\hat{B}_t^{\downarrow} = F_t + \hat{L}_t - l_t^{\downarrow} = F_t + \epsilon_t^{\downarrow} \tag{6}$$

where quantities $\epsilon_t^{\uparrow} = l_t^{\uparrow} - \widehat{L}_t$ and $\epsilon_t^{\downarrow} = \widehat{L}_t - l_t^{\downarrow}$ were defined.

The state-of-energy (SOE) of the BESS is modelled as described in the former section, that is:

$$\text{SOE}_{t+1} = \text{SOE}_t + T_s\left(\eta[B_t]^+ - \frac{1}{\eta}[B_t]^-\right) \tag{7}$$

where T_s is the duration of the sampling interval in hours, and $[\cdot]^+$, $[\cdot]^-$ denote the positive and negative part of the argument, respectively. The boundaries of the state-of-energy evolution over time can be derived by applying (5) and (6) to (7), giving:

$$\text{SOE}^{\uparrow}_{t+1} = \text{SOE}^{\uparrow}_t + T_s\left(\eta\left[F_t - \epsilon^{\uparrow}_t\right]^+ - \frac{1}{\eta}\left[F_t - \epsilon^{\uparrow}_t\right]^-\right) \tag{8}$$

$$\text{SOE}^{\downarrow}_{t+1} = \text{SOE}^{\downarrow}_t + T_s\left(\eta\left[F_t + \epsilon^{\downarrow}_t\right]^+ - \frac{1}{\eta}\left[F_t + \epsilon^{\downarrow}_t\right]^-\right) \tag{9}$$

for all time intervals.

Integrating over time the worst-case battery injections (5)–(6) as in done in (8) and (9) results in a conservative estimate of the energy needs. Rather than using worst-case conditions, time-series scenarios of the forecast uncertainty (which embed time correlations among control actions) result in less conservative scheduling policies for energy storage. The use of scenarios will be illustrated later.

The BESS can provide the subscribed regulation service if its state-of-energy and real power injections are within the allowed energy capacity and converter power rating limits. Based on these operational considerations, one can formulate a constrained optimization problem to determine the (unknown) offset profile subject to these requirements. The optimization problem's cost function can either be a constant value (i.e., feasibility problem) or reflect an operational condition. In this case, since from (4) it follows that the BESS injections correspond to the offset profile if forecasts are correct, we minimize the norm-2 of the offset profile as a best-effort attempt to reduce the charging/discharging duties of the BESS. In addition to the BESS's constraints, we require a dispatch plan lower than a contracted power at the PCC, denoted by $\overline{P}$. This optimization problem reads as:

$$F^o_1, \ldots, F^o_T = \arg \min_{F_1,\ldots,F_T \in \mathbb{R}} \left\{\sum_{t=0}^{T-1} F_t^2\right\} \tag{10a}$$

subject to (for all t)

$$\text{SOE}^{\uparrow}_t + T_s\left(\eta\left[F_t - \epsilon^{\uparrow}_t\right]^+ - \frac{1}{\eta}\left[F_t - \epsilon^{\uparrow}_t\right]^-\right) \leq \overline{\text{SOE}} \tag{10b}$$

$$\text{SOE}^{\downarrow}_t + T_s\left(\eta\left[F_t + \epsilon^{\downarrow}_t\right]^+ - \frac{1}{\eta}\left[F_t + \epsilon^{\downarrow}_t\right]^-\right) \geq \underline{\text{SOE}} \tag{10c}$$

$$\left|F_t - \epsilon_t^{\uparrow}\right| \leq \overline{B} \tag{10d}$$

$$\left|F_t + \epsilon_t^{\uparrow}\right| \leq \overline{B} \tag{10e}$$

$$\hat{L}_t + F_t \leq \overline{P} \tag{10f}$$

where $\overline{\text{SOE}}$ and $\underline{\text{SOE}}$ specify the allowed energy range of the BESS (e.g., 10–90% of the total energy capacity to prevent extreme conditions, and decrease DOD), and $\overline{B}$ is the rating of the power converter.

In this application, the potential of the BESS to provide reactive power is not tapped; if the BESS is used to provide reactive power too, then (10d) and (10e) should be augmented considering the 4-quadrant capability curve of the power converter, as discussed in the former section.

Solving problem (10) requires $\epsilon_t^{\uparrow}$, $\epsilon_t^{\downarrow}$ for all time intervals, which can be computed from a suitable forecasting model of the power demand. A practical example will be given later.

The drawback of the formulation in (10) is its non-convexity due to the positiveand negative-part operators in the state-of-energy constraints. For increased tractability, it can be reformulated as a linear (and convex) optimization problem as discussed in the next section.

Linear convex reformulation Recalling from the former subsection, the battery injections are:

$$B_t^{\uparrow} = F_t - \epsilon_t^{\uparrow} \tag{11}$$

$$B_t^{\downarrow} = F_t + \epsilon_t^{\downarrow} \tag{12}$$

Each battery injection can be split into the difference between its positive and negative part:

$$B_t^{\uparrow} = B_t^{\uparrow +} - B_t^{\uparrow -} \tag{13}$$

$$B_t^{\downarrow} = B_t^{\downarrow t+} - B_t^{\downarrow t-} \tag{14}$$

Solving Eqs. (11) and (12) for the offset profile, equating their terms, and using (13) and (14) yields:

$$B_t^{\uparrow +} - B_t^{\uparrow -} + \epsilon_t^{\uparrow} = B_t^{\downarrow_t +} - B_t^{\downarrow t-} - \epsilon_t^{\downarrow} \tag{15}$$

With these definitions in place, the optimization problem in (10) can be reformulated in terms of the non-negative decision variables $x_t = \left[B_t^{\uparrow +}, B_t^{\uparrow -}, B_t^{\downarrow +}, B_t^{\downarrow +}\right]$.

This reformulation avoids the use of positive- and negative-part operators. Since the battery cannot physically charge and discharge simultaneously, the cost function penalizes positive values of the decision variables to promote mutually exclusive terms in (13) and (14). The constrained linear optimization problem reads as:

$$x_1^o, \dots, x_T^o = \underset{x_1,\dots,x_T \in \mathbb{R}_+^4}{\arg\min} \left\{ \sum_{t=0}^{T-1} \left(B_t^{\uparrow+} + B_t^{\uparrow-} + B_t^{\downarrow+} + B_t^{\downarrow-} \right) \right\} \tag{16a}$$

subject to

$$\text{SOE}_t^{\uparrow} + T_s \left(\eta B_t^{\uparrow+} - \frac{1}{\eta} B_t^{\uparrow-} \right) \leq \overline{\text{SOE}} \tag{16b}$$

$$\text{SOE}_t^{\downarrow} + T_s \left(\eta B_t^{\downarrow+} - \frac{1}{\eta} B_t^{\downarrow-} \right) \geq \underline{\text{SOE}} \tag{16c}$$

$$-\overline{B} \leq B_t^{\uparrow+} - B_t^{\uparrow-} \leq \overline{B} \tag{16d}$$

$$-\overline{B} \leq B_t^{\downarrow t} + -B_t^{\downarrow_t -} \leq \overline{B} \tag{16e}$$

$$B_t^{\uparrow+} - B_t^{\uparrow-} + \epsilon_t^{\uparrow} = B_t^{\downarrow_t +} - B_t^{\downarrow t^-} - \epsilon_t^{\downarrow} \tag{16f}$$

for all t. Once the problem is solved, the dispatch plan can be retrieved from the solution of the problem as (it follows from (11)):

$$F_t^o = K_t^{+o} - K_t^{-o} - \epsilon_t^{\downarrow} \tag{17}$$

for all t.

Linear reformulation with binary variables Instead of penalizing the activation pof the positive and negative parts in the cost function as done in (16), mutually exclusive charge and discharge of the BESS can be achieved explicitly by introducing binary variables. For example, for $B_t^{\uparrow}$, this new set of constraints is introduced:

$$B_t^{\uparrow+} \leq c_t^{\uparrow} \cdot \overline{B} \tag{18}$$

$$B_t^{\uparrow-} \leq \left(1 - c_t^{\uparrow} \right) \cdot \overline{B} \tag{19}$$

$$0 \leq c_t^{\uparrow} \leq 1, \quad c_t^{\uparrow} \in \mathbb{Z} \tag{20}$$

where $c_t^{\uparrow}$ a new integer variable of the problem that determines if the battery charges or discharges at time interval t. These constraints are linear and can be formulated in a mixed-integer linear program (MILP) to determine the offset profile.

The "dispatchable feeder" The dispatchable feeder is a real medium-voltage feeder of the EPFL campus, in Lausanne (Switzerland), with topology as in Fig. 5. It is equipped with a 560 kWh/720 kVA lithium-titanate BESS [7]. The demand in the system is from office buildings and laboratories, with a total peak value of 350 kW. Buildings include 95 kWp rooftop PV generation. The feeder is dispatched according to a 24-hour-long, midnight-to-midnight dispatch plan at a 5 min resolution. The dispatch plan is computed 1 h before the beginning of the operations, at 23:00, with the convex optimization problem discussed above. Figure 6 shows the point predictions of the net demand (dashed line) and its estimated upper and lower bounds (shaded area) for a weekday and weekend day. Here, forecasts are computed by analogy with historical measurements using a k-nearest-neighbor principle: a mix of categorical (weekend, weekday, holiday, working day) and quantitative criteria (temperature and irradiance) are used to select a given number of 1-day-long time series from a historical dataset. Then, the point predictions, $\widehat{L}_t$ for all t, are computed as the element-wise average of the selected time series, and the worst-case realizations $\left(l_t^{\uparrow}, l_t^{\downarrow}\right.$, for all t) as the element-wise maximum and minimum values.

As visible from Fig. 6, the net demand features a peak in the central part of the weekday (nearly 300 kW) and lower values in the weekend day (below 200 kW).

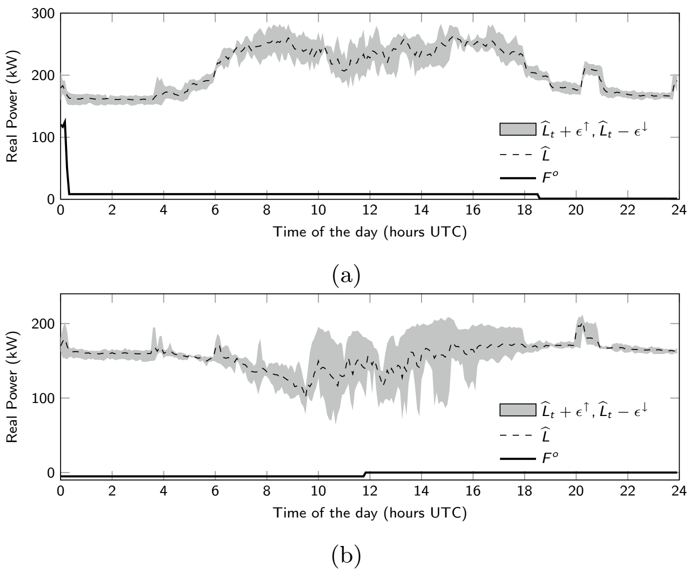

Fig. 6 Point predictions of the net demand, predicted worst-case realizations, and computed offset profiles on a weekday **a** and weekend day **b**

During the weekend day, effects of PV generation are visible during the central hours of the day, which have lower net demand. Prediction intervals are relatively symmetric around point predictions, denoting that the BESS may charge or discharge in equal quantities to compensate for the net demand realization. As discussed earlier, prediction intervals are used in the optimization problem to ensure that the accumulated control action in these worst-case scenarios does not exceed the prescribed state-of-energy and power rating limits.

In Fig. 6a, the computed offset profile is positive for nearly all day and has an initial large value. This is because the BESS starts the day with a low state-ofenergy, which limits the ability to provide up-regulation over time. A positive offset profile determines a dispatch plan with overestimated power demand, inducing the battery to recharge (assuming energy-unbiased forecasts) and recover from a low initial state-of-charge. Conversely in Fig. 6b, the offset profile features a small negative value for the first half of the day. In this case, the demand is underestimated, and the BESS will discharge.

Real-time control aspects related to controlling the BESS to track the dispatch plan effectively are discussed in Sect. 3.

2.3 Load Levelling

Previously, it was shown how to determine a dispatch plan for a set of heterogeneous resources so that deviations from point predictions of the net demand can be compensated using a BESS. The dispatch plan included the charging/discharging needs of the BESS (through the offset profile) and implemented a maximum value of the peak demand to account for a maximum level of contracted power with the utility. In this subsection, that framework is modified to implement load levelling. Load levelling refers to a dispatch plan that is as flat as possible, namely with values near the average value of the predicted net demand at all times. The distance at time t between the dispatch plan and the average predicted net demand $\overline{L}$ is:

$$\left(\hat{P}_t - \overline{L}\right)^2 = \left(\hat{L}_t + F_t - \overline{L}\right)^2 = (\Delta_t + F_t)^2 \tag{21}$$

where (3) has been used, and definition $\Delta_t = \widehat{L}_t - \overline{L}$ is introduced. This expression will be minimized over time in the optimization problem discussed next.

The average value of the predicted net demand is:

$$\overline{L} = \frac{1}{T}\sum_{t=1}^{T} \hat{L}_t \tag{22}$$

Recalling from (4), the battery injection is:

$$B_t = \hat{P}_t - L_t = F_t + \hat{L}_t - l_t \tag{23}$$

As opposed to using worst-case scenarios to characterize BESS's injections as done earlier, we now illustrate the use of scenarios. For simplicity we also assume unitary charging and discharging efficiency of the BESS.[2] Let l_t^d be the realization of the net demand at time t in scenarios d. The BESS's real power injection in scenario d is:

$$B_t^d = F_t + \hat{L}_t - l_t^d = F_t + \epsilon_t^d \tag{24}$$

where $\epsilon_t^d = \widehat{L}_t - l_t^d$ was introduced. Equation (24) can be used to compute the evolution of the BESS's state-of-energy in scenario d.

The problem of finding an offset profile implementing load levelling is:

$$F_1^o, \ldots, F_T^o = \underset{F_1,\ldots,F_T \in \mathbb{R}}{\arg\min} \left\{ \sum_{t=1}^{N} (\Delta_t + F_t)^2 \right\} \tag{25a}$$

subject to (for all t)

$$\left| \hat{B}_t^d \right| \le \overline{B}, \quad d = 1, \ldots, D \tag{25b}$$

$$\underline{\mathrm{SOE}} \le \mathrm{SOE}_t^d + T_s\left(F_t + \epsilon_t^d\right) \le \overline{\mathrm{SOE}}, \quad d = 1, \ldots, D \tag{25c}$$

where D is the number of scenarios.

The load-levelling effect is demonstrated in the following. Assuming that the constraints of problem (25) are not binding, the variables that minimize (25) are:

$$F_t^o = -\Delta_t = \overline{L} - \hat{L}_t, \quad \text{for all } t \tag{26}$$

Replacing (26) in the BESS injections (23) yields:

$$B_t = \overline{L} - \hat{L}_t + \hat{L}_t - l_t = \overline{L} - l_t \tag{27}$$

where l_t is the realization of the stochastic net demand. The realization of the total power demand at the PCC is:

$$P_t = l_t + B_t \tag{28}$$

[2] For lithium-ion BESSs with large charge/discharge efficiency, this approximation may be deemed acceptable depending on the scheduling horizon, or reworked by implementing back-off terms in the state-of-energy constraints.

Replacing the BESS injection in (27) yields to:

$$P_t = l_t + \overline{L} - l_t = \overline{L} \tag{29}$$

which proves that the total power at the PCC matches the average net demand value, achieving ideal load levelling. This is valid under the assumption that constraints of problem (25) are not binding, assuming, for example, very large BESS's power rating and energy capacity values. When constraints become active, load levelling is achieved on a best-effort basis according to the available regulation capacity of the BESS.

Figure 7 refers to the dispatchable feeder setup discussed earlier, now implementing load levelling. Figure 7a shows the point predictions of the net demand and the dispatch plan. The load-levelling action is evident. The dispatch plan, composed of 3 steps with very similar amplitude, is not totally flat because the BESS's energy capacity is not large enough to accomplish an ideal levelling of the highly variable net demand. Figure 7b shows the offset profile. It is given by the difference between the dispatch plan and the net demand point predictions and corresponds to the injection of the BESS if point predictions are exact.

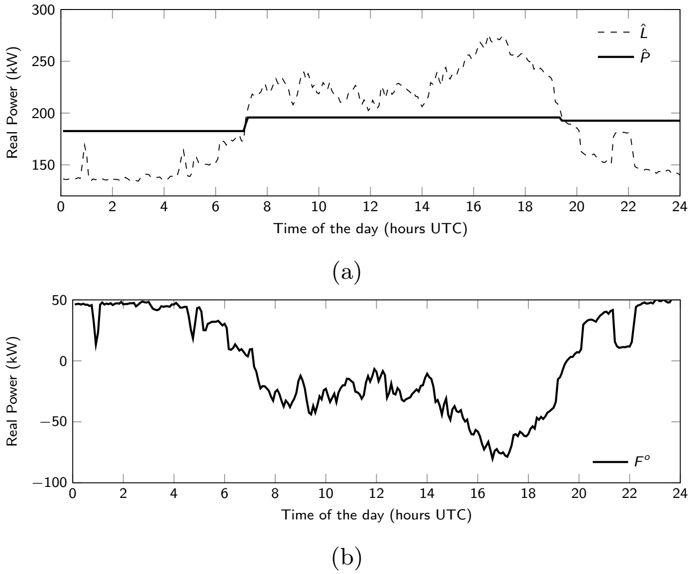

Fig. 7 Load levelling: point predictions of the net demand and dispatch plan **a**, offset profile **b**

2.4 Minimizing the Cost of the Imported Electricity

The total cost of electricity for the case study in Fig. 5 can be expressed as

$$\text{Total electricity cost } = T_s \sum_{t=1}^{T} \hat{P}_t \cdot c_t = T_s \sum_{t=1}^{T} \left(F_t + \hat{L}_t \right) \cdot c_t \tag{30}$$

where T_s is the sampling time (in hours), and c_t is the retail electricity price (in currency/kWh). If the electricity price varies along the day, one can optimize the PCC's power flow to minimize the total cost of operations, possibly storing cheap electricity to re-sell it at a higher price (energy arbitrage).[3]

Equation (30) can be used as a cost function in the same framework discussed earlier to minimize the total electricity cost. Using the scenario approach developed in the former paragraph, this reads as the following linear optimization program:

$$F_1^o, \ldots, F_T^o = \underset{F_1,\ldots,F_T \in \mathbb{R}}{\arg\min} \left\{ \sum_{t=1}^{N} c_t \cdot F_t \right\} \tag{31a}$$

subject to (for all t)

$$\left| \hat{B}_t^d \right| \leq \overline{B}, \quad d = 1, \ldots, D \tag{31b}$$

$$\underline{\text{SOE}} \leq \text{SOE}_t^d + T_s \left(F_t + \epsilon_t^d \right) \leq \overline{\text{SOE}} \quad d = 1, \ldots, D \tag{31c}$$

In (31a), the term $c_t \cdot \widehat{L}_t$ is omitted because it does not depend on the decision variable and does not impact on the location of the minimum.

It is worth highlighting that distribution grid operators are not allowed to perform energy arbitrage. This application is interesting for behind-the-meter applications.

2.5 Maximizing PV Self-Consumption

In the past, several countries have adopted feed-in tariffs for PV generation to incentivize the adoption of such a technology. Feed-in tariffs, which consisted in remunerating PV electricity with a tariff larger than the electricity market price, are now being abandoned since the cost of PV systems is competitive with other forms of

[3] This exercise is usually done under the assumption that the BESS's operator's decisions do not influence the electricity price. This is valid when the amount of power exchanged by the "price-taker" market player (combined with others' correlated action) is negligible compared to the total system demand.

generation. Feed-in tariffs have been replaced with other policies that promote self-consumption of local PV generation. Depending on the country and nature of the PV plant (residential or commercial), these policies range from awarding a premium for self-consumed electricity, net-metering and netbilling to not providing any revenue for the exported PV electricity (see [12] for a review).

To illustrate how to implement a scheduling problem for PV self-consumption with a BESS, we consider a setup as in Fig. 5 where the imported electricity is bought at a retail price c_t and there is no revenue for the exported electricity (excess PV generation). The imported electricity is the positive part of the dispatch plan and can be written as:

$$\text{Imported power}|_t = \left[\hat{P}_t\right]^+ = \max\left(\hat{P}_t, 0\right) = \max\left(\hat{L}_t + F_t^o\right) \tag{32}$$

The cost of importing electricity is:

$$\text{Total imported electricity cost} = T_s \sum_{t=1}^{T} \max\left(F_t + \hat{L}_t\right) \cdot c_t. \tag{33}$$

As oppposed to (30), here there is no revenue coming from exporting electricity to the grid. In order to implement PV self-consumption, the economic cost function (33) replaces Eq. (31). In this setting, the optimization problem avoids exporting electricity to the grid (since this is not conducive to decreasing the cost) and determine an offset profile F_t such that the excess generation is stored in the BESS and used to decrease electricity imports.

The cost function (33) is a convex function, so including it in problem (31) results in a tractable formulation. Combining (31) and (33) results in a minimax problem. It can be reformulated as a linear optimization program by introducing a new slack variable s_t such that

$$s_t \geq 0 \tag{34}$$

$$s_t \geq F_t + \hat{L}_t \tag{35}$$

and rewriting the cost function to minimize as

$$\text{Total imported electricity cost} = T_s \sum_{t=1}^{T} s_t \cdot c_t. \tag{36}$$

2.6 Providing Multiple Services with a Single BESS

A single BESS can be used to provide multiple services to the power grid, contributing to increase the utilization factor of the unit and shorten payback times. In order to effectively provide multiple services simultaneously, the services should not conflict with each other. Examples are the provision of services at different time scales (like primary frequency control and energy dispatch) and provision of real power for grid balancing and reactive power for voltage control in medium- and high-voltage grids. The main challenge when providing multiple services is identifying their real and reactive power needs over time and ensure that the BESS has enough capacity to provide them. The work in [13] proposed to identify, for each service, an energy and power budget. The power and energy budgets for multiple services can then be coordinated so that they respect all BESS' operational constraints. In order to define the proportion to allocate for the various services, budgets can be parameterized according to a priority queue. As an alternative, revenue from electricity and ancillary services markets can be found by solving a constrained optimization problem subject to BESS's constraints.

2.7 Extension to Multiple Controllable Elements

Distribution grids may include multiple controllable resources and units capable of flexible operations, such as shiftable demand. These resources can collectively contribute to achieving a common control objective at their PCC by coordinating their power output. Combining several resources and exploiting existing flexibility, despite having increased communication and monitoring requirements and higher complexity, is advantageous because it reduces the need for new controllable assets. The formulation discussed above can be extended to multiple controllable resources by including their operational constraints in the scheduling optimization problem, as briefly summarized in this section.

The work in [14] proposed and demonstrated an extension of the dispatchable feeder with two controllable elements: a BESS and a flexible building with deferrable electric space heating (45 kW). The building's electrical demand can be shifted in time, helping the BESS to achieve the dispatch action. The flexibility of space heating operations stems from the building thermal mass that allows heating demand to be deferred or anticipated without noticeably affecting the indoor temperature. Under certain assumptions, the flexibility of space heating (more in general, of thermostatically controlled loads) can be modeled in terms of their equivalent energy storage capacity, providing a convenient way to exemplify flexibility, as shown in Fig. 8.

In energy management applications, the building's indoor temperature can be predicted with dynamic thermal models as a function of the heating power, outdoor temperature, and solar irradiance. These thermal models can be estimated from measurements (see, e.g., [15]). Heating power-to-temperature models are typically

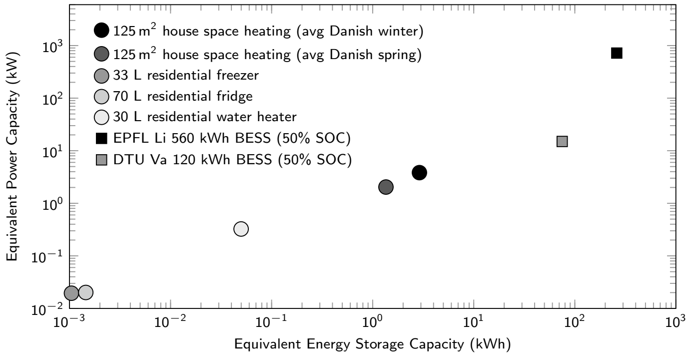

Fig. 8 Equivalent energy storage and power regulation capacity of thermostatically controlled loads compared to two utility-scale BESSs [16]

linear in the decision variable and can be used to extend the dispatch plan problem discussed above to enforce indoor temperature comfort with linear inequality constraints.

With multiple controllable elements, the total dispatch plan at the PCC is given by the sum of the dispatch plan of the BESS and of the building space heating, and the contribution of the remaining uncontrollable resources. The augmented scheduling problem includes both the BESS and space heating models, along with state-of-energy and indoor temperature constraints. In addition to those of uncontrollable resources, the forecasts required by the scheduling problem are for the solar irradiance and outdoor temperature.

Energy management and real-time control should account for the different time dynamics of the resources. For example, space heating actuation is slow and scarcely modulable (on/off, in case of thermostatic control), but it can shift power consumption for many hours depending on the building's thermal mass and is most suitable for energy control. Vice-versa, BESSs can quickly adapt their power output, but they might not have a relevant energy capacity, so they are better adapted to power control. In [14], the authors propose a hierarchical control structure that reflects these physical characteristics, with the space heating controlled at a coarse temporal resolution (tens of minutes) and the BESS controlled at a faster pace (seconds) to achieve energy and power control.

Collecting all the model and constraints in a single optimization problem refers to a centralized optimization problem. For scalability and preserving the privacy of the various resources in the pool, decomposition schemes can be used to decompose the centralized problem into multiple subproblems, one per resource, to be solved until convergence (e.g., [17–19]).

2.8 Including Grid Constraints in the Problem

Existing power distribution grids are designed to accommodate limited amounts of power demand and distributed generation. The increasing levels of power demand (e.g., due to electric vehicles) and distributed PV generation may determine limit violations of statutory voltage levels, cable ampacities, and substation transformer rating, requiring the grid operators to reinforce their network.BESSs connected to distribution grids and can be a valuable non-wire alternative to expensive grid reinforcements.

The problem formulations described previously can be extended with load flow equations to model the distribution grids' operational requirements. This problem is known as optimal power flow (OPF). Load flow equations determine the voltage in a power grid as a function of its topology, cable parameters, and the nodal real and reactive power injections. Including load flow equations in an optimization problem determines a non-convex formulation of the problem. Mathematically more tractable OPF problems have been widely investigated in the literature and include convexification of the non-convex constraints and linearization approaches, see, e.g., [20–23]. The use of linear models in application to OPF problems with BESSs has been widely addressed in the literature, e.g., [19] that outlined a validation in real low-voltage grid.

3 Real-Time Control and Rescheduling

3.1 The Role of Real-Time Control

So far, we have addressed the problem of designing a dispatch plan with suitable features accounting for the energy capacity and power rating constraints of the BESS. The scheduling stage is essential to ensure that the BESS has enough energy to deliver the prescribed services. In real-time, there is the need to compute the control set-points for the BESS so as to deliver these services effectively.

There are several possible strategies to determine the BESS real-time control set-points, depending on the specific service to deliver and the kind of information available in real-time. A simple solution, which entails no computation, is extracting the BESS power set-points from the dispatch plan computed in the scheduling stage and using them as the real-time set-points. However, as point predictions used to design the dispatch plan are subject to forecasting errors, the prescribed service will be not be delivered in the right amount. If no updated information is available from real-time measurements or state-estimation processes, this could be the only practical choice.

If updated information is available, it can be used to compute a more precise control action, also refine the dispatch plan. In this case, one can solve the same optimization problem used for the scheduling stage, but this time using updated input parameters. In this setting, the newly computed control trajectory can be applied in a receding horizon fashion, as done in model predictive control (MPC). More specifically, once the optimization problem is solved, the first element from the control history is implemented and the remaining control points are discarded. The optimization is then solved again ahead of the next time interval.

The drawback of receding horizon optimization is that recomputing the optimization problem might require time, especially when communication among multiple controllable resources is involved. In this case, the compatibility with the requirements of fast real-time control should be assessed, and, if necessary, one could consider a simplified version of the problem (e.g., with a shorter optimization horizon). The authors of [19] have shown that an MPC problem in a real operational setting with 4 batteries and grid constraints of an 18-node low-voltage grid can be solved a few seconds. Receding horizon optimization can also be used to compute a new dispatch plan on the basis of updated information (re-dispatching). Updated information, including measurements and forecasts, improves the situational awareness of the problem, leading to better decision-making and, ultimately, reduced BESS energy capacity requirements (see, e.g., [5, 24]).

A third solution to compute the real-time set-point of the BESS is by using a dedicated real-time controller. In cases where the dispatch plan is at a coarse time resolution (e.g., minutes) that are not compatible with faster timing requirements of real-time control (e.g., primary frequency regulation), a dedicated controller is necessary. Dedicated real-time controllers can be coupled with a recedinghorizon optimization problem to reschedule all dispatchable resources and ensure optimized conditions for effective real-time control. An example of a real-time controller is discussed in the next subsection. Dedicated simple controllers are also a convenient fall-back when other forms of more complex controls may fail, for example, due to communication issues or failure to meet hard real-time requirements.

3.2 A Real-Time Controller for Dispatching Stochastic Resources

To illustrate a real-time controller's formulation, we consider the case of the "dispatchable feeder" developed in the previous section. The real-time controller's objective is to adjust the BESS real power injection so that the average real power consumption on a 5 min interval at the PCC matches a set-point from a dispatch plan.

The index t denotes the time-interval index of the dispatch plan at a 5 min resolution. A second time-interval index, k, at a 10 s resolution refers to the period when the real-time control action is actuated and recomputed. There are thirty 10 s slots into one 5 min interval. At the beginning of each slot k, the former realization of the power flow at the PCC(P_{k-1}), the BESS real power injection (B_{k-1}), and net demand realization (L_{k-1}), become known from measurements, and a new active power set-point for the BESS, B_k^o, has to be computed. The nomenclature is exemplified in the

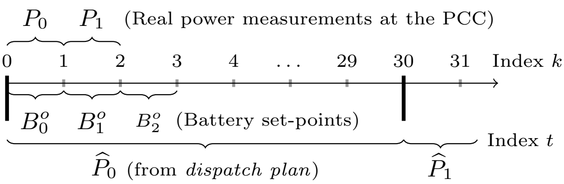

Fig. 9 Real-time operations' timeline, illustrating two time indexes, t and k, at a different pace

timeline in Fig. 9. It refers to the time slot $k = 2$: B_0^o and B_1^o are the BESS set-points actuated in the previous two slots, B_2^o has just been determined using the most recent measurements of the power flow at the PCC P_0 and P_1, and $\widehat{P}_0$ is the dispatch plan set-point to track in the current interval t.

The dispatch set-point, P_k^*, is retrieved from the 5-min-resolution dispatch plan $\widehat{P}_t$ as:

$$P_k^* = \hat{P}_{\lfloor k/30 \rfloor} \tag{37}$$

where $\lfloor \cdot \rfloor$ is the floor function. The k-index of the first 10 s slot of the current 5 min interval k is:

$$\underline{f}(k) = \lfloor k/30 \rfloor \cdot 30. \tag{38}$$

For example, assuming that midnight is at $k = 0$, clock time 00:16 corresponds to $k = 96$, $P_k^* = \widehat{P}_3$, and $\underline{f}(k) = 90$.

At time interval k, the average power flow at the PCC for the current 5 min interval is defined as:

$$\overline{P}_k = \begin{cases} 0 & k = \underline{f}(k) \\ \frac{1}{k - \underline{k}} \cdot \sum_{j=\underline{k}}^{k-1} P_j & \text{otherwise} \end{cases} \tag{39}$$

i.e., 0 at the beginning of the interval when no measurements are available yet, otherwise as the average of the power flow at the PCC considering all available measurements. The dispatch error is given by:

$$e_k = P_k^* - \overline{P}_k \tag{40}$$

We want to find a power injection of the BESS, B_k^o, such that the dispatch error is zero:

$$0 = P_k^* - \left(\overline{P}_k + B_k^o\right) \tag{41}$$

$$B_k^o = P_k^* - \overline{P}_k \tag{42}$$

Equation (42) is the BESS real power set-point to send to the BMS for actuation. A "saturation" block such as

$$\overline{B}_k^o = \min\left(B_k^o, \overline{B}\right) \cdot \operatorname{sign}\left(B_k^o\right) \tag{43}$$

can be used to implement a real power limit $\overline{B}$.

More sophisticated control strategies with better properties can be derived from the scheme described above. For example, to avoid that the BESS discharges at P_k^* when $k = \underline{f}(k)$, one can plugin short-term forecasts of the net-demand in (39) to estimate future values of P_k. A solution of this kind in combination with an MPC that accounts for the voltage constraints of the BESS is presented in [7].

3.3 Primary Frequency Regulation and Multiple Services

A BESS can be controlled to provide primary frequency regulation (PFR) wit. a real power set-point proportional to the frequency deviation from the nomina grid frequency, f_{nom}:

$$B_t^{\text{PFR}} = \alpha \cdot (f_{\text{nom}} - f_t) \tag{44}$$

where α is the frequency-drop-to-power gain and f_t is the grid frequency measurement. A BESS that provides PFR should fulfill certain eligibility criteria, which include, depending on the specific grid code, minimum ramping rates of the power output, minimum activation time, symmetric capabilities, and minimum availability levels. Specifications also define a dead-band around the nominal frequency (e.g., plus/minus 0.01 Hz [25]), where BESSs are not obliged to provide any PFR and can be used for adjusting the state-of-energy.

Proper energy management is essential to ensure that the BESS's state-of-energy will not hit the limits during operations due to BESS's losses, biased grid frequency deviations, and possible other services that the BESS provides. It is implemented by adding to (44) a dynamic offset value that ensures that the BESS energy is maintained in prescribed margins (see, e.g., [26, 27]). It can be calculated with various strategies, including receding horizon optimization problems accounting for forecasts of the services to be provided and the profit to be maximized.

Multiple services can be provided by combining the BESS set-points for the various services. For example, for PFR and dispatch, this reads as:

$$B_t^{\text{total}} = B_t^{\text{PFR}} + B_t^{\text{dispatch}} \tag{45}$$

When using a BESS to provide multiple services, it is important that the services operate at different time scales so that the control objectives do not conflict with each other.

In short, the real-time control of a BESS can be greatly improved by allowing departures of a pre-computed dispatch schedule to take into consideration not only any updated information, but also to allow for the coordination between multiple objectives that the BESS is attempting to meet.

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Smart Grids Optimization: Demands and Techniques

Geraldo Leite Torres and Vicente Ribeiro Simoni

Abstract This chapter discusses the concept, structure and resources of a smart grid, identifying opportunities for optimization applications in the planning and operation of smart grids, and the optimization techniques that have been frequently employed to solve those problems. Because there are many, it is impracticable to provide a complete survey and detailed descriptions of all problems and particular solution techniques in a book chapter. In addition, most of these topics are still open questions, formulation and solution. Therefore, the chapter aims to provide in simple language a flavor of prominent techniques for continuous and discrete optimization, optimization under uncertainty, multi-objective optimization and global optimization, providing good references for additional information on the techniques presented. The chapter also aims to provide a starting point for research in this challenging area, by helping the interested reader to identify research topics related to smart grid optimization.

1 Introduction

Smart grid (SG) is a characterization of modern electrical power systems equipped with advanced information technology resources (sensing, metering, communication and computation structures) and a high degree of operation control and automation to significantly improve its operational efficiency [5, 74]. As underlined in [5], advances in sensing technology are making new information available about the grid, and advances in communication technology are making them available at pertinent locations, and this together with advanced control and automation allow smart decision-making in an automated manner.

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Traditional power grids are designed on the basis that electricity supply follows demand, whereas smart grids are on a demand follows supply basis. The greater efficiency and improved control of energy flows offered by a smart grid provide a varied and comprehensive set of benefits for consumers, electricity utilities and the electrical system as a whole. Smart grid intelligently integrates the actions of all connected users, from power generators to power consumers and "prosumers" (those that both produce and consume electricity) [74]. It allows secure integration of intermittent *renewable energy sources* (RES) to the grid, improving the efficiency of clean energy utilization, and reducing the impact of increasing energy usage on the environment. Echoing [5], the predominant features of smart grids are:

> (1) Enable integration of intermittent renewable energy sources and help decarbonize power systems, (2) allow reliable and secure two-way power and information flows, (3) enable energy efficiency, effective demand management and customer choice, (4) provide self-healing from power disturbance events, and (5) operates resiliently against physical and cyber attacks.

A fundamental component of smart grids are the electronic smart meters, more modern versions of conventional meters, which can offer a number of innovative features, such as reporting events and sending alarms, and remote measurement possibilities. Among several explicit benefits for consumers, in the future, smart grids will allow utility customers to constantly monitor their electricity consumption, possibly obtaining information instantly, and will facilitate remote programming of the connection and disconnection of household appliances, allowing an improvement in electricity consumption in homes. For utilities, smart grid also brings several important advantages over conventional electrical power networks. For example, provides the means to instantly and accurately identify an interruption of energy supply in the grid, and the automatic execution of the necessary maneuvers for the prompt restoration. Another benefit is to enable a more detailed knowledge of the consumption behavior of customers, allowing to better plan the expansion of energy supply, and to adapting the electrical network to these characteristics.

Smart grids are often perceived as instruments that allow the dissemination of RES, through the concepts of *distributed generation* (DG) and *micro generation* (MG). Hence they can be an important tool for developed countries dependent on the generation of energy from fossil fuels to comply with the Kyoto Protocol (reduce global CO_2 emissions through RES). According to [38], the International Energy Agency (IEA) forecasts that 60% of future electrification needed to reach the goal of *energy for all* by 2030 will take place through MG and other small stand-alone systems. Sustainable energy usage is indispensable for sustainable development.

Smart grid allows the connection of small photovoltaic generation systems and wind power in low voltage consumers (residential and commercial customers), in addition to enabling a perfect functioning of these systems in tune with the entire network. Hence smart grid supports democratization of energy supply, contributing to the ability of the power system to respond to increase in consumer demands. In the future (maybe present or past at this time), it will be possible to expand power generation in a decentralized manner (without the need to build large and expensive generation projects), allowing customers to be a micro producer of electricity. This brings greater security in electricity supply, and a reduction in investment to expand the generation, transmission and distribution systems. As pointed out in [10], the development of smart grid technology involves a long list of research areas,

> from power system engineering, signal processing, computer science, communications, business, and finance as well as chemical and wind engineering among other disciplines under the same roof in order to cater to the diverse research needs of this technology.

As a new technology, plenty of challenges [10], smart grid research needs involve engineering research on efficient ways of energy distribution and load management, computer science research on cyber security for reliable sharing of information across the grid, communication and control engineering research on advanced instrumentation facilities (sensing, metering, communication, control) for full grid monitoring and control, engineering research on renewable energy generation and integration to the grid, chemical engineering research on high capacity and cost effective batteries for energy storage, business research on power system market policies, etc.

RES are begin deployed worldwide in diverse configurations and sizes. Utility scale wind and solar photovoltaic power plants are directly impacting the operation and planning of transmission systems, by adding low-cost variable generation that relies on natural resources as wind and solar radiation, which are not dispatchable. On the other hand, *distributed energy resources* (DER), such as solar rooftop generation, are changing the behavior of the existing passive distribution networks, which will have to be modernized and transformed into *active distribution networks* (ADN), in order to accommodate new challenges such as hourly voltage fluctuations, two-ways power flow through lines and transformers, and increased short-circuit levels. ADNs are distribution networks that have systems in place to control a combination of DERs, such as distributed generators, controllable loads and energy storage.

DER, automated metering infrastructure, and modern *distribution automation* (DA) ideas together shape future ADNs [89]. *Demand-side response* (DSR) is an important instrument of ADN, as it allows consumers to modify their electricity profiles to reduce peak demands. In spite of the benefits, DSR requires greater customer supervision, which can cause some annoyance [40]. Energy management and optimization tools are essential to enhance DSR initiatives.

This chapter aims to discuss the very active research area of optimization of smart grids, commenting on optimization problems of smart grids and the optimization techniques that have been employed to solve such problems. It is impossible to present a complete survey of all optimization methods in a book chapter. Therefore, the chapter aims to provide an idea of the prominent approaches to optimization under uncertainty, multi-objective optimization and global optimization, as well as providing great references for additional information on the techniques presented.

The remaining of the chapter is organized as follows. Section 2 presents a brief discussion of the structure and the main operating resources of smart grids, to assist in the identification of optimization applications. Section 3 presents the basics about optimization techniques often used in smart grids. Section 4 presents a review of the optimization applications to energy storage systems, demand-side response, electric vehicles management, congestion management and expansion planning. The conclusions of Sect. 5 end the chapter.

2 Smart Grid Optimization Opportunities

Most RES, mainly wind and solar energy, are variable and intermittent (stochastic) in nature, a feature that can lead to serious operational constraints if variable renewable energy is introduced widely into the grid. Smart grids empower to deal with these difficult operational constraints with greater use of digital control and advanced information technologies and dynamic optimization of the demand-supply balance. Opportunities for optimizing smart grids are many, from demand management and control to efficient RES integration, optimized use of DG and *energy storage system* (ESS), deployment of smart meters, smart devices and customer services.

The development in progress of smart grids has brought serious new challenges to the optimization of electrical grids. For example, widespread use of intermittent RES introduces uncertainties in traditionally deterministic data, such as traditionally dispatchable power generation. Increased use of *plug-in electric vehicles* (PEV) contributes to uncertainty in load estimation, both amount and location. Therefore, some previously *deterministic optimization* problems are turning into *stochastic optimization* problems, which are significantly more difficult to solve.

Increased penetration of RES requires that the transmission grid be significantly reinforced to support these renewables in dispersed areas [5]. Unsettled generations introduce operational challenges in terms of requiring significantly higher levels of regulation and ramping capacity. Increased renewable generation also implies limited dispatchability and increased intermittencies, which are concomitant with increased ancillary services. In addition to uncertainty in power supply, unpredictability is also increasingly touching demand estimation. As already mentioned, increased usage of PEVs will lead to significant new loads on distribution networks, which can be terribly inadequate in terms of monitoring and automation.

2.1 Demand Management (Response)

In traditional electrical networks power generation follows power demand. That is, historically, load has been treated as an uncontrolled external input, so that energy utilities have been operated with a presumed "obligation to serve" [3]. For this, generation is modified (by dispatching more or less generation) to meet constantly changing load demand at all times. However, during peak hours the supplementary generation is usually supplied by less efficient and more expensive sources. Customers of traditional networks do not receive any incentive to modify their energy usage patterns, and utilities then preserve the balance between energy production and demand through the coordinated operation of generation sources.

Energy demand management (or demand response) instruments seek to bring energy demand and supply closer to a perceived optimum, and for this they offer electricity end users benefits for reducing their use of electricity. The main goal of a *demand-side management* (DSM) program, also called *demand-side response* (DSR), is to persuade consumers to use less electricity during peak hours, or to move the time of electricity use to off-peak times such as nighttimes and weekends. Therefore, DSM (or DSR) implies that utility customers adjust their power demand to follow power generation [1]. In [77], demand response is formally defined as:

> Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at time of high wholesale market prices or when system reliability is jeopardized.

In a DSR program, consumers either [77]: (1) obtain a financial incentive to modify their consumption according to the conditions specified in the contract, or (2) modify their consumption in response to changes in the price of electricity. Accordingly, in one approach, customers allow the utility to manage their loads during peak hours, and in the other, the utility has an effect on loads using time-varying prices.

DSR does not necessarily imply that total energy consumption is reduced, but utilities fairly expect to avoid high investments to install extra capacity (power plants and transmission) to supply peak loads. One way to meet growing demand, to some extent, is to use existing energy sources more efficiently. For example, using ESS to store energy during off-peak hours and discharge it during peak hours. A recent application of DSR is to help grid operators to balance the intermittent generation of wind and solar units, particularly when the time and magnitude of energy demand do not coincide with renewable generation [62]. Thus, in order to deal with power intermittence during peak load hours, instead of trying to replace the lost capacity due to the intermittency, one option is to act on the energy demand side, aiming to reduce the consumption in those hours. Currently, DSR procedures are becoming increasingly applicable due to smart grid technology.

In traditional networks, demand response resources generally refers to loads that can respond to electricity price signals or incentive mechanisms. However, microgrid demand resources not only includes load resources but also distributed and energy storage resources [79]. Microgrid distributed resources include two main categories: (1) intermittent RES, as wind and solar, and (2) controllable distributed generation, as micro gas and diesel generation units. Load response resources include three categories: (1) interruptible load, (2) adjustable load, and (3) shiftable load.

2.2 *Management of Plug-in Electric Vehicles*

Plug-in electric vehicles (PEVs) are relevant factors to consider when developing future power grids. For the grid, PEVs (including pure electric vehicles and plug-in hybrids) can be seen as both loads and energy storage units. In the first case (load), charging control consists of shifting the consumption of PEVs over time, in order to limit power peaks on the grid, or to make recharge coincide with periods of high production of RESs. In the second case (storage unit), the batteries of PEVs can be used to absorb or supply energy according to market prices, availability of renewables, and individual consumption. Currently, most power grids lacks enough capacity to meet the increased demand resulting from a large number of charging stations, especially during peak loads. The envisioned critical infrastructure for PEVs must include the capability for information exchange involving energy availability, distances, congestion levels and possibly spot prices or priority incentives [54]. If PEV charging is coordinated, then it is possible to construct aggregated charge profiles that avoid detrimental system impacts and minimize system-wide costs.

As PEVs population grows, their charging increases the energy demand and has the potential to greatly change the demand curve [86]. The power requirement of a large number of PEVs at peak or near peak times can lead to serious challenges in cost, delivery through grid, and even in generation capacity and ramping capabilities [47]. The potential impacts of a high penetration of PEVs on the network are studied in [30, 68]. Approaches to handle this problem usually aim to schedule and shift the charging demand of PEVs to the late evening and very early morning when the overall demand is the lowest. These “valley filling” approaches aim at leveling the overall demand to reduce the need for shutting down and restarting power plants.

Strategies to optimally coordinate charging of PEVs are presented in [53, 55, 86]. Strategies are usually classified as centralized or decentralized, and whether they are optimal or near-optimal in some sense. In centralized strategies a central operator dictates precisely when and at what rate every individual PEV will charge, while decentralized strategies allow individual PEVs to determine their own charging pattern [54]. The outcome of a decentralized approach may or may not be optimal, depending on the information and methods used to determine local charging patterns.

Regarding centralized versus decentralized coordination, some remarks in [53] are: (1) using a centralized coordination, “valley filling” charge patterns are globally optimal, and (2) decentralized coordination can be handled in the context of *non-cooperative dynamic game theory*. According to [86], centralized approaches are difficult to realize and hence unlikely to be accepted; then a decentralized protocol is proposed. Reference [54] presents a decentralized approach thought to be useful in applications where fully centralized control is not possible, but where optimal or near-optimal charging patterns are essential to system operation.

2.3 Energy Storage Systems

Energy storage systems (ESS) are important instruments for mitigating the temporal and often geographic differences between energy generation and load demand, that can be particularly difficult to control when generation is provided by unpredictable RES, since they enable the surplus of energy to be stored during the periods when intermittent generation exceeds demand, and then be used when demand is greater than generation. Reflecting [11], and some references therein:

> Electrical energy storage refers to a process of converting electrical energy from a power network into a form that can be stored for converting back to electrical energy when needed. Such a process enables electricity to be produced at times of either low demand, low generation cost or from intermittent energy sources and to be used at times of high demand, high generation cost or when no other generation means is available.

An extensive review of ESS technologies is shown in [11], from currently available technologies to some still under development. As underlined in [49], intermittent and weather-dependent output of RES may jeopardize power system reliability and cause load curtailment if generation cannot meet the demand. However, ESS such as large batteries, flywheels and heat buffers (hot water tanks) can be used to smooth out intermittent power supply. Moreover, with an increasing market penetration rate of PEVs, *vehicle-to-grid* (V2G) systems are expected to be a critical auxiliary energy storage infrastructure in the future. Therefore, ESS is regarded as an urgently needed technology for DER and intermittent RES supply systems.

Variable generation sources must typically be converted and conditioned using power electronics to serve a typical AC load either on the utility grid or in smaller distributed networks. ESS can be divided into bulk storage, which can output large amounts of power (several MW) over long periods of time (minutes to hours), and distributed storage that can output smaller amounts of energy (kW to MW) over shorter periods of time (milliseconds to minutes). Energy storage technologies that have been used in DER include lead acid batteries, lithium-ion batteries, some types of flow batteries, thermal storage, flywheels, super capacitors, and hydrogen storage. For energy management of microgrids, which require energy storage technologies for low/medium scale grids, the most used storage systems are based on batteries. No single storage system meets all the requirements for an ideal ESS [11]: having long lifetime, low cost, high density and efficiency, and being environmentally friendly.

2.4 Microgrids

The integration of small-scale energy sources, such as rooftop solar panels, energy storage devices and V2G, in local areas, such as a small town, a university campus, a military base, and a commercial area, leads to the formation of local, small-scale and self-contained grids, known as *microgrids* [49]. A microgrid can operate in either a grid-connected mode to enable energy transactions with the main electrical grid, or an islanded (standalone) mode given there is a fault in the main grid. Once the problem is solved, the microgrid can be resynchronized. Besides the economic and environmental benefits, other advantages of microgrids include [49]: (1) energy loss reduction, since micro sources are closer to loads, (2) reliability improvement, since a microgrid can operate in islanded mode if there is a fault in the main grid, (3) energy management improvement, with local coordination of micro sources and loads, and (4) benefits to the main grid, via efficient energy management of microgrids.

A microgrid is controlled by a supervisory controller that decides which energy resources to use and at what times to balance load and generation. This microgrid controller may consider predicted load profile, predicted power price profile, predicted wind or solar power profile, predicted heating or cooling needs (if the microgrid contains cogeneration), emissions and other parameters. Reference [49] discusses the key features of microgrids and provides a comprehensive survey on the *stochastic modeling* and optimization tools for a microgrid. Stochastic models are suitable to characterize the randomness in renewable power generation, the buffering effect of ESSs and PEVs mobility. Therefore, *stochastic optimization* tools can be used for the planning, operation and control of microgrids.

Microgrid planning involves finding the optimal combination, design and sizing of micro-sources to meet future energy demand at minimum lifecycle cost, while meeting system reliability requirements [33]. Microgrid operation mainly involves unit commitment and economic dispatch, and both functions have their analogues in the traditional power grid [16]. Due to the integration of RES and ESS (including V2G), new technical challenges arise in microgrid planning, operation and control. The randomness in renewable generation should be taken into account in addition to randomness in energy demand. The buffer effect of ESS requires the modeling of inter-period buffer state transitions over the entire time frame of microgrid planning, operation and control, leading to high computational complexity. The highly dynamic PEV mobility leads to randomness in the number of PEVs in a specific location and randomness in the capacity of the V2G system. Therefore, *stochastic modeling and optimization* can be used for microgrid planning, operation and control.

3 Techniques for optimization of Smart Grids

Optimization of smart grids is an achievement of interdisciplinary collaboration. Traditionally, grid operation has relied on a single centralized generation structure, with electricity distributed as needed. As solar technology develops, individual homes and industries can generate their own energy, but any excess energy cannot be readily integrated into the main grid due to its DC nature. Houses with solar panels with different outputs must be linked to batteries, all placed in a grid, with minimum wiring cost. At a later stage, alternative battery locations can be obtained. A smart grid can integrate multiple sources of DER using a two-way distribution method.

Renewable energy can often only be generated at certain times. This operational complexity requires a system that can be adapted and expanded without detriment to existing infrastructure. A smart grid that constantly monitors and automatically corrects energy fluctuations is able to minimize energy waste. The techniques for efficient operation and control of smart grids can be classified as [60]: (1) rule-based techniques, (2) optimization techniques, and (3) hybrid techniques. In rule-based techniques, reference points are allocated according to the existing situation and defining some scenarios, usually by means of decision trees. The method can be adapted to system conditions, provides feasible but not necessarily optimal solutions. Optimization-based techniques aim to provide the best local or global solution. The mathematical models consist of maximizing or minimizing an objective function while satisfying all considered constraints. Hybrid techniques put together several methods to take advantage of their best features.

In [39], a review of optimization methods for deployment and operation of RES is presented. Optimization approaches can be classified as exact or approximate. Approximate methods have the advantage of easily managing nonlinear constraints and objective functions, but they cannot guarantee the quality of the results obtained, as they generally employ random searches, and the possibility of finding a global solution decreases as the problem size increases. The exact methods generate an optimal solution when specified in a feasible region. They can be classified as linear (linear programming, integer linear programming and mixed integer linear programming) or non-linear.

Decision-makers often need to make decisions in the presence of uncertainty. Since decision problems are often formulated as optimization problems, then, in many situations, decision makers want to solve optimization problems that depend on unknown parameters [44]. Usually, it is very difficult to formulate and solve these problems, both conceptually and numerically. In formulating optimization problems, it is customary to try to find a good trade-off between the realism of the optimization model, which generally affects the usefulness and quality of the decisions obtained, and the treatability of the problem, so that it can be solved analytically or numerically.

In [49], a comprehensive review on stochastic modeling and optimization tools for microgrid planning, operation and control is presented. The tools can be used to deal with randomness in renewable power generation, the buffering effect of ESS, and the mobility of PEVs in V2G systems. Moreover, unique features of microgrids, like dual operating modes (islanded and grid-connected), the spatial correlation of renewable power generation, and the integration of CHP plants with both electricity and heat outputs, are taken into account. Despite the existence of stochastic modeling and optimization tools for microgrid planning, operation and control in the literature, many microgrid research questions remain to be answered. According to [49], the majority of the existing works is based on *Monte Carlo simulation*. Despite the simplicity in microgrid modeling via Monte Carlo simulation, its high computational load requires highly efficient computational devices, such as powerful servers and workstations, with a not negligible cost.

A major issue in optimization is distinguishing between global and local optima. All other factors being equal, one always want a globally optimal solution to the optimization problem. In practice, it may not be feasible to find a global solution and one must be satisfied with obtaining a local solution. It is usually only possible to ensure that an algorithm approaches a local minimum with a finite amount of resources being put into the optimization process. But since local minimum may still yield a significantly improved solution (relative to no formal optimization process at all), the local minimum may be a fully acceptable solution for the resources available to be spent on the optimization. Several algorithms (random search, stochastic approximation, and genetic algorithms) are sometimes able to find global solutions from among multiple local solutions.

Classical deterministic optimization assumes that perfect information is available about the objective function (and derivatives, if relevant) and that this information is used to determine the search direction in a deterministic manner at every step of the algorithm. It is clear now that there are several different techniques for smart grid optimization, and it is impossible to give a complete survey of all these methods in a book chapter. Therefore, this chapter just aims to provide a flavor of the most commonly used and prominent approaches for optimization of smart grids.

3.1 Linear Programming (LP)

LP is a subset of the broader field of mathematical programming [13, 52], and it has attracted most of its attention in optimization during the last six decades for two main reasons: (1) applicability (there are many real-world applications that can be modeled as LP), and (2) solvability (there are theoretically and practically efficient techniques for solving large-scale LP problems). LP formulations consists of three essential elements: (1) a set of decision variables, which represent the unknown actions that can be taken, (2) an objective function, which describes a criterion to optimize (in the minimization or maximization sense), and (3) a set of constraints, which describe the limitations that restrict the choices for the decision variables.

All functions involved in a LP are linear functions of the decision variables. Each constraint requires that a function of the decision variables is either equal to, not less than, or not more than, a scalar value. A common condition simply states that each decision variable must be nonnegative. All LP can be transformed into an equivalent minimization problem with nonnegative variables and equality constraints [4]. With no loss in generality, the standard form for LPs can be defined as follows:

$$\begin{array}{ll} \min & c^T x \\ \text{subject to} & Ax = b \\ & x \geq 0 \end{array} \tag{1}$$

where $x \in \mathbb{R}^n$ is the vector of decision variables, $c \in \mathbb{R}^n$ is the vector of cost coefficients, $A \in \mathbb{R}^{m \times n}$ is the constraint matrix, and $b \in \mathbb{R}^m$ is the vector of constraint levels. If the set $\mathcal{X} = \{x \in \mathbb{R}^n \mid Ax = b,\ x \geq 0\}$ of *feasible* solutions to (1) is nonempty, then the LP problem (1) is *feasible*. In this case, any solution $x \in \mathcal{X}$ is said to be a *feasible solution*. If $\mathcal{X}$ is empty, then (1) is said to be *infeasible*. An *optimal solution* $x_* \in \mathcal{X}$ is defined as $c^T x_* \leq c^T x$, for all $x \in \mathcal{X}$. Therefore, the optimal solution is a feasible solution such that no other feasible solution has a lower objective value $c^T x$.

The first algorithm for solving LP problems was the *simplex method*, invented by G. Dantzig in 1947 [13]. After seven decades of existence, it still remains as one of the most efficient and reliable methods for solving LPs [4]. Today, the primary alternative to the simplex method is the family of primal-dual path-following *interior-point* (IP) methods. IP methods are generally regarded as being faster than simplex for solving LPs from scratch. However, the wide variety of different LP models and the many different ways in which LP is used, mean that neither algorithm dominates the other in practice. Both are important in computational LP.

Simplex Method Is a computational procedure that starts from an initial basic feasible solution (an extreme point of the feasible polyhedron) and, if this point is not optimal, moves to an adjacent extreme point of the polyhedron, through a change of base that provides a better value for the objective function. This change of base procedure is repeated successively until, in a finite number of steps, the optimal solution is obtained, if one exists. The simplex is a computational procedure that can generate several algorithms. The difference between these algorithms occurs mainly in the way they define a feasible basic solution and the criteria they use to decide on base changes. The simplex method should be initiated with a feasible basic solution. In general, such a solution is not known and it may not be easy to "guess" it. A systematic method is then needed to build an initial feasible basic solution. Most methods formulate an *artificial problem*, which has a known feasible basic solution and whose optimal solution is a feasible basic solution for (1). There are two main artificial problem ideas [4]: a two-phase method, and a big-M method.

Interior-Point Methods The first IP method is attributed to Frisch [22], which is a *logarithmic barrier* method that was later, in the 1960s, extensively studied by Fiacco and McCormick [18] to solve non-linear inequality constrained problems. However, it was in the LP research area that in 1984 the extraordinary computational performance of an IP method was demonstrated in practice [42]. Since then, several IP methods have been proposed and implemented. The first theoretical results for *primal-dual path-following* IP method are due to Megiddo [58]. Primal-dual IP methods that incorporate prediction and correction steps, like Mehrotra's predictor-corrector method [59], are currently accepted as the most computationally efficient IP methods. Further improvements over Mehrotra's predictor-corrector method were subsequently achieved through the use of multiple correction steps [9, 27].

Variants of primal-dual IP methods have been extended to solve all types of problems: linear or non-linear, convex or non-convex. Optimization of power systems is one of the areas where IP methods have been widely applied [67]. IP methods have demonstrated in computational practice to be quite efficient with respect to processing time and convergence robustness. Applications of IP methods to power systems include: state estimation [14], optimal power flow [76, 81], hydro-thermal coordination, voltage collapse, etc. The performance of the applications in [14, 28, 81], in terms of convergence robustness and processing time, sparked the interest in IP methods to solve nonlinear optimization problems in power systems.

A primal-dual IP method to solve LP problem (1) acts on the modified problem

$$\begin{array}{ll} \min & c^T x - \mu_k \sum_{i=1}^{n} \ln x_i \\ \text{subject to} & Ax = b, \end{array} \tag{2}$$

where $\mu_k > 0$ is a *barrier parameter*, which is monotonically decreased to zero as iterations progress. Note that the non-negativity conditions $x \geq 0$ are incorporated into a logarithmic barrier function, which is appended to the objective function. Strict positivity conditions $x > 0$ must be imposed for the logarithmic terms be defined, but these conditions are handled implicitly through step length control.

The most computationally intensive task at each IP iteration involves the solution of a large linear system for the search direction Δy. Since the factorization of the coefficient matrix is much more expensive than two triangular systems solutions, it is possible to improve the performance of the IP algorithm by reducing the number of matrix factorizations (iterations) to a necessary minimum, even at the expense of some increase in the cost of a single iteration. This is the central idea behind Mehrotra's predictor-corrector IP method [59] and its higher-order variants [9, 27].

3.2 Mixed Integer Linear Programming (MILP)

Several instances of optimization involve decisions that are discrete, while some other decisions are continuous in nature. Apparently, the ability to enumerate all the possible values that a discrete decision can take seems appealing. However, in most applications, the discrete variables are interrelated, requiring an enumeration of all combinations of values that the entire set of discrete variables can take. Then, a more efficient technique is needed to solve problems containing discrete variables [71].

Mixed-integer programming techniques do not explicitly examine all possible combinations of discrete solutions, instead examine a subset of possible solutions, and use optimization theory to prove that no other solution can be better than the best one found. This type of technique is known as implicit enumeration. A *mixed-integer linear program* (MILP) is a LP with the added constraint that some (not necessarily all) of the variables must have integer values. That is, a MILP is of the form

$$\begin{array}{ll} \min & c^T x \\ \text{subject to} & Ax = b \\ & x \geq 0, \quad x_i \in \mathbb{Z}, \quad \forall i \in \mathcal{I} \end{array} \tag{3}$$

where $\mathbb{Z}$ is the set of all integer numbers, and $\mathcal{I}$ is the index set of the integer variables x_i. If all variables need to be integer, then it is called an *integer linear program* (ILP). If all variables need to be 0 or 1, then it is called a (0,1) or *binary* LP. The inclusion of integer variables increases enormously the modeling power, but at the expense of a significant increase in solution difficulty. As already mentioned, LP problems can be solved in *polynomial time* with IP methods. However, MILP is a NP-hard problem, and there is no known polynomial time solver.

Relaxation is a fundamental concept about solving MILPs. For MILP (3), its *linear relaxation* is the LP problem obtained by dropping the integrality constraints,

$$\begin{array}{ll} \min & c^T x \\ \text{subject to} & Ax = b \\ & x \geq 0. \end{array} \tag{4}$$

Any solution to MILP (3) is a feasible solution to relaxed problem (4), and each solution to MILP has an objective function value greater than or equal to that of the corresponding relaxed problem. The most commonly used relaxation for a MILP is its LP relaxation, which is identical to the MILP, with the exception that variable integrality constraints are dropped. Clearly, any feasible integer solution to the MILP is also a solution to its LP relaxation, with matching objective function values. Acclaimed MILP solvers employ a combination of *branch-and-bound* and *cutting-plane* techniques. Both techniques are outlined next.

Branch-and-Bound (B&B) Algorithm B&B is essentially a strategy of "divide and conquer". The idea is to partition the feasible region into more manageable subdivisions and then, if required, to further partition the subdivisions. In general, there are a number of ways to divide the feasible region, and as a consequence there are a number of B&B algorithms. The main steps of the B&B algorithm are [71]:

Branch-and-Bound Algorithm

S0 Set the *incumbent* objective $v = \infty$ (assuming that no initial feasible integer solution is available). Set the *active* node count $k = 1$ and denote the original problem as an *active* node. Go to step 1.

S1 If $k = 0$, then stop: the *incumbent* solution is an optimal solution. (If there is no incumbent, i.e., $v = \infty$, then the original problem has no integer solution.) Else, if $k \geq 1$, go to step 2.

S2 Choose any *active* node, and call it the *current* node. Solve the LP relaxation of the *current* node, and make it *inactive*. If there is no feasible solution, then go to step 3. If the solution to the *current* node has objective value $z^* \geq v$, then go to step 4. Else, if the solution is all integer (and $z^* < v$), then go to step 5. Otherwise, go to step 6.

S3 *Fathom* by infeasibility. Decrease k by 1 and return to step 1.

S4 *Fathom* by bound. Decrease k by 1 and return to step 1.

S5 *Fathom* by integrality. Replace the *incumbent* solution with the solution to the *current* node. Set $v = z^*$, decrease k by 1, and return to step 1.

S6 Branch on the *current* node. Select any variable that is fractional in the LP solution to the *current* node. Denote this variable as x_s and denote its value in the optimal solution as f. Create two new *active* nodes: one by adding the constraint $x_s \leq \lfloor f \rfloor$ to the *current* node, and the other by adding $x_s \geq \lceil f \rceil$ to the *current* node. Add 1 to k (two new *active* nodes, minus one due to branching on the *current* node) and return to step 1.

According to [71], a heuristic procedure can be used in step 0 to quickly obtain a good-quality solution to the MILP with no guarantees on its optimality. This solution would then become the initial incumbent solution, and could possibly help conserve

B&B memory requirements by increasing the rate at which active nodes are fathomed in step 4. In step 2 it may have several choices of active nodes on which to branch, and in step 6 it may have several choices on which variable to perform the branching operation. There has been much empirical research seeking for good general rules to make these choices, and these rules are implemented in commercial solvers.

Cutting-Plane Technique The *cutting-plane* (CP) technique, proposed by Ralph Gomory [26], solves a MILP by modifying LP solutions until the mixed-integer solution is obtained. It does not partition the feasible region into subdivisions, as in B&B techniques, but instead works with a single LP, which it refines again and again by adding new linear inequality constraints, termed *cuts*. The new constraints successively reduce the feasible region until an integer optimal solution is found.

The B&B procedures almost always outperform the CP algorithm, but the CP algorithm has been important to the evolution of integer programming. Historically, it was the first algorithm for integer programming that could be proved to converge in a finite number of steps. Moreover, although the algorithm is considered to be inefficient, it has provided insights into integer programming that have led to more efficient algorithms, such as a combination with B&B, called *branch-and-cut* [15].

On Modeling Languages Are programming constructs for optimization model formulation, allowing for model development and flexibility in changing and debugging a model [63]. Among the algebraic modeling languages [20], the most commonly used ones for LP and MILP are AMPL [21] and GAMS [23]. Premium LP and MILP solvers are CPLEX [17], GuRoBi [29], SYMPHONY and CBC (open source), Solver and Xpress-MP [19]. CPLEX, GuRoBi, and Xpress-MP can accept models written in AMPL or GAMS. Xpress-MP also accepts models written in its Mosel modeling language. CPLEX also has its own modeling language, OPL. Unlike AMPL and GAMS, Mosel is a compiled language, making it faster to read into the solver, which AMPL and GAMS only interpret, but Mosel lacks solver versatility.

3.3 Second Order Cone Programming

Second-order cone programming (SOCP) problems can be literally defined as [2]:

> Convex optimization problems in which a linear function is minimized over the intersection of an affine linear manifold with the Cartesian product of second-order (Lorentz) cones. Linear programs, convex quadratic programs and quadratically constrained convex quadratic programs can all be formulated as SOCP problems, as can many other problems that do not fall into these three categories. These later problems model applications from a broad range of fields from engineering, control and finance to robust and combinatorial optimization.

According to [2], SOCP is a special case of *semidefinite programming* (SDP). In fact, SOCP falls between LP and QP and SDP. Like QP and SDP, SOCP problems can also be solved in polynomial time by specialized IP algorithms. When applied to problems of similar size and structure, IP solution for SOCP requires more processing time than for LP and QP, but less time than for SDP. Several codes are available for SOCP, like SDPackage and SeDuMi [75]. A SOCP problem can be expressed as the following standard form [2]:

$$\begin{array}{ll} \min & c_1^T x_1 + \cdots + c_r^T x_r \\ \text{subject to} & A_1 x_1 + \cdots + A_r x_r = b \\ & x_i \succeq_Q 0, \quad \text{for } i = 1, \ldots, r \end{array} \tag{5}$$

where $x_i \succeq_Q 0$ denotes second-order cone inequalities (see [2]). The dual form is:

$$\begin{array}{ll} \max & b^T \lambda \\ \text{subject to} & A_i^T \lambda + s_i = c_i, \quad \text{for } i = 1, \ldots, r \\ & s_i \succeq_Q 0, \quad \text{for } i = 1, \ldots, r \end{array} \tag{6}$$

The specialized IP method to solve SOCP problem (5) acts on the modified problem

$$\begin{array}{ll} \min & \sum_{i=1}^r c_i^T x_i - \mu_k \sum_{i=1}^r \ln \det(x_i) \\ \text{subject to} & \sum_{i=1}^r A_i x_i = b \\ & x_i \succ_Q 0, \quad \text{for } i = 1, \ldots, r \end{array} \tag{7}$$

Similarly to the IP for LP, the KKT first-order optimality conditions are

$$\begin{array}{ll} A_i^T \lambda + s_i - c_i & = 0, \quad \text{for } i = 1, \ldots, r \\ \sum_{i=1}^r A_i x_i - b = 0 & \\ x_i \circ s_i - 2\mu_k e & = 0, \quad \text{for } i = 1, \ldots, r \\ x_i, \ s_i & \succ_Q 0, \quad \text{for } i = 1, \ldots, r \end{array} \tag{8}$$

The application of Newton's method to (8), yields the block matrix form [2]:

$$\begin{bmatrix} A & 0 & 0 \\ 0 & A^T & I \\ Arw(s) & 0 & Arw(x) \end{bmatrix} \begin{pmatrix} \Delta x \\ \Delta \lambda \\ \Delta s \end{pmatrix} = - \begin{pmatrix} Ax - b \\ A^T \lambda + s - c \\ x \circ s - 2\mu e \end{pmatrix} \tag{9}$$

where $Arw(\cdot)$ (an *arrow-shaped* matrix) is meant in the direct sum sense. Several practical implementation issues are discussed in [2].

As second-order cones are convex sets, SOCP is a convex programming problem. If the dimension of a second-order cone is greater than two, it is not polyhedral, and hence, in general, the feasible region of a SOCP is not polyhedral. Since SOCPs are convex, a duality theory for them can be developed. While much of this theory is very similar to duality theory for LP, there are many ways in which the theory for SOCP differs from that for LP. Robust solutions to optimization problems has been an important area of activity in the field of control theory, so that robustness has been introduced into the fields of mathematical programming and least squares. Counterparts of a least squares problem and a LP can be formulated as SOCPs [2].

3.4 Multi-objective Optimization

Multi-objective optimization (MOO), or *vector optimization*, considers optimization problems involving more than one objective function to be optimized simultaneously. MOO problems arise in many fields, such as engineering, economics, and logistics, when optimal decisions need to be taken in the presence of trade-offs between two or more conflicting objectives. In [56], a comprehensive survey of MOO methods is presented. A MOO problem can be expressed as:

$$\begin{array}{ll} \min & f(x) = (f_1(x), f_2(x), \ldots, f_k(x))^T \\ \text{subject to } x \in \mathcal{X} & \end{array} \tag{10}$$

where $k \geq 2$ is the number of objective functions $f_i(x)$, $x \in \mathbb{R}^n$ is the vector of decision variables, and $\mathcal{X}$ is the feasible set of decision vectors, typically defined by

$$\mathcal{X} = \left\{x \in \mathbb{R}^n \mid g(x) = 0,\ h(x) \leq 0\right\}$$

where $g : \mathbb{R}^n \mapsto \mathbb{R}^m$ and $h : \mathbb{R}^n \mapsto \mathbb{R}^p$. Any element $x \in \mathcal{X}$ is a feasible solution.

According to [56], differently from single-objective optimization, a solution to a MOO problem is more of a concept than a definition. Typically, there is no single solution that simultaneously optimizes each of all objectives $f_i(x)$, $i = 1, \ldots, k$. Instead, there exists a set (possibly infinite) of *Pareto optimal* solutions [65]. A solution is called *non-dominated* or *Pareto optimal* if none of the objective functions $f_i(x)$ can be improved in value without degrading one or more of the other objective values. Without additional subjective preference information, all Pareto optimal solutions are considered equally good.

Definition 1 A feasible solution $x_1 \in \mathcal{X}$ is said to (Pareto) dominate another solution $x_2 \in \mathcal{X}$, if $f_i(x_1) \leq f_i(x_2)$ for all indices $i \in \{1, 2 \ldots, k\}$, and $f_j(x_1) < f_j(x_2)$ for at least one index $j \in \{1, 2, \ldots, k\}$. A solution $x_1 \in \mathcal{X}$ is called *Pareto optimal* if there does not exist another solution that dominates it.

All Pareto optimal points lie on the boundary of the *feasible criterion space* $\mathbb{Z}$, also called the *feasible cost space*, which is defined as the set $\{F(x) \mid x \in \mathcal{X}\}$. Often, algorithms provide solutions that may not be Pareto optimal but may satisfy other criteria, making them significant for practical applications [56]. For example, a point is *weakly Pareto optimal* if there is no other point that improves all of the objective functions simultaneously. Since a point is Pareto optimal if there is no other point that improves at least one objective function without detriment to another function, Pareto optimal points are weakly Pareto optimal, but weakly Pareto optimal points are not Pareto optimal. Methods for determining whether a point is Pareto optimal or not are presented in [6]. In [61], the following test for x_* is presented:

$$\begin{array}{ll} \min_{x \in \mathcal{X}, \delta \geq 0} & \sum_{i=1}^{k} \delta_i \\ \text{subject to} & f_i(x) + \delta_i = f_i(x_*), \quad i = 1, \ldots, k. \end{array} \tag{11}$$

If all δ_i are zero, then x_* is a Pareto optimal point. *Efficiency* is another primary concept in MOO, which is defined in [56] as:

Definition 2 A point $x_* \in \mathcal{X}$ is *efficient* iff there does not exist another point $x \in \mathcal{X}$ such that $f(x) \leq f(x_*)$ with at least one $f_i(x) < f_i(x_*)$. Otherwise, x_* is *inefficient*.

There is a wide variety of methods for MOO. They can be broadly classified as: (1) methods with a priori articulation of preferences, (2) methods with a posteriori articulation of preference, (3) methods with no articulation of preferences. The reader is referred to [56] for detailed presentations and analysis of several methods of the three types. Two of them, of the first type, are outlined next.

Weighted Sum Method The most common method to MOO is the weighted sum:

$$f(x) = \sum_{i=1}^{k} w_i f_i(x) \tag{12}$$

If all the weights w_i are positive, then the minimum of (12) is Pareto optimal, i.e., minimizing (12) is sufficient for Pareto optimality. However, the formulation does not provide a necessary condition for Pareto optimality. A detailed discussion of this method, mainly regarding the choice of the weights w_i, is presented in [56].

Lexicographic Method With the lexicographic method, the objective functions $f_i(x)$ are arranged in order of importance. Then, the following single-objective optimization problems are sequentially solved, for $i = 1, 2, \ldots, k$, one at a time:

$$\begin{array}{ll} \min_{x\in\mathcal{X}} & f_i(x) \\ \text{subject to} & f_j(x) \leq f_j(x_j^*), \quad j = 1, 2, \ldots, i-1, \;\; i > 1 \end{array} \tag{13}$$

Here, i represents a function's position in the preferred sequence, $f_j(x_j^*)$ represents the optimum of the j-th objective function, found in the j-th iteration. After the first iteration ($j = 1$), $f_j(x_j^*)$ is not necessarily the same as the independent minimum of $f_j(x)$, because new constraints have been introduced.

Several MOO methods are presented and discussed in [56]. Accordingly, the MOO methods that provide both necessary and sufficient conditions for Pareto optimality are preferable. Other approaches, such as *genetic algorithms* (GA), discussed in this chapter as well, can be adapted to solve MOO problems directly.

3.5 Stochastic Optimization

Stochastic optimization (SO) refers to a collection of methods for minimizing or maximizing an objective function when randomness is present [31, 73]. Examples of SO are [31]: deciding when to release water from a reservoir for hydroelectric power generation, and optimizing the parameters of a statistical model for a given data set. Randomness usually enters the problem in two ways: through the cost function or the constraint set. Therefore, SO is a suitable approach for handling the uncertainties involved in wind and solar energy, load demands, etc.

There is no single solution method that works well for all SO problems [31]. Structural assumptions, such as limits on the size of the decision and outcome spaces, or convexity, are necessary to make problems treatable. Solution methods are then tied to problem structure. The most prominent division is between solution methods for problems with a single time period (single-stage problems) and those with multiple time periods (multi-stage problems). Single-stage problems try to find a single, optimal decision, such as the best set of parameters for a given statistical model data. These problems are usually solved with adapted deterministic optimization methods. Multi-stage problems try to find an optimal sequence of decisions, such as scheduling water releases from hydroelectric plants over a two year period. The dependence of future decisions on random outcomes makes direct modification of deterministic methods difficult in multi-stage problems. Multi-stage methods rely more on statistical approximation and strong assumptions about problem structure.

Single-Stage SO Is the study of optimization problems with a random objective function or constraints where a decision is implemented with no subsequent recourse. Let $\mathcal{X}$ be the domain of all feasible decisions and x a specific decision. The fundamental problem of interest is to search over $\mathcal{X}$ to find a decision that minimizes a cost function, F. Let ξ denote random information that is available only after the decision is made. Since it is impossible to directly optimize the random cost function $F(x, \xi)$, the expected value $\mathbb{E}[F(x, \xi)]$ is minimized instead. The general single-stage SO problem can be formally represented as [31]:

$$\zeta^* = \min_{x \in \mathcal{X}} \{f(x) = \mathbb{E}\,[F(x, \xi)]\}\,. \tag{14}$$

Define the set of optima as $\mathcal{S}^* = \{x \in \mathcal{X} : f(x) = \zeta^*\}$. For all single-stage problems, assume that the decision space $\mathcal{X}$ is convex and the objective function $F(x, \xi)$ is convex in x for any realization ξ. Problems that do not meet these assumptions are usually solved through more specialized stochastic optimization methods.

Multi-Stage SO Aims to find a sequence of decisions, $(x_t)_t^T = 0$, that minimize an expected cost function. The subscript t denotes the time at which decision x_t is made. Usually, decisions and random outcomes at time t affect the value of future decisions. Mathematically, multi-stage SO problems can be described as an iterated expectation [31]:

$$\begin{aligned}\zeta^* = \min_{x_0 \in \mathcal{X}_0} \mathbb{E}\Bigg(&\inf_{x_1 \in \mathcal{X}_1(x_0, \xi_1)} F_1(x_1, \xi_1) + \mathbb{E}\Bigg(\cdots \\ &+\mathbb{E}\Bigg(\inf_{x_T \in \mathcal{X}_T(x_{0:T-1}, \xi_{1:T})} \gamma^{T-1} F_T(x_T, \xi_T)\Bigg)\Bigg)\Bigg)\end{aligned} \tag{15}$$

T is the number of time periods, $x_{0:t}$ is the collection of all decisions between 0 and t, ξ_t is a random outcome observable at time t, $\mathcal{X}_t(x_{0:t-1}, \xi_{1:t})$ is a decision set that depends on all decisions and random outcomes between times 0 and t, $F_t(x_t, \xi_t)$ is a cost function for time period t that depends on the decision and random outcome for time t, and γ is the discount rate. The time horizon T may be either finite or infinite.

There are no multi-stage solution methods that work well for all problems within a broad class, like convex problems or Markov decision processes. The decision sequence space is affected by the curse of dimensionality: the size of the space grows exponentially with T, the number of possible outcomes for ξ_t, and the size of the decision space each time period, $\mathcal{X}_t$. Most successful methods are tailored to problem subclasses with exploitable structure.

3.6 Genetic Algorithms

Genetic algorithms (GAs), introduced by Holland [35], are popular approaches to SO [73], mainly when it comes to global optimization (find the best solution among multiple local minima). The great interest in GAs seems to be due to their success in solving many difficult optimization problems. They represent a special case of the more general class of *evolutionary computation* algorithms [85]. As the name suggests, GA is loosely based on principles of natural evolution and survival of the fittest. Thus, the objective function is often referred to as the *fitness function* to emphasize the evolutionary concept of the fittest of a species. The essence of a GA is clearly summarized in [73], and is closely followed here.

GAs simultaneously consider multiple candidate solutions to the problem, and iterate by moving this population of solutions toward a global optimum. Specific values of x in the population are referred to as *chromosomes*. The central idea in a GA is to move a set of chromosomes from an initial collection of values to a point where the fitness function is optimized. Let N denote the population size (number of chromosomes). An essential aspect of GAs is the *encoding* of the N values of x appearing in the population. This encoding is critical to the GA operations and the associated decoding to return to x. Standard binary (0,1) bit strings have traditionally been the most common encoding method, but other methods include gray coding and basic computer-based floating-point representation of the real numbers in x.

The *selection* and *elitism* steps occur after evaluating the *fitness function* for the current population of chromosomes. A subset of chromosomes is selected for use as parents for the next generation. Here is where the principle of survival of the fittest arises, as parents are chosen according to their fitness value. Although the objective is to emphasize the fitter chromosomes in the selection process, it is important that the chromosomes with the highest fitness values are not given too much priority at the beginning of the optimization, as too much emphasis on the fitter can reduce the diversity necessary for an adequate search of the domain of interest, likely causing premature convergence in a local optimum. Hence, selection methods allow, with some nonzero probability, the selection of chromosomes that are suboptimal.

Many schemes have been proposed for the *selection process* of choosing *parents* for subsequent recombination. One of the most popular is *roulette wheel selection*. In this selection method, the fitness functions must be nonnegative on x. An individual's slice of a Monte Carlo-based roulette wheel is an area proportional to its fitness. The "wheel" is spun in a simulated fashion $N - N_e$ times and the parents are chosen based on where the pointer stops. Another popular approach is called *tournament selection*, in which chromosomes are compared in a "tournament", with the better chromosome being more likely to win. The tournament process is continued by sampling (with replacement) from the original population until a full complement of parents has been chosen. The most common tournament method is the binary approach, where one selects two pairs of chromosomes and chooses as the two parents the chromosome in each pair having the higher fitness value. Empirical evidence suggests that the tournament selection often performs better than roulette selection.

The *crossover operation* creates offspring of the pairs of parents from the selection step. A crossover probability P_c is used to determine if the offspring represents a blend of the chromosomes of the parents. If no crossover takes place, then the two offspring are clones of the two parents. If crossover does take place, then the two offspring are produced according to an interchange of parts of the chromosome structure of the two parents. The final operation is *mutation*. Because the initial population may not contain enough variability to find the solution via crossover operations alone, the GA also uses a mutation operator where the chromosomes are randomly changed. For the binary coding, the mutation is usually done on a bit-by-bit basis where a chosen bit is flipped from 0 to 1, or vice versa. Mutation of a given bit occurs with small probability P_m. Real-number coding requires a different type of mutation operator. That is, with a (0,1)-based coding, an opposite is uniquely defined, but with a real number, there is no clearly defined opposite. Probably the most common type of mutation operator is simply to add small independent normal (or other) random vectors to each of the chromosomes (the x values) in the population.

According to [74], there is no easy way to know when a SO algorithm (including GAs) has effectively converged to an optimum. An obvious way to stop a GA is to end the search when a number of evaluations of the fitness function is reached. Alternatively, termination can be done heuristically based on subjective and objective impressions about convergence. In the case where noise-free fitness measurements are available, criteria based on fitness evaluations may be more useful. See [74] for further details and references.

3.7 Other Optimization Techniques

Computational intelligence algorithms can be applied to a large set of smart grid optimization problems, obtaining acceptable near-optimal solutions in acceptable computation time. Neural networks, fuzzy systems, and evolutionary algorithms are the three major soft-computing paradigms for computational intelligence [85]. Evolutionary algorithms (genetic programming, evolutionary programming, particle swarm optimization, ant colony optimization) are stochastic search methods inspired by the Darwinian model. Neural networks are learning models based on the connectionist model. Fuzzy systems are a high level abstraction of human cognition. Neural networks and fuzzy systems are two major approaches to system modeling.

Concerning deterministic optimization methods, trust region methods have been employed in the search for globally convergent solvers [64, 72]. Recently, global optimization has drawn significant interest. Conic relaxation has been widely used for convexification of a problem to seek global solution. Exact relaxation occurs when the relaxed problem allows to find the solution to the original non-relaxed problem. SDP relaxations have been extensively applied to power systems [50, 51], since the first application proposal [41].

4 Optimization Applications in Smart Grids

In [32], a comprehensive review of optimization methods for optimal planning and integration of RES is presented. The main focus is on optimal placement and sizing of RES. In [60], MILP is used for modeling an energy management problem, since MILP allows to model the features of integrated DER, using integer and binary variables to represent decisions on the operation status of production systems, battery storage units, PEVs and smart appliances in smart homes of the microgrid. To solve the smart grid optimization problem of extended time horizon, two techniques are used: MILP and a *greedy* algorithm, for developing a hybrid technique to obtain an approximate global optimum. In [79], a model for optimal microgrid operation considers DER, environmental constraints and DSR. The microgrid operation cost is minimized without bringing discomfort to customers, effectively increasing the use of clean energy. The optimization problem is solved using a *genetic algorithm*.

Energy Storage Systems The decision on the use of a particular ESS technology should consider technical and economic aspects, such as the required rated power and energy capacity, scalability of the project, services that will be provided to the grid, and possible forms of payment. The benefits of ESS to the network are generally classified by their time scale [8]. Slower timescales are called energy applications, where large amounts of energy are supplied or drained from the grid. Provides functionalities like energy arbitrage, load leveling, peak shaving, and non spinning reserve, improving the flexibility of grid operation. Faster timescales are called power applications, and are often needed to support real-time control of power networks. ESSs can provide a wide range of services for power networks [8]:

- *Frequency regulation*: Support for the primary and secondary frequency control, providing fast frequency response and fine adjustments needed by the automatic generation control (AGC) signal [46].
- *Reduction of start/stop operations of large generators*: Reduce depreciation and high maintenance costs due to start/stop operations for large hydraulic and thermal generators that are dispatched to accommodate renewable intermittence.

- *Overload mitigation and investment deferral*: Defer investments in transmission lines and power transformers in regions that will not experience a significant flow increase in medium term analysis. With an aging energy infrastructure and a steady growth in demand, transmission upgrade deferral is a great benefit of ESS.
- *Energy arbitrage*: Perform electricity arbitrage, purchasing energy during off-peak hours and selling when demand is high. Potential revenue is a function of the hourly energy price and the efficiency of the ESS's roundtrip.
- *Energy time shift*: Decrease active power ramp rates related to the integration of massive renewable generation, mainly solar. Despite being closely related to energy arbitrage, which focus mainly on financial earnings, energy time shift products aim to provide the system with capabilities to handle uncertainties associated with demand and renewable generation.

According to [69], the rapid uptake of RES in the power grid leads to a demand in load shaping and flexibility. ESSs are key elements to provide solutions to these tasks. However, it should be observed a trade-off between the performance-objective of load shaping and the objective of having flexibility in storage for auxiliary services, which is linked to robustness and resilience of the grid. This issue is formulated as a MOO problem, which is resolved by an analysis of the Pareto frontier to quantify the trade-off between the non-aligned objectives, to balance them properly.

The problem of optimal sizing and placement of ESS can be addressed by several methods. In [80], a comprehensive review of optimal sizing and placement of ESS in distribution networks is presented. According to [80], the methods for optimal sizing and placement can be divided into three categories: analytical, mathematical and artificial intelligence methods. In the mathematical methods, LP, MILP and SOCP appear as the most cited techniques. Despite the diversity of techniques, due to the different system requirements and ESS technologies, several solutions can be obtained in general for the size and placement of ESSs in distribution networks [80]. In [82], optimal sizing is obtained using the Fourier-Legendre series expansion to describe the *state of energy* (SOE) in an approximately continuous form. The authors claim that their approach can effectively reduce the error caused by the SOE's discrete expression in size optimization, especially when the planning data is not sufficient to accurately describe the studied operational cycle.

Demand Side Response DSR has changed from an approach to deal with periods of peak demand during specific hours of a year, to a more general procedure in which customers change their consumption pattern in response to changes in the price of electricity [60]. DSR initiatives are commonly classified into two programs: *incentive-based program* (IBP) and *price-based program* (PBP). The IBP program allows utilities to manage customer consumption according to conditions established in contract, specially during peak hours. In the PBP program, customers act by changing their demands as the price of electricity varies.

With regard to microgrids [79], DSR may include DERs, such as variable RES (wind and solar), and controllable distributed resources, such as micro gas and diesel generation units, in addition to ESS. In [88], an optimization scheduling model that considers DER, ESS and DSR is proposed. The results indicate that the scheduling model establishes a coordinated operation of distributed generation, responsive loads and the economic goal of the network.

In [12], a set of users served by a single *load-serving entity* (LSE) is considered. The LSE acquires capacity a day ahead. When random renewable energy is obtained at the time of delivery, the LSE manages the user's load through real-time demand response and purchasing balancing power in the spot market to meet aggregate demand. Optimal supply procurement by the LSE and the consumption decisions by the users must be coordinated over two timescales, a day ahead and in real time, in the presence of uncertainty in supply. This problem is formulated as a *dynamic program* which maximizes the expected social welfare.

Management of Plug-In Electrical Vehicles The expected large population of PEVs in future distribution networks will create not only new challenges, but also new opportunities to increase the controllability of distribution systems. PEVs will be an important resource for distribution systems operators, providing services such as congestion relief and voltage regulation [43, 45]. According to [43], which presents comprehensive research on the active integration of PEVs to distribution networks, rather than being considered a passive asset, PEVs should be integrated as an active resource. The interaction between PEV and RES allows a simultaneous reduction in the dependence on fossil-fuels in electricity generation and in the transport sector.

In [45], a *genetic algorithm* is applied to increase the penetration of *photovoltaic* (PV) solar energy in distribution networks through the optimized management of PEV storage. In addition, to maximize their participation in ancillary services, PVs are allocated optimally through network feeders and buses. It is shown that PV penetration can be increased by 50% with 25% of PEV penetration in the selected distribution network. In [43], a *multi-objective optimization* approach for day-ahead PEV scheduling is proposed. As PEVs are commonly single-phase connected, they can significantly contribute to worsening the load imbalance in the distribution network. The approach in [43] uses an unbalanced optimal power flow to include constraints on which phase PEV can be connected. The formulation also includes voltage dependence on modeled residential loads, and voltage and flow limits.

Upgrade Deferral and Congestion Management Utility services including the transmission and distribution networks are mainly benefited by ESS through upgrade deferral of these networks, by providing resource adequacy and congestion relief. Through proper deployment of ESS, infrastructure upgrade can be delayed or entirely avoided providing economic benefits. They can also provide cheaper alternatives to generation upgrade and alleviate congestion in the networks during peak hours [37]. In [87], a method for determination of the optimal deployment of battery ESS for the purpose of deferral of feeder capacity upgrades is presented, together with determination of the economic consequences of such deferral.

In [7], an approach for congestion management in a smart grid is proposed. The approach considers a distribution grid interconnecting a number of flexible consumers. Each consumer is under the jurisdiction of one *balancing responsible party* (BRP), who buys energy at a day-ahead electricity market on behalf of the consumer. The BRP utilizes the flexibility of the consumers to move load in time, minimizing imbalance between consumed and purchased energy, avoiding trading balancing energy at unfavorable prices. The approach involves the solution of a convex optimization problem. Because sharing of information in competitive energy market is unlikely, the optimization problem is decomposed and solved distributed.

In [34], an approach for congestion management in smart grids through DSR is proposed. Two objectives, acceptable congestion and congestion cost, are optimized by choosing a mix of generation rescheduling and demand response of participating buses, minimizing the impact on revenues and customer satisfaction. The approach employs the meta-heuristic *ant colony optimization* to optimize the individual options and uses a *fuzzy satisfying* technique to choose the best compromise solution from the set of Pareto optimal solutions.

Economic Dispatch and Loss Minimization The goal of optimal ADN operation is usually to ensure economical, efficient and secure operation through the coordination of DERs and network topology. In [36], ADN active power loss is minimized using the power output of distributed generation, the status of tie-lines switches and the controllable loads as decision variables. In [24], coordinated dispatch of active and reactive power through optimal control of tap changers, reactive power compensation and charge/discharge power of ESS, is proposed. The approach uses a branch flow model of relaxed optimal power flow to formulate a mixed integer SOCP problem.

Expansion Planning of ADNs Important challenges for the operation, planning and optimization of ADNs are discussed in [48, 66]. In contrast to existing passive distribution networks, in which expansion and planning analysis are based on snapshots of the worst-case scenarios, planning studies on future ADN would have to consider time-dependent and operational aspects to obtain cost-effective alternatives.

ADN expansion planning is discussed in several works [48, 66, 70, 78]. Traditional distribution networks have been planned with the goal of meeting further increases in peak demand, while maintaining the quality and reliability of energy supply. As these distribution networks become active, planning engineers must take into account the new *advanced metering infrastructure* (AMI) and massive integration of DERs. Expansion planning is an important issue in the studies of distribution network optimization, including network reconfiguration.

In [70], a planning model that uses MILP to minimize investments and operational costs in ADNs is proposed. The approach considers replacing and adding circuits, and improving the power supply reliability by addition of ESS. The optimal daily dispatch of ESS is obtained using the locational marginal prices at substation nodes. In addition, topological radiality constraints are considered, requiring that the topology provided by the model respects the basic rules of the distribution network operation.

In [78], a rating index system is established based on economic, environmental protection, voltage quality and network security indicators. Then, a multi-objective planning approach for ADN, which includes ESS operation strategies, is proposed. Considering that the bulk network is mainly supplied by fossil fuels plants, the environmental benefits are quantified by the reduction in the purchase of electricity after adding DER to the distribution network. Despite interesting discussions about the proposed multi-objective planning model, no further details are provided on the optimization methods used.

The massive integration of DER will greatly modify the operation and planning of transmission and distribution networks. In [57], the implications for the stability of connecting ADN to transmission networks are investigated. As observed, an ADN can operate in islanded mode, so its disconnection from the transmission grid can be considered a disturbance in which an equivalent load or generation is lost. Moreover, the results presented indicate that full dynamic modeling of distribution network may be necessary for short-term stability studies, while distribution network equivalents are sufficient for long-term stability analysis.

In [84], a charging-discharging operation strategy of ESS in the context of ADN planning is proposed. The ESS optimal operation focuses on energy arbitrage and peak load shifting. In [83], an approach for optimal reconfiguration of distribution networks in real-time is proposed. For cost minimization, the optimal scheduling strategy considers network topology, distributed generation, and responsive loads. The network reconfiguration problem is solved using *particle swarm optimization*.

4.1 Interdisciplinary Research Collaboration

The text has so far discussed several optimization applications in smart grids. The modern grids, involving more operating resources, have introduced new decision variables, objectives and operating constraints, such that grid optimization models are becoming increasingly complex, challenges to problem modeling and solution. Widespread use of intermittent RES introduces uncertainties in energy supply, while increasing use of PEVs introduces uncertainties in demand. Therefore, *stochastic optimization* is growing fast in importance, since stochastic models are suitable to characterize the randomness of RES, buffer effect of ESSs and PEVs mobility. With more operating resources to control, smart grid planning often involves multiple conflicting objectives, so that *multi objective optimization* turns crucial. The number of discrete-integer variables in the models has also increased. All of these features lead to increasingly complex problems. This scenario requires power engineers with expertise in classical optimization methods like LP, ILP, MILP, and NLP, to expand knowledge into stochastic optimization, dynamic programming, game theory, second-order cone programming, semidefinite programming, etc. Computational intelligence algorithms, already popular in power system optimization, are also essential. The development of the computational tools for smart decision-making in automated manner will be possible only with the joint collaboration of experts on advanced optimization, power system modeling, software development, etc.

5 Conclusions

By incorporating advanced information technologies, control and automation, new technologies of energy production and energy storage, mechanisms for effective customer participation, etc., smart grids are able to develop the perfect balance among reliability, availability, efficiency and cost, with benefits for all participants involved: utilities, customers, and the power system as a whole. Given the diversity of energy sources with individual characteristics, effective demand management instruments, distributed generation resources and energy storage, etc., along with the complex operational constraints introduced, there are many opportunities for optimization of smart grids, to get the best out of the grid. This chapter has outlined several of these opportunities, and presented the most frequently used techniques for continuous and discrete optimization, optimization under uncertainty, multi-objective optimization and global optimization, to help the interested reader to identify open research topics.

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Load Flow in Microgrids

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Abstract Microgris (MGs) may operate in two modes: the islanded and grid-connected. In grid-connected, the MGs operate connected to the main grid, and its possible to import or export reactive and active power from the main grid. In islanded mode, the MG must maintain its power balance, supplying the consumers with its generation. In both operation modes, the load flow analysis is essential for any planning or operation studies. In this context, this chapter aims to present the power flow formulation in both operation modes, highlighting the mathematical considerations, balance equations and the peculiarities of the methods available in the literature. To represent an MG, a modified test system composed of 37 buses is employed in order to exemplify the power flow in both modes. The test system presents a low load imbalance. Thus, the three-phase power flow is compared with the single-phase power flow in order to demonstrate the application of positive sequence in some MGs. In grid-connected mode, the main grid is represented by the swing bus. However, in islanded mode, the swing bus is not present, and the frequency is considered as a state variable of the problem because generally the generation in an MG is formed predominantly by small-scale units, which may not be able to guarantee that the frequency remains constant.

Keywords Microgrids · Power flow · Active distribution networks · Grid-connected · Islanded operation · Load flow

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1 Introduction

Load flow is an essential tool for any study in the expansion, planning, and operation issues of electric power systems. The determination of the system's state, that is, voltage and phase angle of all buses, enables the operator to know the lines loading, generation dispatch, system's stability robustness, and other variables of interest from a known operation point.

For large power systems, characterized mainly by long transmission lines, the Newton–Raphson Method (NRM) is commonly accepted in traditional literature as an efficient tool for power flow analysis. However, it finds some convergence limitations in systems with radial topology and low X/R ratio, which are predominant characteristics in distribution systems.

To overcome such problems, many authors use the backward-forward sweep (BFS) method for power flow analysis in distribution systems, as shown in [1, 2]. This method has good computational performance and simplicity of implementation. The main characteristic of the BFS method is to determine the voltage and phase angles of high unbalanced systems, something that the traditional Newton–Raphson method presents specific convergence difficulties [3].

The BFS still presents convergence difficulties when the system is highly meshed, or when the presence of Distributed Generators (DG) is large or in stressed load scenarios. For these scenarios, the Newton–Raphson current injection (NRCI) algorithm can be a solution. The NRCI can solve unbalanced three-phase meshed systems, additionally, the Jacobian matrix changes little during the iteration process.

Typically, the Microgrids (MG) have the characteristics of a distribution system; however, the MGs can have two operating modes: grid-connected and islanded. In the grid-connected mode, the main grid maintains the frequency and voltage of the MG. In the islanded mode, the MG operates disconnected from the main grid. Then, the DGs of the MG maintain the frequency and the voltage.

The power flow in grid-connected mode can be treated as the power flow in the distribution system. Thus, BFS and NRM with modifications can be applied. However, MGs and smart-grids are active distribution networks, with the presence of new components and controls that can be considered in power flow, like DGs and their operation modes, electric vehicles, energy storage devices, demand-side management, and smart voltage control devices [4–6].

In the islanded microgrids context, references [7–11] consider the generators' droop equations in the algebraic formulation and use the NR algorithm to solve the load flow problem. Reference [12] proposes a methodology for power flow in MR which the advantage over the others is the absence of a swing bus in its formulation. This characteristic is understood as an essential consideration, as it is assumed that there may not be large generators to keep the terminal voltage constant in an eventual MR islanding. The literature presents some tools that can complement the method used in [13], including the axis rotation and the Levenberg–Marquardt method, to overcome the NRM convergence problem resulting from the low X/R ratio.

This chapter presents to the reader a mathematical formulation behind the implementation of a power flow algorithm for microgrids, showing the main features in each operation mode, i.e., islanded and grid-connected. Some peculiarities differ from those used in traditional systems and will be explained to the reader step by step in the next sections. The implementation of the power flow is applied to a slightly unbalanced MG; thus, the single-phase (positive sequence) representation is presented. The hypothesis of the balanced three-phase power flow (positive sequence) is that the system imbalances can be neglected. However, in some cases, the unbalances of loads and the presence of non-three-phase branches cannot be ignored [14]. Therefore, a comparison between the results of the balanced and unbalanced power flow formulation applied to a slightly unbalanced MG is presented.

2 Load Flow in Active Distribution Networks

2.1 A Case Study

In order to show the characteristics of each operation mode, simulations are carried out in the next subsection using the system shown in Fig. 1. Table 1 shows the generation parameters of the system. More details on this system can be found in [15].

2.2 Grid-Connected Operation

In the grid-connected mode, the MG power flow is like the power flow in distribution systems [4–6, 16]. Then, the conventional BFS and NRM with modifications can be applied. However, some considerations must be made.

- The Point of Common Coupling (PCC) of the MG is considered the swing bus;
- The PCC frequency and voltage are constant because the main grid is robust to keep these values fixed.
- The operation modes of the DGs must be considered (PV, droop, or PQ).

The NRM for MGs operating in grid-connected mode is presented in this section, considering in the formulation the points explained above.

2.2.1 System's Representation

The first step to solve the power flow is to identify each bus type, thus determining the unknown and know variables in the system. Four types of buses are present in grid-connected MG power flow:

Fig. 1 Test system

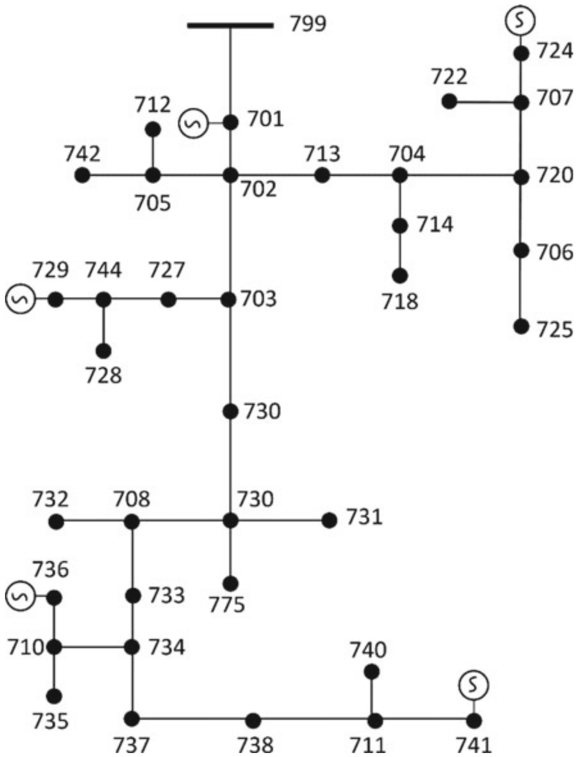

Table 1 Microgrid generation parameters

Bus number	m(Hz/kW)	n(kV/kVA)r	$P_{\max}$(kW)	Q_{max}(kVAr)	Q_{min}(kVAr)
701	8.4×10^{-4}	1.5×10^{-3}	1000	900	−900
736	8.4×10^{-4}	1.5×10^{-3}	1000	900	−900
729	8.4×10^{-4}	1.5×10^{-3}	1000	900	−900
741	6×10^{-4}	9×10^{-4}	1300	800	−800
724	6×10^{-4}	9×10^{-4}	850	600	−600

(1) Swing bus: as in conventional power flow, the voltage magnitude and angle are specified for this bus. Therefore, the PCC is considered as the swing bus;

(2) PQ bus: the active and reactive powers are specified. This bus can be used to represent the loads or intermittent generation. When representing the intermittent generation, the concept of "negative loads" can be used when the generation is higher than the load of the bus. Figure 2 outlines the concept of a negative load.

A photovoltaic system and a battery energy storage system (BESS) are connected to a generic bus with a load in Fig. 2. Note the flow direction for each element.

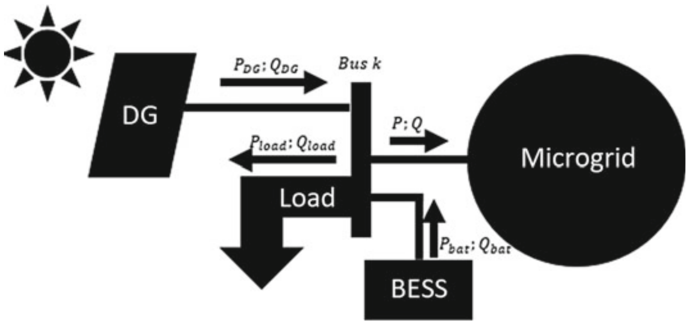

Fig. 2 Negative load representation

Depending on the total load and generation values, this bus supplies or absorbs power from the network. The net load of the bus takes the form given by (1) and (2):

$$P_k = P_{load_k} - P_{DG_k} \pm P_{Bat_k} \tag{1}$$

$$Q_k = Q_{load_k} - Q_{DG_k} \pm Q_{Bat_k} \tag{2}$$

where

P_k and Q_k	net active and reactive powers at bus k, respectively;
P_{load_k} and Q_{load_k}	active and reactive power of the load connected at bus k, respectively;
P_{DG_k} and Q_{DG_k}	active and reactive power of the non-dispatchable Distributed Generation connected at bus k, respectively;
P_{bat_k} and Q_{bat_k}	active and reactive power of the BESS connected at bus k, respectively;

Equations (1) and (2) are valid for every bus with a non-dispatchable generation or BESSs operating in constant power mode, with or without a load. In addition to (1) and (2), the BESS's power varies according to the charging and system state. The BESSs discharge when there is a lack of generation and charge if there is excess.

(3) PV bus: active power and the voltage magnitude are known;
(4) VF bus: the dispatchable DGs in MGs normally operate in PQ or PV mode, however, it is possible to the DG operates in Droop mode, wherein both active and reactive generation depend on the frequency and the terminal voltage.

The droop control can be expressed through (3) and (4).

$$\omega = \omega_{\text{ref}} - m_k P_{g_k} \tag{3}$$

$$V_k = V_{ref_k} - n_k Q_{g_k} \tag{4}$$

where

m_k and n_k	active and reactive droop coefficients, respectly;
ω and V_k	system's frequency and voltage at bus k, respectively;
ω_{ref} and V_{ref_k}	reference values of frequency and voltage at bus k, respectively;
P_{g_k} and Q_{g_k}	active and reactive power generation at bus k, respectively.

The active and reactive power generation in (3) and (4) can be represented as follows:

$$P_{g_k} = \frac{\omega_{ref} - \omega}{m_k} \tag{5}$$

$$Q_{g_k} = \frac{V_{ref}^k - V^k}{n_k} \tag{6}$$

In (5) the frequency of the grid is constant. Thus, the active power in the Droop bus is also constant [4]. In (6) the voltage at bus k is a function of the operating scenario. Thus, the reactive power will depend on the voltage at bus k. The same representation can be used to the DGs that operate in reactive power support mode via volt-var.

Table 2 summarizes the relationship between the state variables and the bus types that make up a microgrid in grid-connected mode.

The VF mode in Table 2 can represent the DC/AC power electronic converter operating in reactive power support mode via volt-var.

As the MG in Fig. 1 is slightly unbalanced, a simplification can be performed to transform this system into a balanced equivalent. To this end, the recommendations presented in [17] and listed below are adopted in this section:

- The line impedance is given by only the positive sequence component;
- Loads distributed along a feeder are considered as concentrated, and they are equally divided between the buses of the feeder.

For the representation of the network in positive sequence components, the Fortescue Theorem is used, which relates the matrix of phase impedances (own and mutual) of a transmission line with its symmetric component matrix, thus obtaining the line's positive sequence component. This relationship is given by (7).

$$[\boldsymbol{Z}^{\boldsymbol{+-0}}] = [\boldsymbol{A}][\boldsymbol{Z}^{\boldsymbol{abc}}][\boldsymbol{A}]^{-1} \text{ and } [\boldsymbol{B}^{\boldsymbol{+-0}}] = [\boldsymbol{A}]^{-1}[\boldsymbol{B}^{abc}][\boldsymbol{A}] \tag{7}$$

Table 2 Type of buses in grid-connected mode

	Type of bus			
	Swing	PQ	PV	VF
Known	V, δ	P, Q	P, V	P
Unknown	P, Q	V, δ	Q, δ	Q_g, V, δ

where

$[\boldsymbol{Z}^{+-0}]$ and $[\boldsymbol{B}^{+-0}]$	components sequence matrix of series impedance and shunt susceptance, respectively;
$[\boldsymbol{Z}^{abc}]$ and $[\boldsymbol{B}^{abc}]$	matrix of series impedance and shunt susceptance, respectively;
$[\boldsymbol{A}]$	Fortescue transforming matrix, defined as $\begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$; $a = 1\measuredangle 120°$.

2.2.2 Load Flow Equations

For simplicity, the representation of a balanced equivalent system is presented. The power flow in the grid-connected mode can be represented as follows:

$$\boldsymbol{f}(\boldsymbol{x}) = 0; \boldsymbol{x} = \begin{bmatrix} \boldsymbol{\delta} \\ \boldsymbol{V} \end{bmatrix}; \boldsymbol{f} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{8}$$

where

$\boldsymbol{f}$	set of system's load flow equations;
$\boldsymbol{x}$	state variables of load flow;
$\boldsymbol{\delta}$	voltage angles;
$\boldsymbol{V}$	voltage magnitudes;
$\boldsymbol{\Delta P}$, $\boldsymbol{\Delta Q}$	active and reactive power mismatches, respectively;

Note that the power flow representation in (8) is not different from the conventional NRM power flow. The procedures for the power flow calculation are given as follows:

Step 1: Calculate the admittance matrix ($\boldsymbol{Y_{bus}}$) of the system;

Step 2: Initialize the states of $\boldsymbol{V}$ and $\boldsymbol{\delta}$, set counter $j = 0$;

Step 3: With the states of $\boldsymbol{V}^j$ and $\boldsymbol{\delta}^j$, calculate the power mismatches, through (9) and (10);

$$\Delta P_k = \left(P_{g_k} - P_k\right) - P_{calc_k}; k = (1, 2, 3 \ldots nb) \tag{9}$$

$$\Delta Q_k = \left(Q_{g_k} - Q_k\right) - Q_{calc_k}; k = (1, 2, 3 \ldots nb) \tag{10}$$

where

ΔP_k and ΔQ_k	mismatches of active and reactive powers at bus k, respectively;
P_k and Q_k	active and reactive net powers at bus k, respectively;
P_{calc_k} and Q_{calc_k}	calculated active and reactive powers at bus k, respectively;

P_{g_k} and Q_{g_k} active and reactive generation from dispatchable units in VSI mode at bus k, respectively;
nb number of buses.

Note that, in (10) if the bus is operating in reactive power support mode via volt-var or in VF mode, the Q_{g_k} must be calculated through (6).

Step 4: With the states of $\boldsymbol{V}^j$ and $\boldsymbol{\delta}^j$, it is calculated the Jacobian Matrix of the system. The Jacobian Matrix can be represented as follows:

$$\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}} = [\boldsymbol{J}] = \begin{bmatrix} \left[\frac{\partial \Delta \boldsymbol{P}}{\partial \boldsymbol{\delta}}\right] & \left[\frac{\partial \Delta \boldsymbol{P}}{\partial \boldsymbol{V}}\right] \\ \left[\frac{\partial \Delta \boldsymbol{Q}}{\partial \boldsymbol{\delta}}\right] & \left[\frac{\partial \Delta \boldsymbol{Q}}{\partial \boldsymbol{V}}\right] \end{bmatrix} \tag{11}$$

$$\frac{dP_k}{d\delta_m} = \begin{cases} -\sum\limits_{k=1k\neq m}^{nb} V_k V_m |Y_{km}| \sin(\delta_{km} - \theta_{km}) \ if \ k = m \\ V_k V_m |Y_{km}| \sin(\delta_{km} - \theta_{km}) \qquad if \ k \neq m \end{cases} \quad \forall\, k \ and \ \forall\, m \neq 1 \tag{12}$$

$$\frac{dQ_k}{d\delta_m} = \begin{cases} \sum\limits_{k=1k\neq m}^{nb} V_k V_m |Y_{km}| \cos(\delta_{km} - \theta_{km}) \ if \ k = m \\ -V_k |Y_{km}| \cos(\delta_{km} - \theta_{km}) \qquad if \ k \neq m \end{cases} \quad \forall\, k \ and \ \forall\, m \neq 1 \tag{13}$$

$$\frac{dP_k}{dV_m} = \begin{cases} 2V_k |Y_{kk}| \cos(\theta_{km}) + \sum\limits_{k=1k\neq m}^{nb} V_k V_m |Y_{km}| \cos(\delta_{km} - \theta_{km}) \ if \ k = m \\ V_k V_m |Y_{km}| \cos(\delta_{km} - \theta_{km}) \qquad if \ k \neq m \end{cases} \tag{14}$$

$$\frac{dQ_k}{dV_m} = \begin{cases} -2V_k |Y_{kk}| \cos(\theta_{km}) + \sum\limits_{k=1k\neq m}^{NB} V_k V_m |Y_{km}| \sin(\delta_{kn} - \theta_{km}) \ if \ k = m \\ V_k |Y_{km}| \sin(\delta_{km} - \theta_{km}) \qquad if \ k \neq m \end{cases} \tag{15}$$

where

$|Y_{kk}|$ Absolute value of the diagonal element of the admittance matrix;
$|Y_{km}|$ Absolute value of the off diagonal element of the admittance matrix;
θ_{km} Angle of the element $|Y_{km}|$ of the admittance matrix.

Note that, the Jacobian Matrix must consider the generate reactive power Eq. (6)—for the bus that is operating in reactive power support mode via volt-var or in VF mode. Thus, the derivate of the reactive power by the voltage for the VF bus is given as follows:

$$\frac{dQ_k}{dV_m} = \begin{cases} 2V_k |Y_{kk}| \cos(\delta_{kk}) + \sum\limits_{k=1k\neq m}^{NB} V_k V_m |Y_{kn}| \cos(\delta_{kn} - \theta_{kn}) + \frac{1}{n_k} \ if \ k = m \\ V_k |Y_{kn}| \cos(\delta_{kn} - \theta_{kn}) \qquad if \ k \neq m \end{cases} \tag{16}$$

Step 5: The new increments of V and δ, must be calculated through:

$$\Delta \boldsymbol{x}^j = \begin{bmatrix} \Delta \boldsymbol{\delta}^j \\ \Delta \boldsymbol{V}^j \end{bmatrix} = \boldsymbol{J}^{-1} \begin{bmatrix} \Delta \boldsymbol{P} \\ \Delta \boldsymbol{Q} \end{bmatrix} \tag{17}$$

Step 6: Upgrade the states of $\boldsymbol{x}^{j+1} = \boldsymbol{x}^j - \Delta \boldsymbol{x}^j$.

Step 7: Evaluate the increments $\Delta \boldsymbol{x}^j$, if one of these is higher than a tolerance e, go to **Step 3**, otherwise, the algorithm ends.

To illustrate the power flow in the connected mode, let's consider the system presented in Fig. 1. Wherein, all dispatchable generators initially operate in VF mode with the reference values $V_{ref} = 1$ *p.u.* and $\omega_{ref} = 60$ Hz. The grid frequency operates at 60 Hz and the voltage in the substation at 1 $p.u.$

The voltage and generation profile for the base case are given in Figs. 3 and 4. Due to the droop mode, the converter will change the reactive power generation according to the terminal voltage and the droop coefficient (n), which can be observed in Fig. 4. In this figure, the reactive power generation will differ in each converter since the voltage is a local variable. The DGs of the buses 701 and 724 are dispatching the maximum reactive power, and the other DGs still have available capacity.

Since the DGs operate in VF mode and the frequency of the system is 60 Hz, the DGs active power will be zero. Typically, the converters do not operate in VF mode when in grid-connected operation, since the frequency is maintained for the main

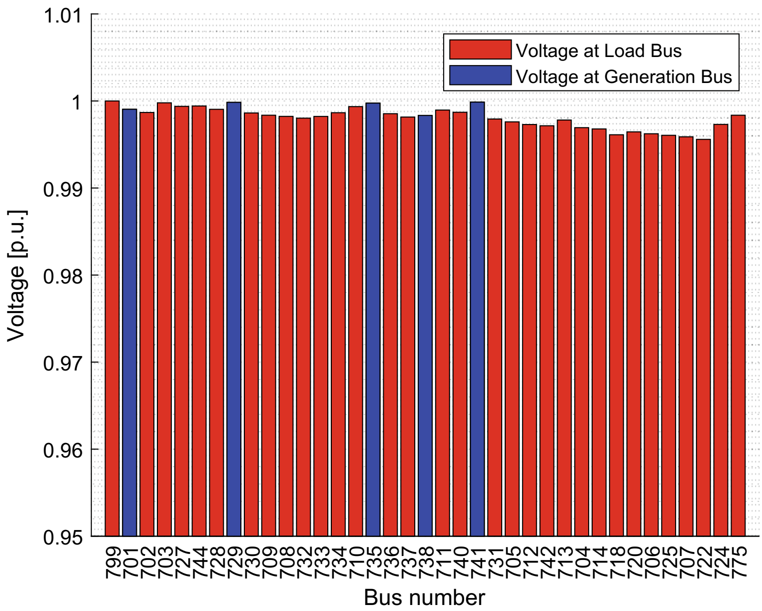

Fig. 3 Grid-connected voltage profile

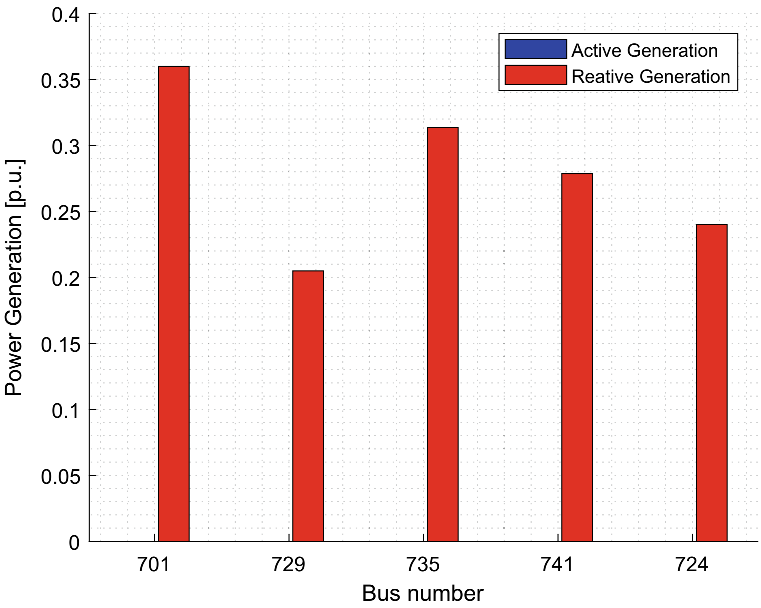

Fig. 4 Grid-connected generation profile

grid. However, the voltage droop can be applied in the converters to support the MG voltage regulation.

Table 3 gives the total generation and load for the system. It can be seen that the main grid consumes the surplus of reactive power generated by the MG. This feature occurs due to the characteristics of the distribution system and the low X/R ratio. Thus, the voltage regulation in each bus depends not only on the reactive power but also on the active power. Therefore, the DG must generate much reactive power to control the voltage at a specified value.

The results presented above considers the system balanced (positive sequence). However, balanced representation is not always sufficient in distribution systems. Thus, to compare the positive sequence representation result with the unbalanced power flow, let's consider the same system presented in Fig. 1 with all DGs disconnected. The power flow of the balanced version of the system is achieved through the NR algorithm, while the unbalanced version is achieved through the NRCI algorithm

Table 3 Generation and load at grid-connected operation

	Active	Reactive
Load [p.u.]	0.9828	0.4808
Generation [p.u.]	0	1.3968
Main grid [p.u.]	1.0288	−0.8815

presented in [18]. The NRCI power flow uses the voltage in the rectangular representation and the current mismatches instead of the power mismatches. The voltage increment in the NRCI power flow is calculated by (18).

$$\begin{bmatrix} \Delta \boldsymbol{I}_{m1}^{abc} \\ \Delta \boldsymbol{I}_{r1}^{abc} \\ \hline \Delta \boldsymbol{I}_{m2}^{abc} \\ \Delta \boldsymbol{I}_{r2}^{abc} \\ \hline \cdots \\ \Delta \boldsymbol{I}_{mn}^{abc} \\ \Delta \boldsymbol{I}_{rn}^{abc} \end{bmatrix} = \begin{bmatrix} \boldsymbol{J}_{11} & \boldsymbol{J}_{12} & \cdots & \boldsymbol{J}_{1n} \\ \boldsymbol{J}_{21} & \boldsymbol{J}_{22} & \cdots & \boldsymbol{J}_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \boldsymbol{J}_{n1} & \boldsymbol{J}_{n2} & \cdots & \boldsymbol{J}_{nn} \end{bmatrix} \cdot \begin{bmatrix} \Delta \boldsymbol{V}_{r1}^{abc} \\ \Delta \boldsymbol{V}_{m1}^{abc} \\ \hline \Delta \boldsymbol{V}_{r2}^{abc} \\ \Delta \boldsymbol{V}_{m2}^{abc} \\ \hline \cdots \\ \Delta \boldsymbol{V}_{rn}^{abc} \\ \Delta \boldsymbol{V}_{mn}^{abc} \end{bmatrix} \tag{18}$$

$$\boldsymbol{J}_{ki} = \begin{bmatrix} \frac{\partial \Delta \boldsymbol{I}_{mk}^{abc}}{\partial \boldsymbol{V}_{ri}^{abc}} & \frac{\partial \Delta \boldsymbol{I}_{mk}^{abc}}{\partial \boldsymbol{V}_{mi}^{abc}} \\ \frac{\partial \Delta \boldsymbol{I}_{rk}^{abc}}{\partial \boldsymbol{V}_{ri}^{abc}} & \frac{\partial \Delta \boldsymbol{I}_{rk}^{abc}}{\partial \boldsymbol{V}_{mi}^{abc}} \end{bmatrix} \tag{19}$$

where

$\Delta \boldsymbol{I}_{ri}^{abc}$ and $\Delta \boldsymbol{I}_{mi}^{abc}$	columns vectors for the real and imaginary current mismatches of the i^{th} bus for each phase;
$\Delta \boldsymbol{V}_{ri}^{abc}$ and $\Delta \boldsymbol{V}_{mi}^{abc}$	columns vectors for the real and imaginary voltage increments of the i^{th} bus for each phase;
$\boldsymbol{J}_{ki}$	element of the Jacobian matrix;

The voltage results for the NRCI algorithm is presented in Fig. 5. The NRCI algorithm calculates the voltages for each phase, thus Fig. 6 presents only the positive sequence for both algorithms. Note that the voltage calculated in the NR algorithm is very similar to the positive sequence voltage calculated by the NRCI algorithm, wherein a maximum error of 0.05% is achieved between the results.

For an unbalanced system with low load imbalance as the MG in Fig. 1, the presented simplification can be performed. However, for a system with high load imbalance or single-phase branches, this simplification cannot be performed. Thus, the NRCI or the three-phase BFS algorithms must be applied to solve the power flow. The BFS algorithm can be applied for radial systems, but the NRCI has a better convergence rate than the BFS algorithm for very meshed systems.

2.3 Islanded Operation

Microgrids are electrical systems that have particular operational characteristics, mainly in islanded mode. Consequently, the traditional power flow via NRM needs to be modified to be applicable in this operation mode. The main modifications are presented below [9–11]:

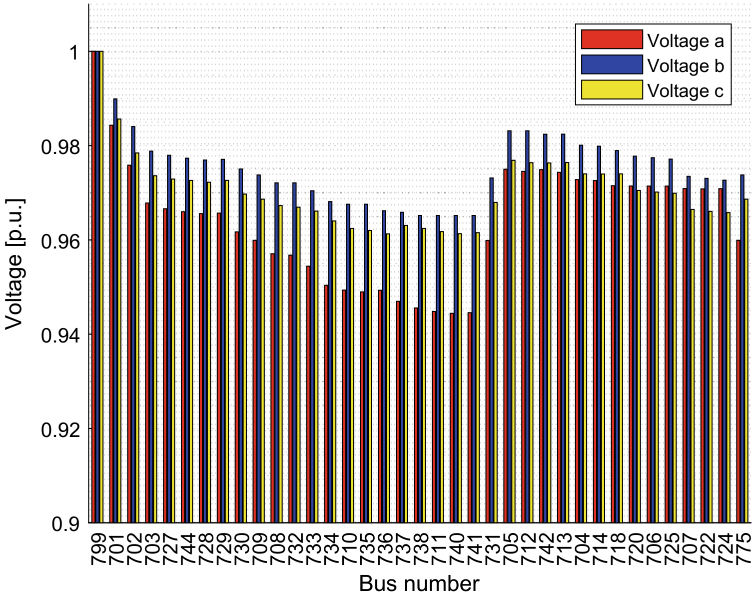

Fig. 5 Grid-connected voltage profile for both NRCI algorithm

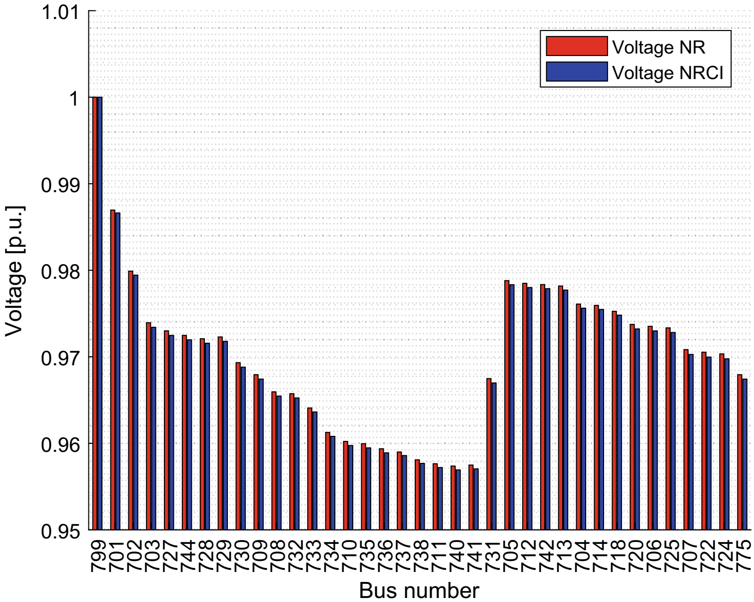

Fig. 6 Grid-connected voltage profile for both NR and NRCI algorithms

- There is no swing bus since the generation is a predominant small-scale. Therefore, an infinite bus cannot be used for this purpose;
- Distributed Generators may have limited capability and reduced inertia, which compromises the maintenance of voltage and frequency at constant values;
- Any variation in the demand may lead the system to voltage and frequency deviations;
- The distribution lines have a predominance of resistance over inductive impedance;
- There is a high level of generators that cannot be considered as dispatchable units.

A Modified Newton–Raphson Method (MNRM) to solve the power flow problem for islanded microgrids is then presented throughout this section. The MNRM considers the combination of the generators' primary control with the convergence process of traditional NRM. This methodology is based on the work proposed in [9].

2.3.1 System's Representation

The first step in power flow analysis is to identify each type of bus. Since the microgrid's characteristics are significantly different from those of transmission systems, three types of buses are adopted in the MNRM. These buses define the unknown variables of the problem, as described in Sect. 2.3.1.

1. VF bus: both active and reactive power generation is dependent on frequency and terminal voltage, respectively. These values are updated in each load flow iteration as functions of new frequency and voltage values. This behavior can be expressed through the droop control, represented by (3) and (4). The main difference from the VF bus in grid-connected mode is that the active power generation is now unknown.
2. PV bus: active power generation and the terminal voltage are known. This PV bus is identical to that used in the traditional power flow for transmission systems. Reactive power generation is a function of the operating scenario since it must always be defined to maintain the terminal voltage;
3. PQ bus: commonly used to represent the load buses, this bus has the active and reactive powers specified. The voltage magnitude and phase angle are unknown. Additionally, this bus can be used for an intermittent generation when the unit supplies the demand in the concept of "negative loads," i.e., with a constant power factor [19]. In summary, Table 4 shows the relationship between the variables and the types of buses in a microgrid. The absence of a swing bus is

Table 4 Type of buses in islanded mode

	Type of bus		
	PQ	PV	VF
Known	P, Q	P, V	–
Unknown	V, δ	Q, δ	P_g, Q_g, V, δ

highlighted here, as well as the fact that the IEEE Guide for Design, Operation, and Integration of Distributed Resources in Island Systems with Electric Power Systems and Standard on Smart Inverters reports do not advise the use of converters in PV mode when the system operates islanded from the main network [12].

In addition to the buses shown in Table 4, converters that operate in reactive power support mode via volt-var can be easily implemented based on the VF bus, having only the active power specified [2]. Besides, any bus can assume the angular reference of the system. Here we assume as reference the bus that performs the coupling with the main system in grid-connected operation mode.

2.3.2 Load Flow Equations

In general, traditional power flow methods consider four main variables for each bus: voltage magnitude and angle, active and reactive power. Some of these variables are known, while others are unknown (Table 4).

Here, both the reference bus voltage and the system frequency are treated as unknown variables in the power flow formulation. As shown in [9], the power flow problem is modeled assuming the frequency and reference bus voltage as state variables in addition to the variables traditionally considered, as shown in (20).

$$f(\boldsymbol{x}) = 0;\ x = \begin{bmatrix} \boldsymbol{\delta} \\ \boldsymbol{V} \\ V_1 \\ \omega \end{bmatrix};\ \boldsymbol{f} = \begin{bmatrix} \boldsymbol{\Delta P} \\ \boldsymbol{\Delta Q} \\ \Delta Q_{sys} \\ \Delta P_{sys} \end{bmatrix} \tag{20}$$

where

$\boldsymbol{f}$	set of system's load flow equations;
$\boldsymbol{x}$	state variables of load flow;
$\boldsymbol{\delta}$	voltage angles;
$\boldsymbol{V}$	voltage magnitudes of all buses;
V_1	voltage magnitude at reference bus;
ω	frequency of the system;
$\boldsymbol{\Delta P}, \boldsymbol{\Delta Q}$	active and reactive power mismatches of the buses, respectively;
$\Delta Q_{sys}, \Delta P_{sys}$	reactive and active power mismatches of the entire system, respectively;

The method considers the traditional mismatches of the power balance in each bus. The net scheduled power is calculated as given below.

$$\Delta P_k = \left(P_{g_k} - P_k\right) - P_{calc_k};\ k = (1, 2, 3 \ldots nb) \tag{21}$$

$$\Delta Q_k = \left(Q_{g_k} - Q_k\right) - Q_{calc_k};\, k = (1, 2, 3 \ldots nb) \tag{22}$$

where,

ΔP_k and ΔQ_k	mismatches of active and reactive powers at bus k, respectively;
P_k and Q_k	active and reactive net load at bus k, respectively;
P_{calc_k} and Q_{calc_k}	calculated active and reactive powers at bus k, respectively;
P_{g_k} and Q_{g_k}	active and reactive generation from dispatchable units in VSI mode at bus k, respectively.

The critical point is to consider the active (P_g) and reactive (Q_g) power generation as frequency and voltage-dependent in the iterative process. In the VF type bus, the generation of active and reactive power is calculated based on the controllers' droop characteristics, as shown in (5) and (6). Note that ω and V_k are power flow state variables. Therefore, the generation is updated until the method converges.

The scheduled power is expressed by (23) and (24):

$$P_{calc_k} = |V_k| \sum_{n=1}^{nb} \left|Y_{kn}^{+}\right| |V_n| \cos(\delta_k - \delta_n - \theta_{kn}^{+}) \tag{23}$$

$$Q_{calc_k} = |V_k| \sum_{n=1}^{nb} \left|Y_{kn}^{+}\right| |V_n| \sin(\delta_k - \delta_n - \theta_{kn}^{+}) \tag{24}$$

being $\left|Y_{kn}^{+}\right|$ and θ_{kn}^{+} the magnitude and angle of the positive sequence equivalent admittance between bus k and n; nb the number of buses and ng the number of generators. Note that, differently from grid-connected mode, the terms of Y_{kn}^{+} are not constant in islanded situations. The reason is the frequency, which changes according to the operation point and the reactive impedance is a function of it.

Concerning the system's power mismatches, two equations are considered, as shown in (25) and (26). They are the difference between what is generated and what is consumed within the system and the losses.

$$\Delta Q_{sys} = \left(\sum_{k=1}^{nb} Q_{load_k} + Q_{loss}\right) - \sum_{k=1}^{ng} Q_{g_k} \tag{25}$$

$$\Delta P_{sys} = \left(\sum_{k=1}^{nb} P_{load_k} + P_{loss}\right) - \sum_{k=1}^{ng} P_{g_k} \tag{26}$$

In such a way, the lines' losses can be calculated as exposed in (27) and (28).

$$P_{loss} = \frac{1}{2} \sum_{k=1}^{nb} \sum_{n=1}^{nb} \Re\left(Y_{kn}\left(V_k^{*} V_n + V_n^{*} V_k\right)\right) \tag{27}$$

$$Q_{loss} = -\frac{1}{2}\sum_{k=1}^{nb}\sum_{n=1}^{nb}\Im\left(Y_{kn}\left(V_k^*V_n + V_n^*V_k\right)\right) \tag{28}$$

According to Newton's method, the estimate of the new vaslues in $(t + 1)$ is calculated as:

$$\boldsymbol{x}^{t+1} = \boldsymbol{x}^t - \left([\boldsymbol{J}]^{-1}\right)^t \boldsymbol{f}^t \tag{29}$$

In (29), $\boldsymbol{x}$ is the set of state variables, $\boldsymbol{f}$ stands for the set of equations and $[\boldsymbol{J}]$ corresponds to the Jacobian Matrix of the system (the set of partial derivatives of all equations concerning all state variables). The Jacobian matrix of MNRM is formed as:

$$\left[\frac{d\boldsymbol{f}}{d\boldsymbol{x}}\right] = [\boldsymbol{J}] = \begin{bmatrix} \left[\frac{d\boldsymbol{P}}{d\boldsymbol{\theta}}\right] & \left[\frac{d\boldsymbol{P}}{d\boldsymbol{V}}\right] & \frac{d\boldsymbol{P}}{dV_1} & \frac{d\boldsymbol{P}}{d\omega} \\ \left[\frac{d\boldsymbol{Q}}{d\boldsymbol{\theta}}\right] & \left[\frac{d\boldsymbol{Q}}{d\boldsymbol{V}}\right] & \frac{d\boldsymbol{Q}}{dV_1} & \frac{d\boldsymbol{Q}}{d\omega} \\ \frac{dQ_{sys}}{d\boldsymbol{\theta}} & \frac{dQ_{sys}}{d\boldsymbol{V}} & \frac{dQ_{sys}}{dV_1} & \frac{dQ_{sys}}{d\omega} \\ \frac{dP_{sys}}{d\boldsymbol{\theta}} & \frac{dP_{sys}}{d\boldsymbol{V}} & \frac{dP_{sys}}{dV_1} & \frac{dP_{sys}}{d\omega} \end{bmatrix} \tag{30}$$

The partial derivatives of the Jacobian matrix shown in (30) are presented in detail in (31)–(39). P and Q's partial derivatives to voltage magnitudes and angles are almost the same as those used in the classical NRM. The only difference now is that it considers all system voltages and also the reference bus. The reference bus has the voltage calculated in the process and it is the only one to have a defined angle.

The derivatives of P and Q concerning ω are given as in (31) and (32):

$$\frac{d\boldsymbol{P}}{d\omega} = |V_k|\sum_{n=1}^{nb}\left[\frac{d\left|Y_{kn}^+\right|}{d\omega}|V_n|\cos(\delta_k - \delta_n - \theta_{kn}) + \frac{d\theta_{kn}}{d\omega}|V_n||Y_{kn}|\sin(\delta_k - \delta_n - \theta_{kn})\right] \tag{31}$$

$$\frac{d\boldsymbol{Q}}{d\omega} = |V_k|\sum_{n=1}^{nb}\left[\frac{d\left|Y_{kn}^+\right|}{d\omega}|V_n|\cos(\delta_k - \delta_n - \theta_{kn}) + \frac{d\theta_{kn}}{d\omega}|V_n||Y_{kn}|\sin(\delta_k - \delta_n - \theta_{kn})\right] \tag{32}$$

Note from (31) and (32) that:

$$\frac{d\left|Y_{kn}^+\right|}{d\omega} = -\frac{\frac{X_{kn}^+}{\omega}}{\left(R_{kn}^{+2} + X_{kn}^{+2}\right)^{\frac{3}{2}}} \text{ and } \frac{d\theta_{kn}}{d\omega} = -\frac{\frac{X_{kn}^+}{\omega R_{kn}^+}}{1 + \left(\frac{X_{kn}^+}{R_{kn}^+}\right)^2} \tag{33}$$

The partial derivatives of P_{sys} and Q_{sys} depend on the output impedances of the converters. That is, being (1) and (2) the conventional generators' droop, the considered coupling is P/f and Q/V. To reaches this coupling, the output impedance must have a high X/R ratio.

Additionally, the power of the entire system can be interpreted as the total of generation, that is,

$$P_{sys} = \sum_{k=1}^{ng} \frac{\omega_{ref} - \omega}{m_k} \tag{34}$$

$$Q_{sys} = \sum_{k=1}^{ng} \frac{V_{ref}^k - V^k}{n_k} \tag{35}$$

Thus, partial derivatives concerning state variables are given as:

$$\frac{dP_{sys}}{d\delta_k} = 0 \; e \quad \frac{dP_{sys}}{dV_k} = 0 \quad \forall k \tag{36}$$

$$\frac{dQ_{sys}}{d\delta_k} = 0 \; e \quad \frac{dQ_{sys}}{d\omega} = 0 \quad \forall \, k \tag{37}$$

$$\frac{dP_{sys}}{d\omega} = \sum_{k=1}^{NB} -\frac{1}{m_k} \tag{38}$$

$$\frac{dQ_{sys}}{dV_k} = \begin{cases} -\frac{1}{n_k} & if \;\; bus \, k \, if \; VF \\ 0 & if \;\; bus \, k \, is \; PQ \end{cases} \quad \forall k \tag{39}$$

Finally, the greatest magnitude of the error associated with ***f*** is assessed. If this value meets the convergence criterion, the process is finished. Otherwise, the state variables are updated, and the algorithm is executed again, updating frequency-dependent loads and the impedance values. Besides, after convergence, both reactive and active power limits are assessed. If a generator bus with a droop control violates one of its limits, it has the generation fixed in the violated limit, and the convergence process is repeated.

The convergence of the load flow represents the primary level of control, i.e., the response of frequency and voltage facing the demand variation. The system can reach a new operation point out of safe limits, determined by regulatory agencies. In these situations, load shedding [20] or secondary control [21] may be necessary to re-establish the grid's safe operation.

Special attention should be paid because the distribution lines' resistance is predominant over the inductive impedance. The X/R ratio is low, impairing the conventional coupling between active power–frequency and reactive power-voltage. So, a high computational effort to solve the power flow problem of the traditional method is required.

To overcome any convergence problems, two mathematical techniques may be used: axis rotation [13] and Levemberg-Marquardt Method [22]. Both of them can

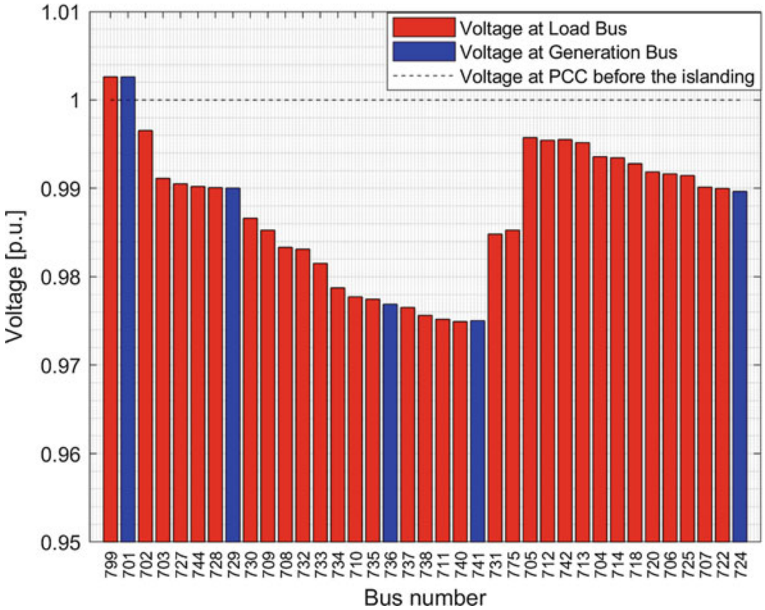

Fig. 7 Voltage profile

be easily incorporated in the load flow algorithm, which reduces the computational effort during the problem-solving.

Consider the system presented in Fig. 1 to illustrate the MNRM for the power flow analysis in islanded microgrids. All dispatchable generators initially operate in Voltage Source Inverter (VSI) mode with the reference values at $V_{ref} = 1$ *p.u.* and $\omega_{ref} = 60$ Hz (VF bus).

The voltage profile in the base case is shown in Fig. 7 and the generation profile in Fig. 8. The algorithm converged in six iterations until reaching a tolerance of 10^{-6}.

Due to the system's mode of operation (VF), the converters change the terminal voltage according to each reactive droop coefficient, which implies voltages different from the reference value (Fig. 7). In this sense, the droop coefficients are responsible for controlling the reactive generation dispatch.

A similar idea occurs with frequency, calculated here as 0.9961 p.u., or 59.7 Hz. Unlike the voltages, the frequency is a global variable, i.e., the same for the whole system. Thus, the active power droop coefficient is responsible for controlling the active generation's dispatch. Figure 8 shows the generation for all generating units. Two crucial points should be mentioned:

- Buses 701, 729, and 736 have the same parameters (see Table 1), but the reactive power generation is different since the voltage is a local variable;
- Although Bus 724 has the lowest capability, its power generation is the largest, as it has the lowest active droop coefficient, which can be explained in (11) and (12).

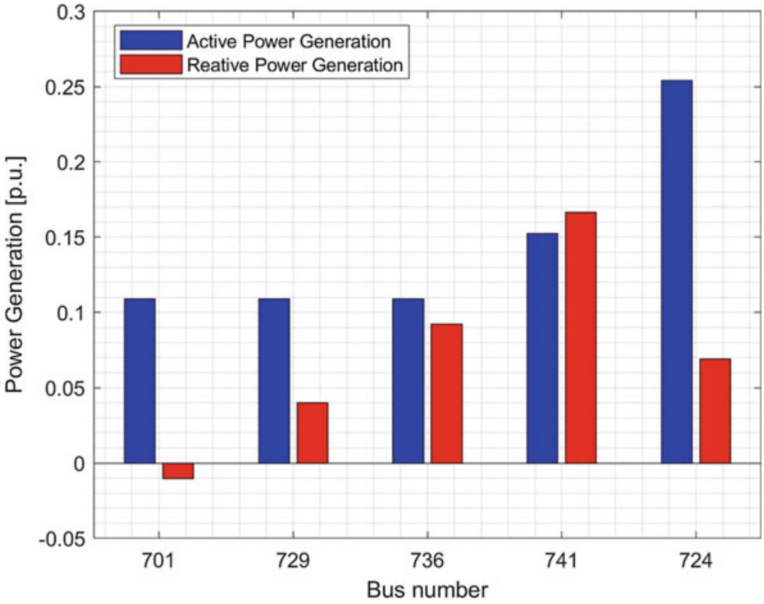

Fig. 8 Generation profile

Table 5 Generation and load at operation

	Active	Reactive
Load [p.u.]	0.7228	0.3512
Generation [p.u.]	0.733	0.3571
Loss [p.u.]	0.0102	0.0059

Finally, Table 5 gives a summary of the total generation. The losses are divided among all units, showing that the algorithm converges to a balanced operation point, that is, the generation supplies all loads and the losses of the system.

3 Summary

This Chapter has been devoted to showing the typical power flow strategies employed in MGs operating in grid-connected and islanded modes. The power flow is an essential tool for any study in the expansion, planning, and operation issues for MGs.

In grid-connected mode, the MG presents characteristics of a distribution system, thus it is possible to employ a conventional power flow method to solve the system. However, some operations and control aspects differ from the traditional distribution system, such as high DG penetration and voltage control. Thus, these aspects must be considered in the power flow, such as the volt-var strategy presented in Sect. 2.2.

Some particularities are considered in the power flow when the MG operates in an islanded mode. In the absence of the connection to the main grid and the swing bus, the distributed generators and energy storage systems present in the MG must maintain the frequency and voltages at the appropriate levels. Consequently, the traditional power flow must be modified, so that it considers the frequency as a state variable and the possibility of the generation sources operating by controlling the voltage and frequency of the MG (VF Mode).

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Microgrid Operation and Control: From Grid-Connected to Islanded Mode

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Abstract This chapter discusses the MG operation and control main aspects in islanded mode and its transition between the connected and islanded modes. The MG control focus relies on the hierarchical control structure, in which the primary, secondary, synchronization and autonomous operation control levels are covered. Hierarchical control is necessary to ensure the continuous operation and stability of the MG, when it changes from grid-connected to islanded mode, by an intentional or unintentional island event, during the islanded operation and when MG reconnects to the main grid. The primary control is responsible for voltage and frequency stability and power sharing between the DGs in the islanded mode. The secondary control is responsible for voltage and frequency regulation. The autonomous control is responsible for energy management to maintain the MG autonomy. When the main grid returns to its normal operation conditions, the MG synchronization control is responsible for the connection of the MG with the main grid. Some strategies proposed in the literature for each control level are introduced and simulated under islanding, islanded operation and syncronization events. A MG topology based on the CIGRE benchmark LV distribution network is employed.

Keywords Microgrid Operation · Primary control · Secondary control · Synchronization control

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1 Introduction

A Microgrid (MG) is made up of Distributed Energy Resources (DERs) and local loads. DERs are divided into Distributed Generators (DGs) and Energy Storage Systems (ESS). DGs that use intermittent primary sources, such as photovoltaic (PV) and wind generators, are said to be non-dispatchable. DGs that use non-intermittent sources, such as small hydroelectric or biogas generators, and ESS can supply desired or necessary active power to the grid, therefore they are said to be dispatchable [1–3].

MGs must be able to operate connected to the main grid (grid-connected mode) or isolated from the grid and operating as a local power system (islanded mode). During operation in connected mode, MG manages its energy resources and controls the flow of active and reactive power exchanged with the main grid. In this mode, dispatchable DERs operate in active and reactive power control objectives (PQ mode). In island mode, MG needs to control its voltage and frequency, so dispatchable DERs operate in voltage and frequency control objective (Vf mode). Non-dispatchable DERs normally operate in PQ mode continuously, typically aiming to maximize the active power provided by the primary source. From the point of view of MG operation and control, the biggest challenges are the transition from the grid-connected mode to the islanded mode (islanding); the islanded operation, wherein the MG must be able to supply the power demanded by its loads with reliability and quality and control its voltage and frequency; and the transition from island to grid-connected mode (synchronization with the main grid) [4–7].

This chapter aims to present the main aspects of the MG operation and control in islanded mode and its transition between connected and islanded modes. To achieve these objectives, MG uses a hierarchical control formed by primary, secondary, and tertiary controls. The primary and secondary controls operate at different time scales to provide power balance between DERs and loads, power-sharing between the DERs, and stabilizing and controlling the voltage and frequency of the MG [6, 8, 9].

Figure 1 shows the operation of an MG through a timeline. In this timeline, the typical events that occur in the MG operation are marked. From the islanding and connection events, the MG operation periods in the grid-connected mode and islanded mode are delimited. Also, from the events, Fig. 1 shows the moments of action and the electrical quantities controlled by the primary control, secondary control, and synchronization control of the MG, during the islanded operation.

It is considered that at the beginning of the operation in the timeline, the MG is operating connected to the main grid. In this operation mode, the MG voltage and frequency are imposed by the main grid and the function of the MG is to control the exchange of active and reactive power between the MG and the main grid, based on the management of its energy resources [6]. Then the islanding event occurs, which may be intentional or not, and the MG starts operating in the islanded mode, starting to control its voltage and frequency and supply the power demanded by its loads, within its service possibilities. Both in the event of islanding and the events of variations in load or generation, MG undergoes power imbalances and consequently variations in voltages and frequency, which must be controlled.

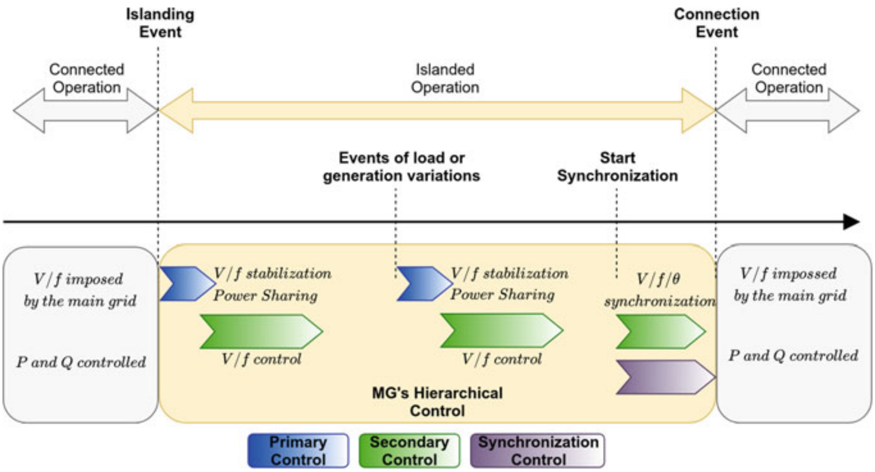

Fig. 1 MG controls and events

Additionally, in the islanded mode, due to the inherent randomness and uncertainty of renewable energy power generation, an energy management system (EMS) must be employed to guarantee the autonomy of the MG [10]. The EMS must optimize the dispatched power to maintain the operation for as long as possible. In most cases, load shedding must be employed to ensure the availability of electrical power to all essential and, most importantly, critical loads. The capacity of the MG to maintain the operation in the islanded mode as long as possible is denominated MG autonomy [11, 12].

When it becomes possible and desirable for the MG to return to grid-connected mode, the synchronization process starts, from which the synchronism control acts, using the secondary control to align the electrical quantities of the MG with the main grid. As soon as the synchronism conditions are reached, the connection event is carried out and the MR starts operating again connected to the main grid [13].

2 Hierarchical Control in Microgrids

The control of the islanded MG must guarantee the stability of both frequency and voltage, economically efficient operation, and synchronization with the main grid. These control actions have different time scales and objectives, which demands a hierarchical control structure. According to [9], the hierarchical control in MG is composed of three levels:

- Primary control: this control is responsible for maintaining the frequency and voltage stability of the MG and power-sharing among the DGs. Usually, this control is implemented locally in each DG of the MG. This control emulates

the droop characteristics of the synchronous machines for both frequency and voltage. Wherein, if the power balance of the MG changes, the DGs will change their active and reactive power output. To achieve the power-sharing among the DGs, deviations in frequency and the voltage occurs;
- Secondary control: this control aims to compensate for the frequency and voltage deviations caused by the operation of the primary control. Normally, the secondary control acts over the primary control, changing the references of the primary control;
- Tertiary control: this control is responsible for the power flow control in grid-connected mode.

Other definitions of secondary and tertiary control can be found in the literature. According to [6], the secondary control aims to find the optimal dispatch of the available DG units, so it is also referred to as MG EMS, where the regulation of both frequency and voltage are achieved through the optimization of the MG dispatch. However, [9] considers that secondary control is responsible for compensating the frequency and voltage deviations. The definition presented in [9] for the primary and secondary control will be considered in this chapter.

Other authors propose different definitions of tertiary control. In [8], for example, the tertiary control is responsible for the optimal management of the MG, wherein the losses and cost minimization are achieved. In islanded mode, this optimal management is carried out by the EMS, which is responsible for guaranteeing the autonomy of the MG [11, 12].

3 Microgrid Model

To show the concepts addressed in this Chapter, an MG based on the CIGRE benchmark LV distribution network is adopted. The CIGRE MG is an unbalanced three-phase European distribution system, with a nominal frequency of 50 Hz and a nominal voltage of 400 V [14]. For simplicity, in this chapter, the CIGRE MG is modified to become a balanced three-phase system. The unifilar diagram of the MG is shown in Fig. 2.

The MG includes two PV systems, with 21 kW each, and two battery energy storage systems (BESS) with 45 kVA each. The PV systems are composed of PV panel strings connected to the MG through DC/AC power electronic converters, which adopted the voltage-source converter (VSC) topology. The BESS are composed of a battery connected to the MG through DC/AC power electronic converter, also using the VSC topology. The VSC inverter bridge is implemented by using the average model [15]. The BESS converters are capable of operating in PQ and Vf modes. They operate in PQ mode when the MG is connected to the main grid, and in Vf mode when the MG is islanded. The converters of the PV systems operate only in PQ mode.

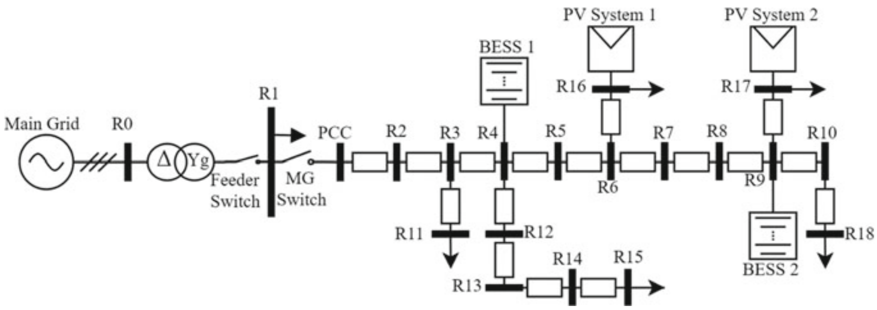

Fig. 2 Modified CIGRE benchmark LV distribution topology

The MG is connected to the main grid through the PCC (Point of Common Coupling), which is located in the grid low voltage bus. The PCC must be controllable to allow the MG to connect and disconnect to the main grid.

4 Operation in Islanded Microgrids

4.1 Islanding

Islanding is the event in which MG disconnects from the main grid and starts to operate autonomously. This transition between grid-connected mode and islanded mode can happen intentionally and unintentionally. In order to open the PCC and change the control mode for islanding events, MG must have islanding detection elements.

4.2 Islanding Detection

To perform the islanding detection, techniques normally classified into local and remote techniques are used. Remote techniques are based on communication between the MG and remote equipment, which requires a communication infrastructure between the MG and the upstream facilities that make up the main grid. Local techniques are based on the measurement of local MG parameters and are divided into active, passive, and hybrid methods [16].

Passive methods directly monitor variables such as frequency, voltage, phase, and power flow to detect islanding. These methods are economically attractive and can detect islanding quickly, however, they are more susceptible to false island detection and have a large Non-detection Zone (NDZ). Active methods intentionally inject disturbances in the electrical network and monitor their effects on parameters such as frequency, voltage, current, and impedance to detect islanding. The active methods have a lower NDZ than the passive methods but introduce degradations in the power quality of the network. Hybrid methods combine passive and active detection techniques to obtain the advantages of both methods. In hybrid methods, active techniques are applied only after islanding is detected by passive techniques, which allows the hybrid method to obtain a small NDZ and not significantly affect the power quality of the network [16, 17].

4.3 Switching Controls

The need for switching controls of the DERs on MG islanding event stems from the widely used practice in the literature of operating dispatchable DERs with different control strategies to achieve the objectives of PQ control, in grid-connected mode, and Vf control, in islanded mode [5, 8, 9]. In the event of MG islanding, MG and its dispatchable DERs must be able to change their control objective, starting to use hierarchical control for the islanded operation. In this way, islanding detection should drive the change in control, so the time of islanding detection is a very important variable that directly influences MG's control capacity after the event. Studies on the influence of switching controls due to the time delay of island detection are essential to ensure the islanded operation of future MGs.

Some authors claim that switching DERs control topologies, depending on the grid-connected or islanded mode of the MG, has the challenges of achieving a smooth transition of control and a rapid change of control objectives, which requires rapid detection of islanding. Thus, these authors propose the use of control strategies in dispatching DERs that meet both the PQ control objective, in the grid-connected mode, and the Vf control objective, in the islanded mode, without the need for control switches in the islanding event [18–20].

The islanding examples presented in this chapter use dispatchable DERs operating with different control strategies in grid-connected and islanded modes of the MG. The switching of the DER controls is performed at the exact time of islanding time, without considering the time of islanding detection.

4.4 Intentional Islanding

The intentional islanding is a previously planned event and has the intention of operating the MG islanded from the main grid. This type of event can occur, for example, in scheduled maintenance and in situations in which the poor power quality of the main grid can compromise the MG and there is enough time to plan the islanding event. In these cases, adjustments in the active and reactive power exchanged between the MG and the main grid, and in the DERs and MG controls can be previously done, resulting in small transients after the MG islanding [4, 6].

In the example in Fig. 3, the MG operates in the grid-connected mode and its loads consume more power than the intermittent sources are capable of supplying. While the MG operates in the grid-connected mode, the main grid compensates the MG active and reactive power deficit through the PCC power exchange and the two BESSs do not supply any power. For some reason, the need to operate the MG in islanded mode arises and intentional islanding is planned to occur in 0.4 s of the simulation. To avoid power imbalances and electrical oscillations after the island event, the MG prepares itself for the event and commands the BESSs to supply power in such a way that the flow of active and reactive power through the PCC is zeroed.

In Fig. 3, it can be seen that, in 0.2 s, the BESSs start to provide active and reactive power and that the power flow in the PCC is zeroed. When the power flow through the PCC is zeroed, the MG voltage rises, since there is no longer a voltage drop in the transformer, as can be seen in Fig. 4. As the loads are modeled by the constant impedance model, this voltage rise increases the power consumption of the loads, making the total power supplied by the BESSs after setting at 0.2 s slightly higher than the power previously supplied by the grid.

In 0.4 s smooth islanding occurs and the MG starts to operate islanded without suffering major variations in voltage and frequency after this event. The variations observed in Fig. 3 and Fig. 4 are due to switching in the BESS controls.

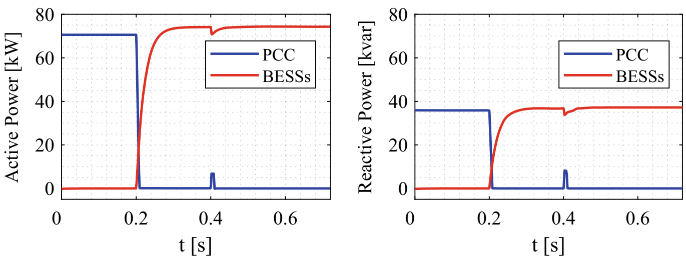

Fig. 3 Active and reactive power in intentional islanding

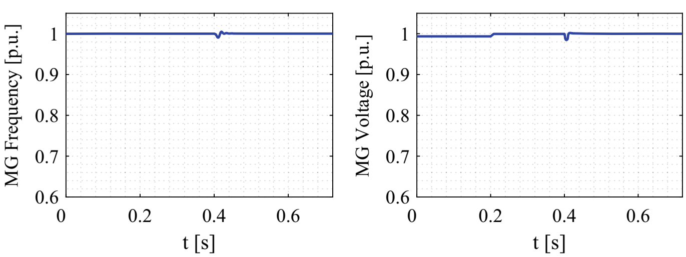

Fig. 4 MG voltage and frequency in intentional islanding

4.5 Unintentional Islanding

Unintended islanding occurs without any predictability, at a random time, without any intention that the MG operates autonomously. This type of event can occur due to grid faults, equipment failures, human errors, natural events, and other unscheduled events that are unknown to the MG. Due to its unpredictability, in the unintended islanding event is not possible to make previous adjustments to the MG, which can cause severe transients to the MG after the island event and hinder the success of its operation in islanded mode. Unintentional islanding can occur by an action of the MG itself or by the main grid shutdown [4, 6]:

- Islanding by MG action is performed in the events of failures or major disturbances in the main grid, where MG detects this event and, to protect itself, disconnects from the main grid by opening the PCC.
- Islanding due to main grid shutdown can occur due to upstream outages in the electrical system or grid failures unknown to the MG, causing the MG to be isolated instantly. In these situations, MG must detect that it is isolated, to carry out the necessary protection and control actions for its continuity of operation.

After an islanding event, MG must be able to maintain the power supply to its loads, meeting the parameters of power quality and reliability. For this, MG must identify the islanding and start using its control resources. Therefore, the MG must have protection systems operating with appropriate islanding detection techniques, enabling the disconnection of the MG and the changes in control strategies that are imperative for the continuity of MG operation.

Figure 5 shows the active and reactive power of the MG operating in the same way as in Fig. 3; however, in this case, an unintentional islanding event occurs in 0.4 s. As the event is not previously known by MG, it is not able to make previous adjustments to zero the active and reactive power through the PCC. In this way, when the islanding occurs, in 0.4 s, the MG is receiving an active and reactive power flow from the main grid and the BESSs are not providing any power. After the islanding, the active and reactive power supplied by the main grid is abruptly interrupted and the BESSs start to supply the required active and reactive power.

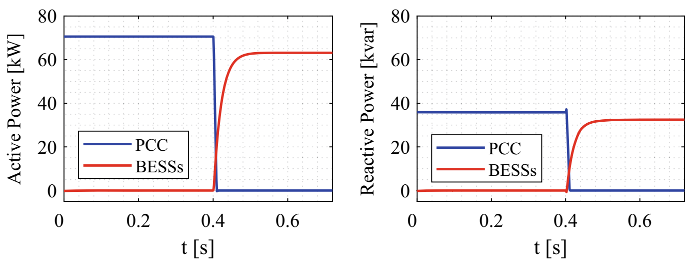

Fig. 5 Active and reactive power in the unintentional islanding

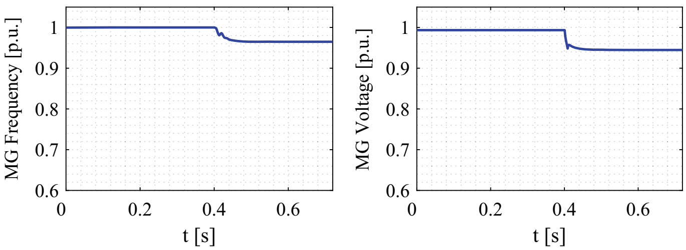

Fig. 6 MG voltage and frequency in unintentional islanding

Figure 6 shows that after the islanding event, the MG undergoes variations in voltage and frequency and the two BESSs respond to these variations through their primary control. The two BESSs then supply the active and reactive power, which were previously provided by the main grid, demanded by the loads and stabilize the voltage and frequency of the MG after the transient. As there is a voltage drop after the islanding, the power consumed by the loads decrease, and the power supplied by the BESSs is less than the power supplied by the main grid before the islanding.

For both intentional and unintentional islanding shown, MG successfully maintains its operation in islanded mode, with acceptable voltage and frequency deviations that secondary control can correct later. In these cases, intermittent DG sources, like PV, maintain their power supply to MG.

However, unintentional islanding can occur under more severe conditions than the one presented and MG may not have enough resources to control variations and meet the demand for all its loads. These situations can lead to DG and loads disconnections and even the entire MG collapse. To avoid it, load-shedding strategies can be implemented. In these strategies, only low priority loads of the MG are cut off, preventing the collapse of the entire MG [21].

4.6 Primary Control

The primary control is the first level of the hierarchy control, with the fastest response time. Therefore, after the islanding occurs, the primary control is the first to stabilize the voltage and frequency of the MG and provide power-sharing between the DGs. The primary control techniques may use communication links or be decentralized [3, 6, 8].

The primary control techniques based on communication may offer superior voltage and frequency regulation and power-sharing compared to the decentralized techniques. Besides, the MG voltage and frequency are closer to their reference values without using the secondary control [3]. However, these techniques require communication links between the DGs, which results in higher costs and complexity for the MG, in addition to reducing the reliability and plug-and-play characteristics of the DGs [3].

Due to the greater reliability of the decentralized techniques, these have been the most applied primary control methods [3, 22]. The decentralized techniques are usually based on the droop control, which idea is to mimic the behavior of a synchronous generator for the DER's DC/AC inverters [9].

This is achieved with the frequency/voltage decrease in response to active/reactive power increase. This idea is used to form the P/f and Q/V droop, respectively, and they are given by [9]:

$$\omega_k = \omega_{ref_k} - m_k P_{gk} \tag{1}$$

$$V_k = V_{ref_k} - n_k Q_{gk} \tag{2}$$

where.

- P_{gk} and Q_{gk} are the k^{th} DG active and reactive output power;
- m_k and n_k are the proportional droop gains of the k^{th} DG;
- ω_{ref_k} and V_{ref_k} are the angular frequency and magnitude of the reference voltage of the k^{th} DG;
- ω_k and V_k are the frequency and voltage reference to be sent to the inner control loops of the k^{th} DG.

One may see by (1) and (2) that the droop control allows the frequency and voltage to stabilize in values different from their nominal, so it is necessary the use of the secondary control to regulate the frequency and voltage to their nominal values [8, 9].

In addition to the deviations in the frequency and voltage values, the droop control also presents other disadvantages such as the decoupling between active and reactive power not normally observed in MGs, poor reactive power-sharing, difficulty to deal with nonlinear loads, etc. [8]. Many modified droop control techniques have been proposed by the literature to solve these issues, such as those found in [6, 8]. This chapter uses the virtual impedance technique to improve the reactive power sharing issue of droop control.

The virtual impedance technique modifies the voltage output, V_k, from the Q/V droop through a virtual drop voltage, which is a product of the DG output current i_k and a virtual impedance Z_{v_k} [23]. This may be seen as:

$$V_{v_k} = V_k - Z_{v_k} i_k \tag{3}$$

The Z_{v_k} is a value that must be carefully designed because as greater its value, the smaller will be the V_{v_k} sent to the voltage control of the DG, and it may occur a voltage instability if this value becomes too small [24]. However, if the virtual impedance is correctly designed, it can substantially improve the reactive power-sharing between the DGs [23, 24].

In order to demonstrate the dynamic behavior of the DGs operating with the droop control, simulations are carried out using the MG shown in Fig. 2. In these simulations, the BESSs are the only dispatchable sources and, therefore, the only

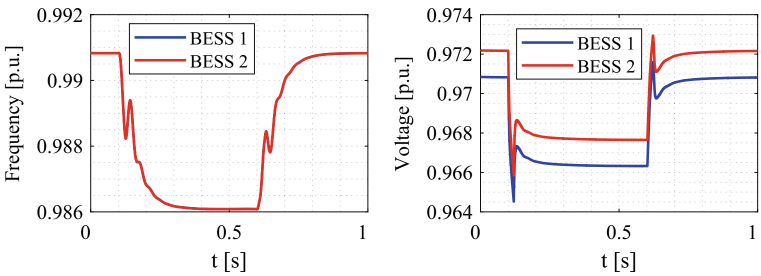

Fig. 7 Frequency and voltage during islanded mode

DGs operating in Vf mode and with droop control. The PV systems will operate in PQ mode dispatching their maximum active power with unitary power factor.

The events in this case are given as follows:

- The MG initiates operating islanded with 31.58% of the total demand;
- At $t = 0.1$ s, the MG load increases by 5%;
- At $t = 0.6$ s, the MG load decreases by 5%.

Figure 7 shows the frequency and terminal voltage dynamic for the two BESSs. It is seen that the frequency and voltage drop as the load increases, according to (1) and (2).

Moreover, the frequency of the two BESSs stabilizes at the same value, which does not occur with the voltages. The voltage differences are observed because unlike the frequency, the voltage is not a global value in the MG, and because of the different impedance of the lines and asymmetric position of the loads in the MG, the terminal voltages end up differently. This behavior influences the dynamics of the active and reactive power since they are regulated through the droop control using the frequency and voltage according to (1) and (2).

In Fig. 8 it is shown the active and reactive power for both BESSs. As can be seen, the active power provided by each BESS is the same at the steady state, and the reactive power is different between them, as their voltages are different. This poor reactive power-sharing may be problematic in heavy load scenarios, where smaller

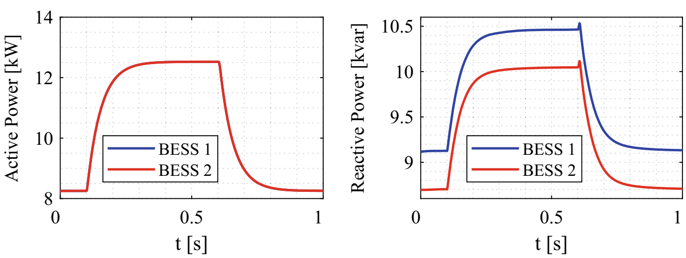

Fig. 8 Active and reactive power during the islanded mode

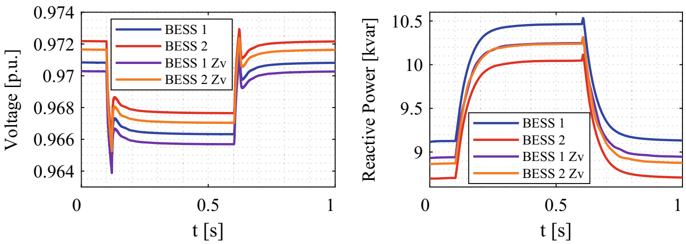

Fig. 9 Influence of the virtual impedance in the voltage and reactive power during the islanded mode

DGs may reach their current limit because of the reactive overloading and trip due to the DG protection. This may generate a chain reaction and cause a collapse of the MG. The virtual impedance technique can be used to solve the reactive power sharing problem.

Figure 9 compares the voltages and the reactive power-sharing of the DGs between the case mentioned above, without virtual impedance, and after addicting 1 mH as a virtual inductance for the BESS 1 control. Although the virtual impedance improves the reactive power sharing, there is a decrease in the values of the voltages of the BESSs, so the virtual impedance must be designed appropriately.

4.7 Secondary Control

As seen in Sect. 4.2 the primary control causes deviations in both frequency and voltage. To ensure that the MG does not present high deviations, secondary control must be employed. The secondary control acts on the primary control, changing the values of the droop references as follows:

$$\omega_k = \omega_{ref_k} - m_k P_{gk} + \Delta\omega_k^{SC} \tag{4}$$

$$V_k = V_{ref_k} - n_k Q_{gk} + \Delta V_k^{SC} \tag{5}$$

where.

- $\Delta\omega_k^{SC}$ is the secondary control correction in frequency droop control;
- ΔV_k^{SC} is the secondary control correction in voltage droop control;

In the literature, secondary control can be classified in [25]:

- Centralized: the secondary control is performed in the MG Central Controller (MGCC). The MGCC must receive the state of the MG variables through a communication link and send the new references to the DGs. This strategy presents high dependence on the communication link;

- Distributed: the secondary control is performed in local controllers. Each controller exchanges information with its neighbor, thus the communication network in this control is sparse. This strategy presents better reliability than the centralized, however, it still depends on the communication structure;
- Decentralized: the secondary control is performed in local controllers, without a communication structure. Each controller regulates the frequency and voltage only according to the state of the local variables.

Other classifications of the secondary control can be found in [26] and [27].

Leaving aside the communication network, the simplest secondary control strategy is the centralized proportional integrative (PI) control, which only the frequency and the voltage are measured in PCC [9]. This control is represented in (6) and (7).

$$\Delta\omega_k^{SC} = \left(K_{\omega p} + \frac{K_{\omega i}}{s}\right)\left(\omega_{ref}^{SC} - \omega_{PCC}\right) \tag{6}$$

$$\Delta V_k^{SC} = \left(K_{Vp} + \frac{K_{Vi}}{s}\right)\left(V_{ref}^{SC} - V_{PCC}\right) \tag{7}$$

where.

- $K_{\omega p}$ is the proportional gain of the secondary frequency control;
- $K_{\omega i}$ is the integrative gain of the secondary frequency control;
- ω_{ref}^{SC} is the reference of the secondary frequency control;
- ω_{PCC} is the frequency measured at the PCC;
- K_{Vp} is the proportional gain of the secondary voltage control;
- K_{Vi} is the integrative gain of the secondary voltage control;
- V_{ref}^{SC} is the reference of the secondary voltage control;
- V_{PCC} is the voltage measured at the PCC.

In the centralized PI control, the dynamic, stability, and the reliability of the control are highly dependent on the communication network. References [28, 29] present the influence of the communication network in the centralized secondary control.

Figure 10 illustrates the centralized secondary control behavior for the MG, where the following events are considered:

- The MG is operating with the droop control and with 31.58% of the total demand;
- At $t = 0.5$ s, the centralized secondary control initiates;
- At $t = 1.5$ s, the MG load increases by 5%.

It can be seen in Fig. 10, that the frequency value for the centralized secondary control is controlled at the reference value (1 $p.u.$). When the load increases, at $t = 1.5$ s, the frequency drops, and without secondary control the MG frequency is maintained in a value different from the reference. On the other hand, with secondary

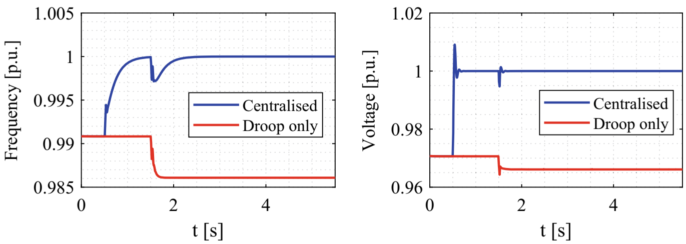

Fig. 10 The MG frequency and voltage considering the centralized secondary control

control, the MG frequency is restored to the reference value. However, for different secondary control strategies, the MG dynamics have different behaviors.

With the centralized control strategy, the steady-state voltage at the PCC is controlled at the reference value (1 $p.u.$) after and before the load increases, as shown in Fig. 10.

The distributed secondary control strategies normally adopt a protocol to indicate the actions of each controller. The controllers share variables of interest to each other and try to synchronize to achieve a goal, defined by the protocol [26]. The event-triggered-based strategies may be adopted in the centralized and distributed secondary control strategies. These strategies can drastically decrease the number of actuator updates and communication burden [25].

The decentralized secondary control strategies can be classified in [25]:

- Local-Variable-Based: the secondary control in each controller uses only local variables;
- Estimation-Based: a cooperative control is implemented in each decentralized controller, wherein each controller estimates the states of the others.
- Washout-Filter-Based: the secondary control may be implemented in the droop control as follows:

$$\omega_k = \omega_{ref} - m_k \left(\frac{s}{s + K_p} \right) P_{gk} \tag{8}$$

$$V_k = V_{ref} - n_k \left(\frac{s}{s + K_q} \right) Q_{gk} \tag{9}$$

where.

- K_p is the control parameter for the frequency washout filter;
- K_q is the control parameter for the voltage washout filter.

The Washout-Filter-Based strategy can restore the frequency and the voltage to the reference's values. Reference [30] presents the relationship between the centralized secondary control and the Washout-Filter.

To illustrate the operation of the Washout-Filter-Based secondary control, the following events are considered in the MG of Fig. 2:

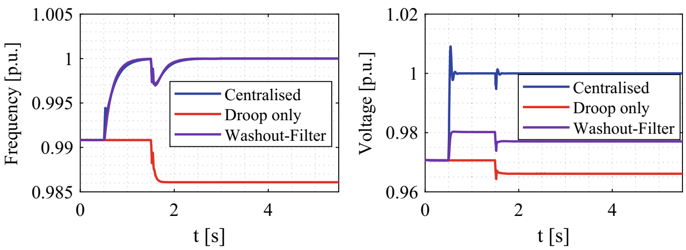

Fig. 11 The MG frequency and voltage considering the Washout-Filter-Based control

- The MG is operating with the droop control and with 31.58% of the total demand;
- At $t = 0.5$ s, the decentralized secondary control initiates.
- At $t = 1.5$ s, the demand for the MG increases by 5%.

As shown in Fig. 11, decentralized control behaves similarly to centralized control. Both strategies can regulate the frequency of the MG in the reference value.

The steady-state voltage at the PCC, shown in Fig. 11, is controlled by the centralized control exactly at the reference value, before and after the load increase. On the other hand, the voltage at the PCC is not controlled exactly at the reference value by the decentralized control. This behavior occurs because the Washout-Filter-Based strategy controls the terminal voltage of the converter before the virtual impedance of each DG, while the centralized strategy directly controls the voltage at the PCC.

4.8 Microgrid Autonomous Operation

The optimal energy management problem in MGs consists of the optimal operation of each DER available in the system. Figure 12 shows, schematically, the energy management problem in an MG [10]. It is a problem of considerable complexity, presenting a non-linear and discontinuous nature, which requires an automated solution in real-time [6, 10, 31, 32].

In grid-connected mode, the EMS seeks to combine the available DERs to meet the variable demand of consumers with the minimum possible cost and respecting the restrictions of the system, taking advantage of local intermittent renewable sources and the possibility of power exchange with the main grid [10, 12].

In the islanded mode (or autonomous mode), after the MG controls stabilize, the EMS must guarantee the MG autonomy, so that the output power of the DERs must meet the total load demand of the MG. It is sometimes necessary to undergo a load shedding process to match generation and demand. The main objective in this mode is to maintain the MG's operation as long as possible, supplying the most important loads. Other objectives can be achieved in the EMS, as operation cost optimization and minimizing losses [6, 10].

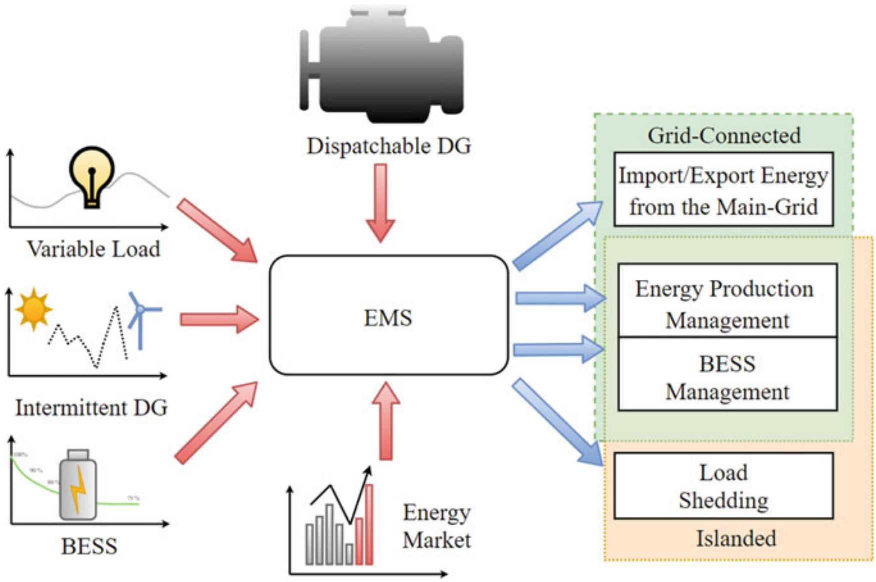

Fig. 12 The energy management problem in an MG

To achieve these objectives, whether in grid-connected or islanded mode, the EMS must calculate and send the active power setpoints to all DERs. These setpoints are calculated through an optimization process, which is traditionally classified as a mixed-integer nonlinear problem. To address this problem, heuristic optimization techniques are often applied [6, 10, 12].

4.9 Synchronization Control

Once the stability of the secondary control has been established during the islanded operation, the MG can start the synchronization process if it is desired to connect the MG to the main grid. The transition from islanded to grid-connected mode is another challenge about MG operation and control. The connection with the main grid may result in significant variations in the MG voltage and frequency behavior. It occurs because the condition that the MG assumes while the islanding operation may be much different compared to the grid-connected mode condition [6].

The islanded operation condition of the MG is a result of the reliability and continuity requirements of this operation mode and because of that, it is possible to verify different values of phase angle, amplitude, and frequency between the voltages of both sides of the PCC. Thus, if the MG and the main grid are connected during this condition, high levels of electromagnetic and electromechanical transients may occur resulting in damages to the MG components [6].

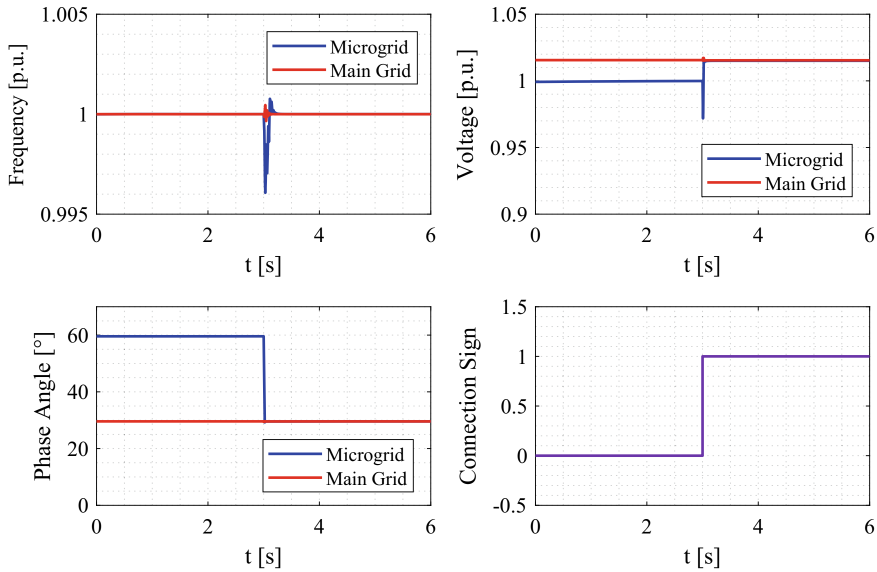

Fig. 13 Microgrid and main grid magnitudes during the connection out of sync

The worst scenario for a connection between two systems out of sync is when there is a phase angle difference between them. Combined with a difference in frequency or voltage, the damage to the DG sources connected to the MG can be even worse. In order to illustrate the possible damage caused to the elements connected on the MG presented in the case study in Fig. 2, some tests were carried out to verify the result of the connection between the MG and the main grid out of sync.

The MG and main grid frequency, voltage, and phase angle behavior are given in Fig. 13. The voltage, frequency, and power of the two BESSs, are shown in Fig. 14.

The events in this case are given as follows:

- The MG initiates in islanded mode;
- At $t = 3.0$ s the MG connects to the main grid out of sync.

In this test, there were voltage and phase angle differences between both systems before the connection event. Until $t = 3{,}0$ s, the PCC voltage at the MG side was set as 1.0 $p.u.$, but at the main grid side, the voltage was 1.015 $p.u.$ The phase angle difference between both systems was 30° before the connection event. Because of that, the MG and the main grid were out of sync and should not be connected.

When the connection event occurs, at $t = 3.0$ s, it results in large transients in the DG source, as seen in Fig. 14. The main variations occur on the frequency, active and reactive power of both BESSs. Those variations could result in several damages to these elements, such as the reduction of the life cycle of the batteries.

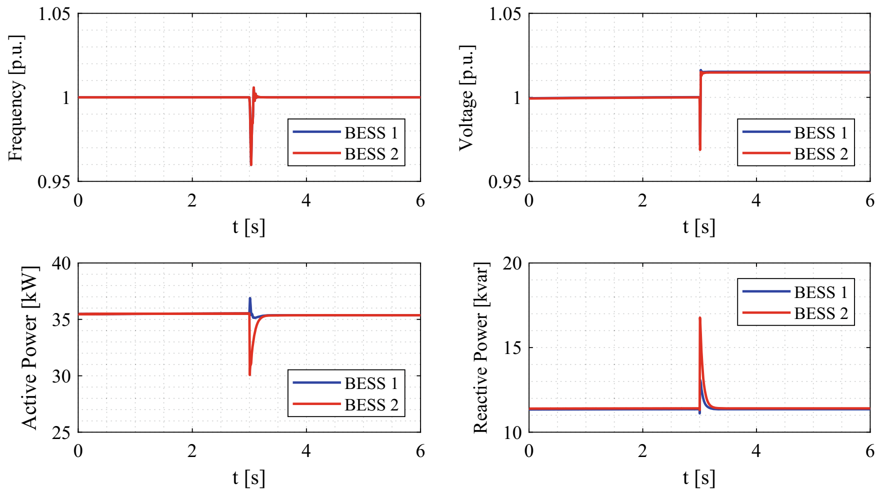

Fig. 14 BESSs variation during the connection out of sync

To reduce the impacts resulting from the connection between the MG and the main grid, it is necessary to check the synchronization conditions at the PCC. Such verification concerns in the analysis of the voltage amplitude, phase angle, and frequency of both systems, and the closure of the PCC switching device must occur when the differences between the main grid and the MG are within acceptable limits, in other words, the systems should be synchronized to be connected [33].

The IEEE Standard 1547–2018 [34] presents the normalization of these difference values limits acceptable for connections between systems. The specified values, presented in Table 1, are used as typical MG synchronization parameters. These criteria are adjusted according to the total installed capacity of the DERs connected to the system and they have the main objective of reducing the transients of the connection between electrical power systems.

For the MG connection to occur within limits shown in Table 1 and avoiding damage to the elements present, it is necessary the application of MG synchronization techniques. Currently, two control methods for synchronization are mainly investigated: the centralized and the distributed control.

Table 1 Synchronization limits for synchronous interconnection between electrical power systems (IEEE Standard Association 2018)

Rating of DG units	Frequency Difference [Hz]	Voltage Difference [%]	Phase angle Difference [°]
0 - 500	0,3	10	20
> 500 - 1500	0,2	5	15
> 1500	0,1	3	10

The main feature of the application of centralized control is the presence of a central controller that makes decisions regarding the operation mode of the MG and all DG units. With the centralized control technique, to achieve the MG synchronization, the central controller must communicate with the synchronization controller, which calculates the difference values at the PCC and calculates the adjustments for frequency, amplitude, and phase angle voltage.

Then, the adjustment values are sent to the central controller that communicates with all DG control units sending the adjustments values to synchronize the MG. At the same time, the synchronization controller monitors the PCC differences until they are zero or close to zero. At this moment, the synchronization controller sends a signal to the PCC switching device to enable its closure and also sends a signal to the central controller to enable the change of DG sources operation modes, since now the MG will be operating in grid-connected mode.

To illustrate the effectiveness of applying the synchronization techniques, centralized control was applied to synchronize the MG presented in Fig. 2. This control technique sends the frequency and voltage set points to the DG sources calculated according to the PCC differences until these differences are close to zero, and then the MG can be connected with the main grid smoothly.

For this case, the MG and main grid frequency, voltage, and phase angle behavior are given in Fig. 15. The voltage, frequency, and power of the two BESSs are shown in Fig. 16.

The events in this case are given as follows:

- The MG initiates in islanded mode;
- At $t = 2.0$ s the synchronization control starts;

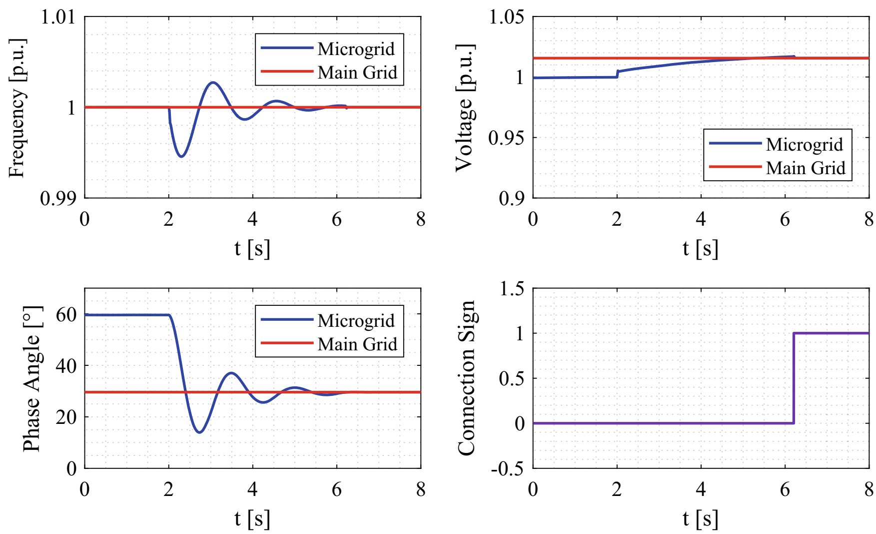

Fig. 15 MG and main grid magnitudes during the connection with synchronization control applied

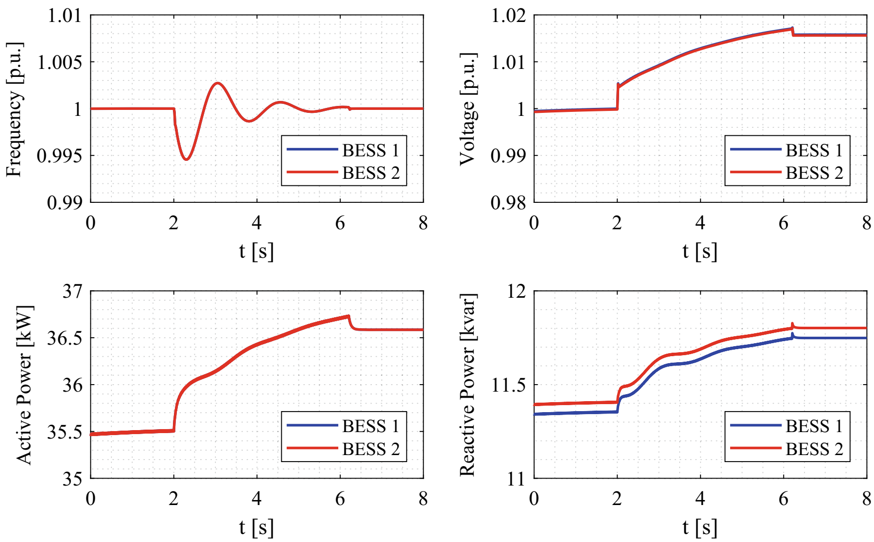

Fig. 16 BESSs variation during the connection with synchronization control applied

- At $t = 6.0$ s the MG and the main grid are synchronized and the connection occurs.

Before the synchronization control action, the differences between both systems were the same as the out of sync test shown in Fig. 13. After $t = 2.0$ there are some smooth variations in the MG magnitudes because of the synchronization control action. The connection with the main grid occurs when both systems are synchronized within the limits described in Table 1.

The synchronization control acts directly in the active and reactive power of both BESSs to achieve the phase angle and voltage synchronization at the PCC. This action results in smooth variations in the BESSs' magnitudes, as shown in Fig. 16, which will not result in damages to these elements.

In order to read the status of the main grid and the MG and then enable the closing of the PCC switching device, the Intelligent Electronic Device (IED) can be used. Thereafter, the adjustment of frequency, voltage amplitude, and phase angle in the PCC is carried out sequentially to allow the alignment with the main grid voltage. In this way, the transition between the operating modes occurs smoothly, without transients in the MG [35, 36].

A feature of the centralized control is the simplicity of the rules for adjusting the DG sources since all local controllers receive the set-points information from the central controller. Despite the ease and simplification of the implementation of centralized control, this technique requires a robust communication system between all DG sources, the central controller and synchronization controller, so the application of this type of control in MGs with distributed buses can become complex since its reliability depends on the communication channel.

The presence of multiple buses, loads, and DG sources installed in a distributed way in an MG justifies the use of distributed control to adjust the voltage and frequency in the PCC and synchronize the MG. The interaction between different sources and the autonomy of local controllers is preserved by applying this type of control, with its wide use being investigated by researchers.

The distributed control treats the synchronization process as decomposing a complex problem into a series of minor problems that are easier to solve. In other words, this strategy starts with the assumption that each DG unit is an autonomous operator responsible for a portion of the MG synchronization process. In this context, a distributed control technique commonly investigated in the current bibliography concerns Multi-Agent Systems (MAS) [36].

The synchronization carried out through MAS is characterized by a structure in which each MG agent is defined by a set of rules which take as input signals those received from the nearest neighboring agents. In most MAS applications, the topology of the communication system between agents is sparse and distributed, with different types of agents being determined, such as "master" and/or "slaves" agents.

A decentralized control structure based on MAS includes the synchronism agent which has communication with one or more master agents of the MG. In turn, the master agents can communicate with some slave agents which establishes sparse communication with each other. In this way, the flow of information is reduced, increasing control flexibility, and facilitating the plug-and-play of new DG sources.

5 Summary

This Chapter has been devoted to showing the typical strategies of primary control, secondary control, and synchronization of an MG, discussing the main concepts of the operation of an MG. These strategies are necessary to ensure the continuous operation of an MG. Without proper control actions, the MG cannot operate in islanded mode due to intentional or unintentional islanding, nor can it return to grid-connected mode.

The primary control is essential during the switch to islanded mode, being responsible for the frequency and voltage stability and the power-sharing during the MG operation in this mode. In Sect. 4.2 it was seen that this control level is usually implemented by the droop control, and because of the poor reactive power-sharing, it was necessary to add virtual impedance to correct this issue. However, how to determine the values of virtual impedances and how to make them adaptative for the load condition are still challenges and have been the topic of many types of research in the last years.

The secondary control acts over the primary control to compensate for the frequency and voltage deviations. This control essentially maintains the MG voltage and the frequency near the nominal values. It was presented in Sect. 4.3 that the various secondary control strategies can be employed in the MG. However, each strategy has its benefits and drawbacks, thus, improving the secondary control is still a hot research line and presents challenges.

Finally, to achieve the transition of islanded mode to grid-connected mode, it was presented in Sect. 4.4 the main criteria and considerations about the MG synchronization. The process of synchronizing two systems includes the application of control techniques capable of reducing and almost null the voltage magnitude, phase angle, and frequency differences between the MG and the main grid. This synchronization control is essential to guarantee a smooth transition during the connection event avoiding damages to the DG sources.

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Hosting Capacity and Grounding Strategies in Microgrids

A. B. Nassif

Abstract The planning, design and operation of microgrids introduce technical challenges to system operators that are not common in systems that operate in an interconnected fashion. Two of these challenges are associated with renewable, inverter-based sources supplying the microgrid when operating disconnected from the utility. The two challenges addressed in this chapter are determining the hosting capacity and ensuring effective protection and grounding. This chapter proposes a method to determine the microgrid hosting capacity based on frequency response and frequency protection elements. When the hosting capacity limit is exceeded, the microgrid will necessitate the incorporation of a BESS and a microgrid controller. This chapter also develops the framework for protection and grounding in the microgrid environment of reduced short-circuit levels. The proposed method ensures protection dependability and security, while ensuring the system is effectively grounded from a performance grounding standpoint. A frequency and voltage-based scheme becomes the primary protection philosophy. A real case study is used to illustrate both challenges and their solutions.

1 Introduction

Microgrids can be categorized in a few different ways. One popular classification categorizes microgrids in five main groups: campus, community, remote off-grid, military base, and commercial (C&I) and industrial microgrids. A more general classification would be to categorize microgrids in one of two groups, either being connected to the Bulk Electric System (BES), encompassing campus, community and C&I microgrids, or off-grid, encompassing remote communities and military base microgrids. This second group typically represents mission critical applications and have grown in number by being backed up by strong justification or business cases.

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Regardless on how the industry realizes this categorization, it is a foundational requirement that during its islanded state, a microgrid performs in a safe and reliable way. This safe and reliable operation requires the system meets certain standards of stability, power quality, protection and grounding. These are a direct result of the power system design and penetration level of Distributed Energy Resources (DER). Two of these very complex subjects are addressed in this chapter. The first part discusses how the hosting capacity of inverter-based generation is limited by the frequency stability of microgrids, whereas the second part highlights the importance of ensuring the microgrid is effectively grounded and equipped with practical protective schemes. The theory presented in this chapter was derived for a real remote off-grid microgrid but is directly employable to any category of microgrid.

2 Part 1—Hosting Capacity in Microgrids

Microgrids are either connected to the BES or are completely isolated and supplied by isolated generation. If there is a tie to the BES, the reliability and security of the bulk power system is ensured via a set of electric reliability standards defined by the North American Electric Reliability Corporation (NERC), adopted by the utilities, and enforced by regulators. For remote microgrids, NERC standards do not apply, but utilities strive to provide service of comparable quality. In this sense, generated and consumed energy must be balanced to maintain frequency and voltage within acceptable limits. Three main areas are the focal point of essential reliability services:

1. Frequency support: frequency increases and decreases from nominal must be controlled and restored to normal levels;
2. Load balancing and ramping: supply and demand must always be closely matched.
3. Voltage support: voltage must be controlled to ensure the intended flow of active and reactive power.

While small amounts of variable energy sources can be generally integrated in a microgrid without a problem, higher penetration levels require measures to ensure they do not disturb the system and introduce reliability issues.

High penetration of inverter-based generation can lead to degraded frequency stability in microgrids due to the following reasons: (1) lack of inertia, or very low inertia due to their power electronics interfaces, leading to an overall decreased system moment of inertia and increased rate of frequency change, and (2) spinning reserve displaced by inverter-based generation, which can lead to large frequency excursions resulting from system disturbances, as described by Kerdpohl et al. [1], Shi et al. [2], and Engleitner et al. [3]. Many approaches have investigated these two challenges, being the second one the focal point of this section.

Frequency stability in a microgrid is a parameter that can greatly limit the hosting capacity of inverter-based generators. This necessitates either installing energy storage or limiting the amount of inverter-based generation. Energy storage, predominantly in the form of a BESS, is an important component in the reliable operation of microgrids. It becomes increasingly more importance as the share of renewable energy sources grows. Technologies such as flywheels and batteries can respond very quickly to changes in demand and can provide frequency support and reserve capacity in even more effective ways than traditional synchronous generators. BESS can act as a generation or load, and respond very quickly, contributing to system flexibility.

While BESS are the solution to stability issues in systems with high penetration of variable energy sources, it is not always present. In some implementations, BESS may not be part of a project, and in other implementations, it may be installed at a later stage of a initial project step. In a multi-stage deployment, the system owner and operator may deploy as much variable energy sources at first, and the BESS in a subsequent stage. In this interim operation, the microgrid can experience instability if not well planned and designed. In these cases, the grid-forming device is typically a rotating synchronous generator, such as a gas-fired turbine or a diesel reciprocating engine.

To address this need, Sumanik et al. [4] have proposed limiting the penetration of renewable energy resources by either reducing the installed nameplate or by curtailing renewable energy output to ensure energy balance in the system. Zrum et al. [5] is more relevant to this chapter and has proposed monitoring frequency and voltage excursions to determine the maximum renewable resources penetration based on how well these excursions stay within predefined bands. The research was based on a case study of a small scale northern isolated grid and, while providing insight on system hosting capacity, it was reliant on a case study and difficult to expand to different systems.

The next section introduces a hosting capacity method that can be used to determine the maximum utility-scale penetration of inverter-based renewable generation prior to interconnecting a BESS. It is based on the capability of synchronous generator(s) to ride through large disturbances caused by rapid reduction in renewable generation production and on typical relay frequency settings. The result is a set of practical charts that can be directly adopted to guide utility engineers in integrating renewable generation in microgrids prior to the installation of a utility scale BESS. The charts were developed for a generic system but sensitivity studies allow expanding their application to any microgrid.

3 Hosting Capacity Determination

The principle behind determining maximum hosting capacity is to ensure any or all synchronous generator(s) have sufficient margin to allow their governors to recover from large disturbances without losing stability or exhibiting excessive frequency fluctuation. In this section, the extreme disturbance is represented by sudden reduction in renewable generation output. The classic examples of sudden output variations

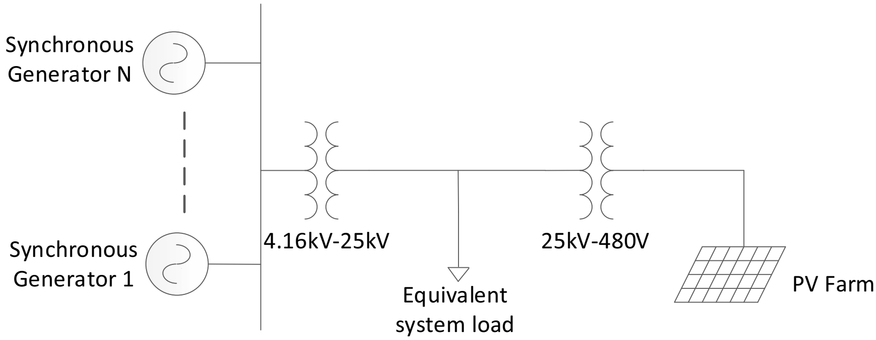

Fig. 1 Simplified system topology

are rapid cloud coverage or insufficient ride through capability that can lead photovoltaic inverters to trip upon system disturbances, such as a lateral fault. To note, compliance with IEEE Std. 1547 [6] does not guarantee low-voltage ride through for such events, for inverters of Category I and II of this Standard for example. In the context of typical microgrids, where a photovoltaic generation plant is in the order of a few hundreds of kW, the production drop can be instantaneous.

The generic system used to derive this method is illustrated Fig. 1. In this system, a number of synchronous generators are connected to a common bus. Their terminal voltage is chosen to be 4.16 kV as this is a common voltage level for this application. The analysis in this section is not affected by this choice. A photovoltaic generation plant is connected near the synchronous generator powerplant. The total system equivalent load is condensed as shown in the figure as well. This topology reflects the real case study that will be presented in a later section of this chapter.

The purpose of the tests shown in this section is to examine the impact on the system frequency response. To capture worst-case scenario, the assumptions are:

1. Only one generator is running at full output.
2. The photovoltaic generation plant reduces output from ac nameplate to zero in less than one cycle.
3. System load is constant power and at unity power factor

The result for different photovoltaic plant sizes is shown in Fig. 2, which illustrates expected frequency excursions for different penetration levels (percent of operating load). In this simulation, the photovoltaic system ceases to energize at 5 s. The figure suggests that penetration levels as low as 28% can result in frequency nadir nearing 57 Hz, and for a penetration level of 83%, the frequency nadir nears 51 Hz. Clearly, some of these penetration levels are very likely to cause the synchronous generator frequency relay pick-up and trip initiation. This results in a microgrid-wide blackout, as all generation sources will trip for the simple fact the photovoltaic inverter ceased to energize, even though the synchronous generator has capacity to pick up this load.

Rather than to ascertain whether a frequency relay will pick up or not, it is more useful to determine the amount of time the frequency deviates below a certain

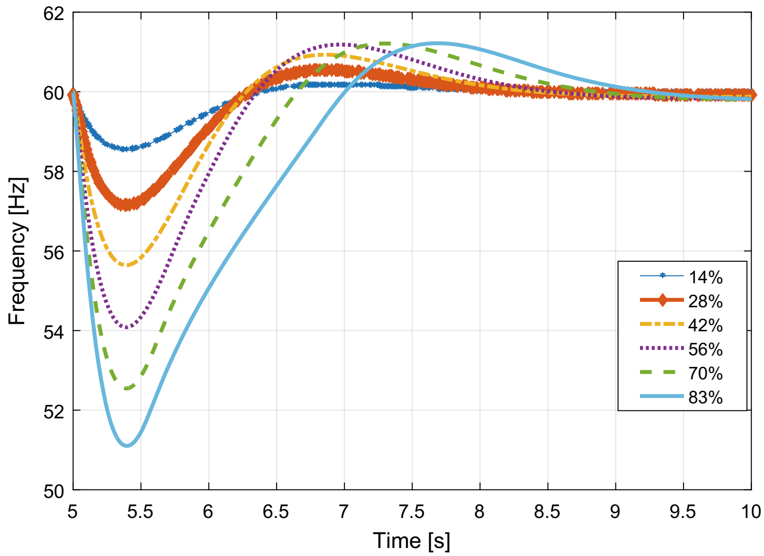

Fig. 2 Frequency response for total loss of PV farm

threshold. Figure 3 illustrates the time at which the frequency dips below different thresholds (57, 58, and 59 Hz) as the photovoltaic generation penetration level increases. To note, utilities supplying remote microgrids often employ relaxed trip levels and a common trip setting in Northern Canada is 57 Hz with a delay of 3 s. This level is lower than those specified in the Western Electricity Coordinating Council (WECC) WECC Off Nominal Frequency Requirements (effective December 5, 2003) and OPP 804 "Off-Nominal Frequency Load Shedding and Restoration" [7] that are applicable to the interconnected transmission grid. Sensitivity studies can be conducted to expand the findings of this chart to other systems.

4 Hosting Capacity Charts

The chart presented in Fig. 3 was developed based on the parameters and topology of a real system. For the purposes or replicating the results in Fig. 3, the parameters of the synchronous generator are presented in Table 1. This generator is a real unity employed in a remote microgrid. The governor and Automatic Voltage Regulator (AVR) were tuned during commissioning (site acceptance testing) and their parameters are not varied in this study.

The derivations of the figures presented in this section were obtained by repeating Electromagnetic Transient (EMT) simulations at each penetration level, resulting in hundreds of simulated data stored and plotted in the same graph. Figure 4 shows the impact of generator inertia constant, measured in seconds, on the time at which the

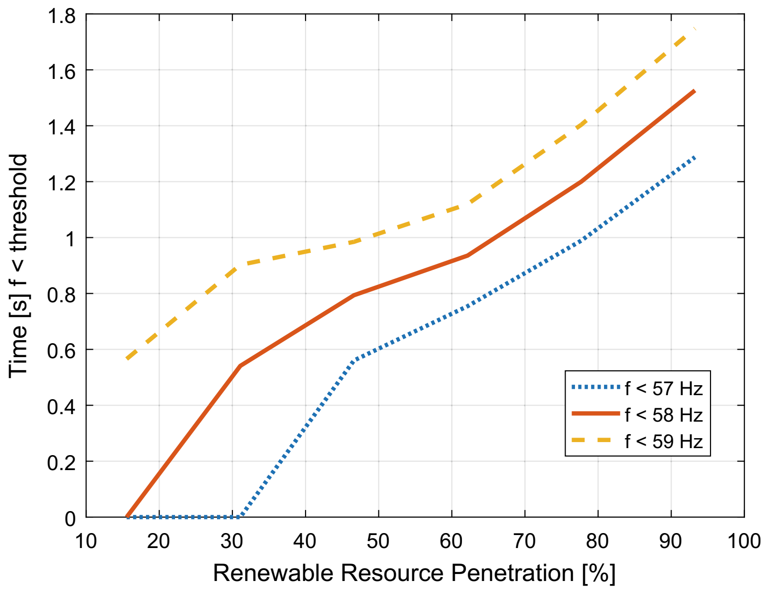

Fig. 3 Timing the frequency dips below threshold at variable penetration levels

Table 1 Generator nameplate

$P_{nominal}$	X_d	X'_d	X''_d	H
1.43 MW	1.56 p.u	0.29 p.u	0.17 p.u	0.6 s

frequency dips below 57 Hz. As expected, the lower the inertia constant, the faster the synchronous generator will respond to a disturbance, recovering from the frequency dip more rapidly. Larger values of inertia constant result in a slower response, dipping for longer.

The instantaneous synchronous generator loading factor is also a very impacting parameter. While the instantaneous system loading varies, the generator output is routinely controlled by the dispatch strategy and generators stacking order by the plant programmable logic controllers. It is also a normal practice to dispatch a second generator when the running unit(s) reach about 90% of its (their) rated output, to provide spinning reserve for riding through disturbances. Intuitively, the more loaded a generator, the less capable it will be to recover from a disturbance. This is quantified in Fig. 5.

Finally, the aggregate load power factor is varied to analyze its impact. Intuitively, a lower load power factor (lagging) will necessitate a generator to produce VARs (overexcited operation). This overexcitation strengthens the field excitation voltage, increasing stability margin and causing the generator to respond to disturbances more promptly. This is confirmed by Fig. 6, which quantifies the effect and confirms that as the load power factor is reduced, the frequency dip lasts for less time. This analysis

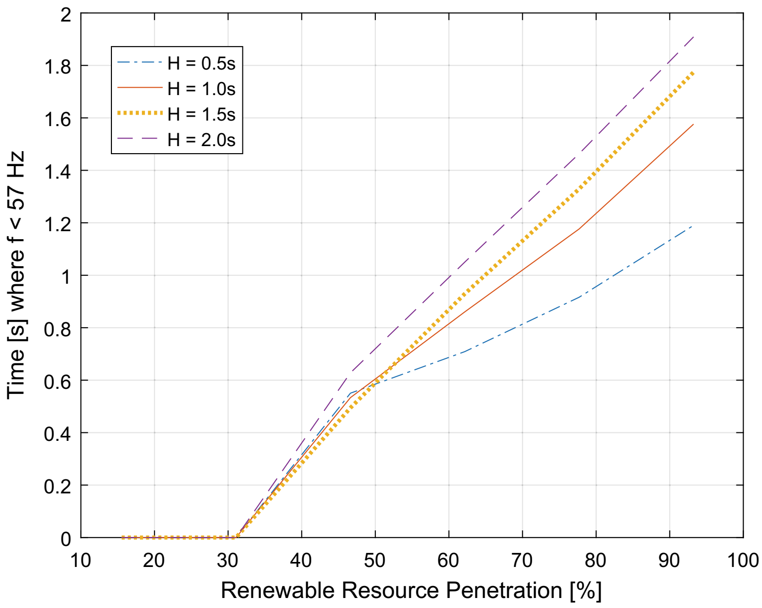

Fig. 4 Renewable generation penetration sensitivity study for different inertia constant values

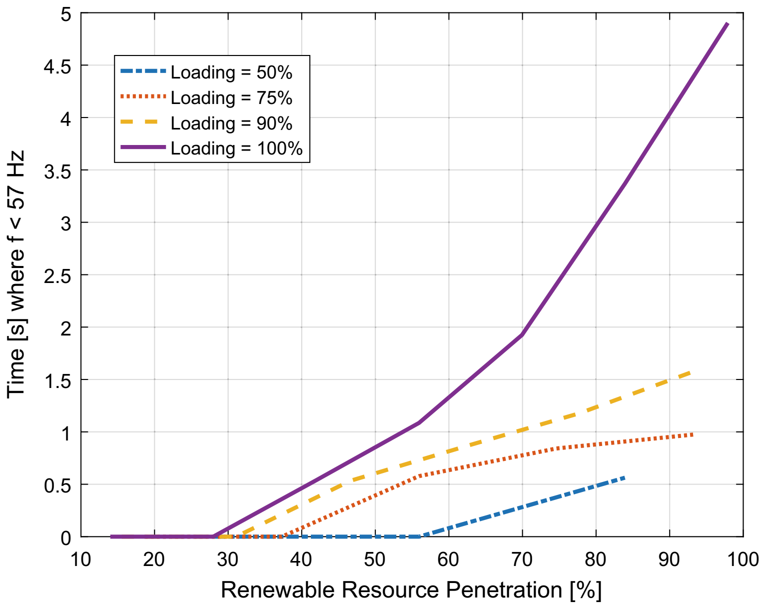

Fig. 5 Renewable generation penetration sensitivity study for diesel generator loading factors

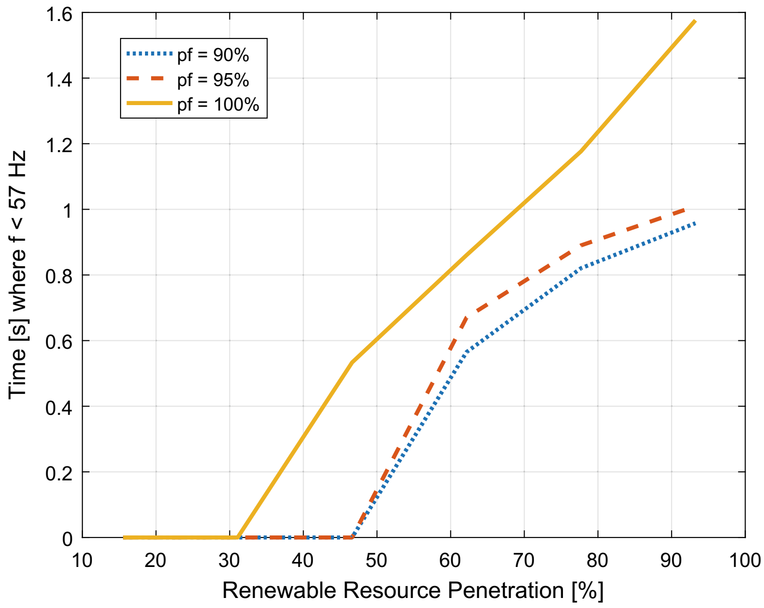

Fig. 6 Renewable generation penetration sensitivity study for different load power factor values

assumes the photovoltaic inverters operate at unity power factor, their default factory setting.

5 Case Study: Remote Off-Grid Microgrid—Frequency Deviation

The case study presents an isolated community, which is one of the oldest European settlements in the province of Alberta, Canada. Currently, it houses three First Nations with a total population of close to 900 dwellings. There is no natural gas supply in this community, and residents are reliant on diesel heating and electricity only. The electricity is generated at 4.16 kV and stepped up to 25 kV. All four diesel generators are identical and rated 1.15 MW/1.28 MW/1.45 MW (nominal/prime/overload ratings). The distribution system comprises two 25 kV feeders, which supply some load near the plant and emanate about 8 km south, where they supply most of the town load.

A historic yearly consumption data for both feeders combined is shown in Fig. 7, containing 8760 h of powerplant metered data. The data suggests higher consumption during fall and winter, and lower consumption during spring and summer, as it would be expected in Northern locations. During warm summer days, the load is sufficiently low that only one diesel generator unit can supply the entire community, while during

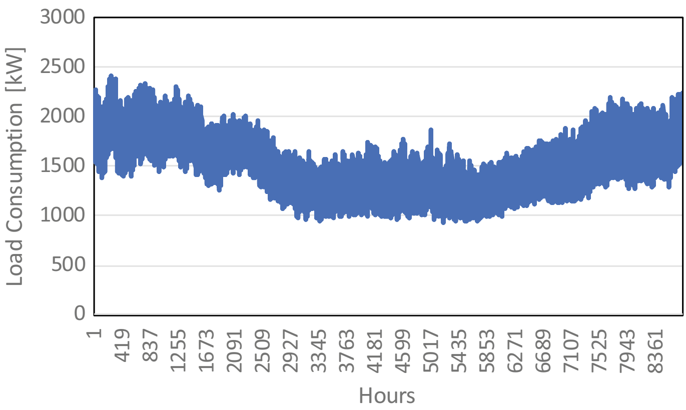

Fig. 7 Historic yearly total load supplied by the system

dark winter nights three diesel generators must run simultaneously to supply the system.

The community has experienced unprecedented load growth, supporting municipal infrastructure upgrades such as the uprate of a waste water treatment plant, a refurbished pumping system, and a new recreational center. As part of this project, the load growth sensitivity analysis was completed until 2023. A portion of this analysis is shown in Fig. 8. Three forecast levels were produced, and all of them suggest a substantial and continued growth.

The community is only accessible by an ice road in the winter, for an average of 6 weeks when the ice road is sufficiently strong to support refueling trucks. The issue

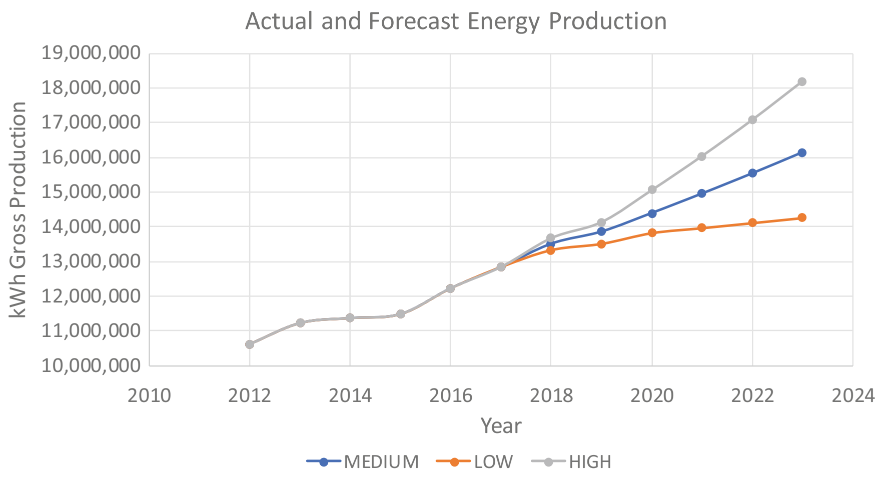

Fig. 8 System load forecast up to 2023

faced by the utility is that the powerplant contains 12 diesel tanks, with total storage of about 3,300,000L capacity. The analysis revealed that the diesel storage capacity has become insufficient to supply the community between times refueling. In response, the electric utility has spearheaded planning efforts that employ two PV farms, phased into two stages. In 2019, a 450kWac/600kWdc plant was commissioned to offset some of the load consumption. This size was chosen to optimize the diesel savings to offset the immediate shortage of diesel storage and to ensure system frequency stability. This is the focus of this first part of the chapter. Further expansion of the renewable generation plant and the addition of a BESS is the second stage of the project and will be presented in the second part of this chapter. In short, to further address the issue of diesel storage, a larger solar farm, sized 1.9MWac/2.2MWdc was installed in 2020, in the second stage of the project. This amount of generation is very large as compared with the historic system load. In response, the utility has also employed a 1.6 MW/1.6MWh BESS, as well as a microgrid controller. The reasoning for choosing a combination of photovoltaic generation and BESS, as well as the sizing optimization exercise, was presented in Nejabatkhah et al. [8].

The small photovoltaic farm installed early in 2019 was located very close to the diesel plant. The size of the photovoltaic farm was the result of a techno economical optimization that is out of the scope of this chapter. Among the technical requirements, the EMT analysis presented in the previous section was a deciding factor in not exceeding 600kWdc/450kWac. Figure 9 shows a simplified system diagram.

During the photovoltaic plant commissioning, a condition of full PV output (450kWac) and two generators running at about 650 kW each was captured. Under this condition, the photovoltaic plant was intentionally tripped by opening the overhead three-phase interrupter. Measurements were recorded and compared with a similar loading simulated case. This is shown in Fig. 10. While not an exact match, the results are close enough to validate the model and methodology. The measurements were acquired by using a portable power quality monitor that samples the three phase voltages and currents at a sampling rate of 1024 samples/cycle and stores continuous waveform data. Data post-processing is then carried out to calculate several system parameters, including frequency.

For the case study, the electric utility determined a safe hosting capacity for its utility scale PV farm would be about 40% of the size of the diesel generator. For most disturbances, the studies contained in the paper deem this penetration level to be safe.

6 Part 2—Protection and Grounding Strategies in Microgrids

Reliable protection and grounding schemes have been well established for power systems connected to the BES. With the advent and proliferation of microgrids, however, these subjects need to be revisited as traditional philosophies are no longer

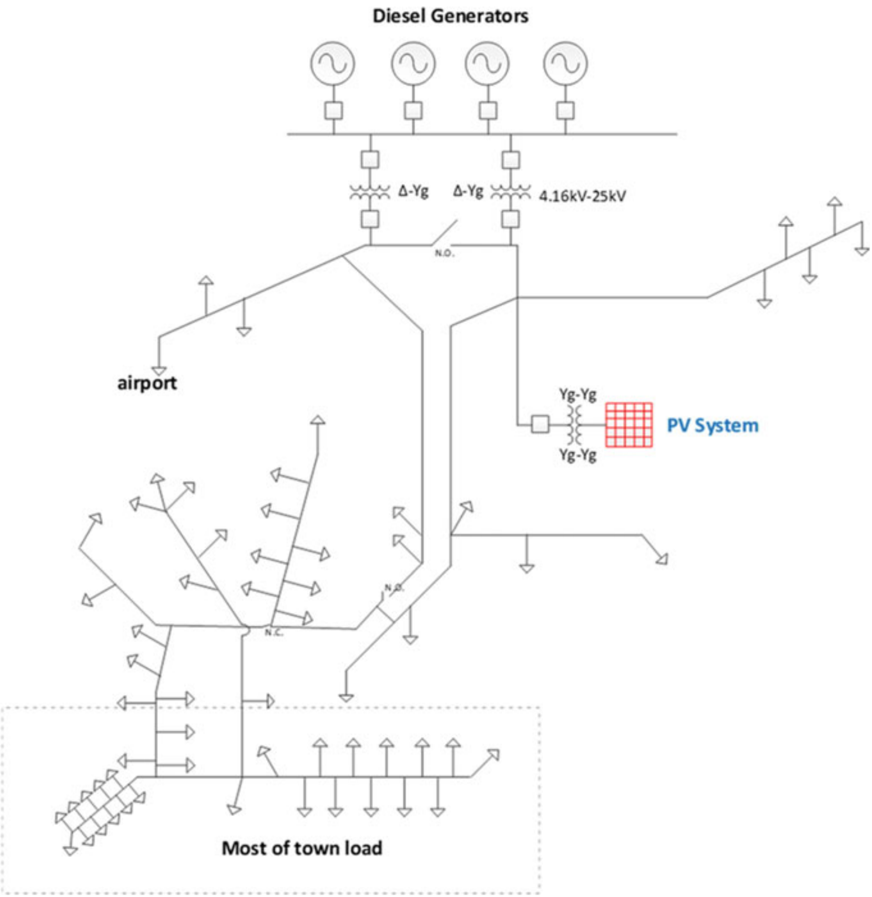

Fig. 9 Simplified electrical system topology

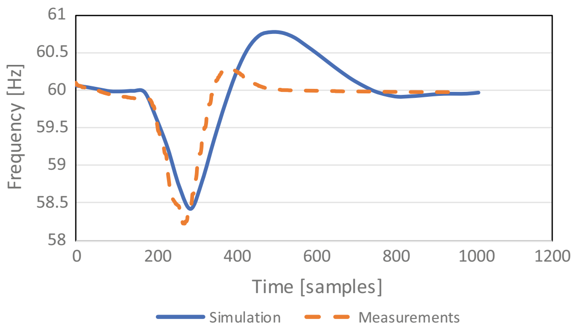

Fig. 10 Simulation and measurements for PV plant disconnection

sufficient to cope with reduced short circuit levels of DER. A DER-dominated microgrid will experience a limitation in the functionality of traditional overcurrent elements. This can degrade protection coordination and selectivity and requires a philosophy that is nonstandard in distribution systems. Furthermore, with most DERs operating as constant current sources and not naturally supplying ground current, performance grounding also becomes a fundamental problem of microgrids. Additional ground sources are required and must be appropriately sized for the needs of the microgrid. The next sections of this chapter present a practical protection and grounding scheme and their application. Much of the theory was developed tailored to a real off-grid microgrid and serves to reinforce the need for new philosophies that consider practical aspects of real systems.

7 Traditional Protection Philosophies

Protection and grounding are strongly interrelated subjects and to properly describe grounding requirements, it is imperative to first provide a background on traditional protection practices.

Distribution system protection is predominantly employed as non-directional definite-time and timed overcurrent protection. These elements can reliably protect systems containing only one source (i.e., a substation or a generation plant). In multi-sourced systems, where the protection sensing element can experience reverse current in both steady-state and short-circuit conditions, it becomes necessary to employ overcurrent protection with torque control. These adaptations worked well when emerging DERs were predominantly rotating synchronous machines, which supply considerable amounts of short-circuit current in case of system faults.

The proliferation of inverter-based generation, however, has introduced a new problem. These topologies typically supply only small (compared with their nameplate) amounts of short-circuit current, which tend to render static overcurrent protection ineffective. Even adaptive protection schemes, such as the one described in Brahma et al. [9], do not necessarily enable fault detection because most inverters supply a constant current balanced supply. While grid-forming BESS inverters are typically capable of supplying imbalanced currents, their fault currents are normally comparable in magnitude with their nameplate steady-state current. Hence, it is imperative to employ protection philosophies that do not rely on current sensing for fault detection in microgrids with high penetration of inverter-based DERs. At the same time, while researchers have made great strides in advancing adaptive protection schemes, these are still considered complex and have not achieved a high degree of commercial maturity for applications in mission critical systems such as remote communities.

Among mature relaying elements, undervoltage has been employed in microgrids, as described in Zamani et al. [10], and is commonly present in the protection suite of generators. In these cases, undervoltage elements are used to protect the generator, rather than the system. Relying on this element represents a paradigm shift because:

1. This is an element not typically used to protect distribution systems. As such, it is not easy to determine adequate settings;
2. It is difficult to ensure required trip times are achieved as the voltage behavior is not as predictable as current. EMT simulations highly depend on modeling assumptions;
3. Protection coordination between undervoltage and overcurrent schemes is not easy to perform. These have independent time characteristics;

With this being said, islanded microgrids may have to rely on undervoltage elements in today's state of technological maturity, especially in mission-critical applications where risk tolerance is very low. The advantage of inverter-based DERs is that these inverters are normally more resilient to abnormal voltage and frequency conditions, allowing voltage pickup settings to be extended in wider ranges. To increase dependability, underfrequency elements can also be used. Both voltage and frequency behaviors of the BESS cannot be characterized easily by using generic models. While a vendor-provided model can help characterize the voltage envelope by conducting short-circuit studies, the frequency behavior requires EMT simulations and the use of a very accurate BESS model.

8 Effective Grounding in Microgrids

Effective grounding is a condition required for the safe and reliable operation of power systems by multiple standards. The following excerpt from IEEE Std. C62.92.1 [11] highlights the importance of grounding and serves as a preamble to its application. "There is no simple answer to the application of grounding. Each of a number of possible solutions to a grounding problem has at least one feature that is outstanding, but which is obtained at some sacrifice of other features that may be equally worthy".

In the context of microgrids and power systems in general, protection and grounding have conflicting requirements. Temporary Overvoltages (TOV) usually result from in insufficient ground currents during a ground fault. The classical and extreme example is a three-wire delta system, where a ground fault results in the two healthy phases to rise to line-to-line values, while the faulted phase does not supply any fault current to ground. Conversely, a fully grounded system will not experience any voltage rise in the healthy phases but will have large fault current to ground ($Z_0 = Z_1$). Hence, having adequate ground sources ensures TOV is mitigated to an acceptable level. The problem arises when ground sources are distributed across the distribution system, resulting in reduced fault current from the main source (substation or generation plant) and desensitizing the main feeder relay overcurrent elements. This desensitization effect was well documented by Nassif [12], and represented in Fig. 11, which illustrates the de-sensitization effect due to DER infeed (in this case, the substation fault current will be reduced in magnitude due to the DER fault contribution to the fault).

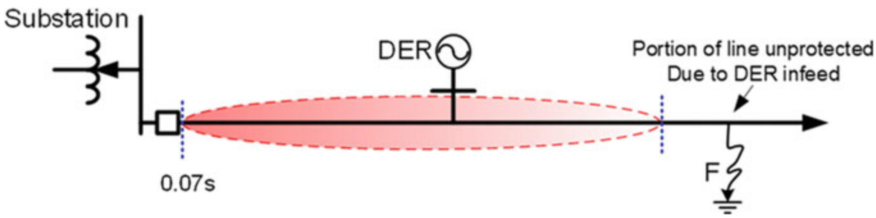

Fig. 11 Illustration of the infeed effect

For a symmetrical fault, only the positive-sequence network exists, and it can be shown that the substation fault current contribution is governed by equation below.

$$i'_{S\_f} = i_{S\_f} - i_{G_f} \times \frac{Z_{L2}}{(Z_S + Z_{L1} + Z_{L2})}, \tag{1}$$

where Z_s is the positive-sequence substation source impedance, Z_{L1} is the positive-sequence impedance of the line segment between the substation and the DER location, Z_{L2} is the positive-sequence impedance of the line segment between the DER location and the fault location, i_{s_f} is the original substation fault current contribution, and i_{G_f} is the DER short-circuit current.

Similarly, a single-line-to-ground fault results in the following infeed, caused by the DER:

$$i'_{S\_f0} = \frac{V_0}{Z_{S\_0} + Z_{L1\_0} + Z_{L2\_0} + \left(\frac{[Z_{S\_0}+Z_{L1\_0}]\times Z_{L2\_0}}{Z_{G\_0}}\right)}, \tag{2}$$

where Z_{s_0} is the zero-sequence substation source impedance, Z_{L1_0} is the zero-sequence impedance of the line segment between the substation and the DER location, Z_{L2_0} is the zero-sequence impedance of the line segment between the DER location and the fault location, Z_{G_0} is the zero-sequence subtransient (or equivalent) source impedance of the DER and V_0 is the equivalent zero-sequence voltage.

As one can see, a DER that injects large ground current into a fault will desensitize upstream protection elements. As it will be shown next, this represents a conflicting requirement between protection and ground, and a balance must be struck. This section contains a review of grounding parameters and the classification of grounding practices based on their calculations.

8.1 Degree of Grounding and Effective Grounding

IEEE Std. 142 [13] prescribes the requirements for a system to be considered effectively grounded. It defines the Degree of Grounding (K) as

$$K = Z_0/Z_1. \tag{3}$$

According to IEEE Std. 142 [13], a location is called *effectively grounded* if it is grounded through a sufficiently low impedance such that for all system conditions the ratio X_0/X_1 is positive and not greater than 3 and the ratio R_0/X_1 is positive and not greater than 1. It is also possible to express TOV as a function of the degree of grounding (K).

8.2 Temporary Overvoltage (TOV)

Temporary Overvoltage is defined as the voltage ratio between the highest phase voltage of an un-faulted (healthy) phase during a ground fault and the pre-fault voltage (both are phase-to-ground voltages). It can be proven that the TOV can be expressed as a function of the degree of grounding K (proof omitted to save space):

$$TOV = \left| \frac{1-K}{2+K} + 1\angle -120^{\circ} \right| \tag{4}$$

This equation enables the following observations:

- For $K = 1$ ($Z_0 = Z_1$), TOV = 1 (this condition is called fully grounded);
- For $K = 3$, TOV = 1.25 (boundary condition);
- For $K = \infty$ ($Z_0 = \infty$), TOV = $\sqrt{3}$ (this condition is called ungrounded).

8.3 Coefficient of Grounding and Effective Grounding

The Coefficient of Grounding (COG) is defined as the highest rms line-to-ground power–frequency voltage on a sound phase, at a selected location, during a line-to-ground fault affecting one or more phases, as explained in IEEE Std. 141 [14] and 142 [13]. It can be formulated as:

$$COG = \frac{V_{max-line-to-ground}(duringfault)}{V_{line-to-line}(prefault)}. \tag{5}$$

If the COG is below 80%, the location is called effectively grounded. This equation is equivalent to:

$$COG = \frac{V_{max-line-to-ground}(duringfault)}{\sqrt{3} \times V_{line-to-ground}(prefault)}. \tag{6}$$

As discussed in IEEE Std. 141 [14], this translates to defining the condition of an effectively grounded system as $TOV = \sqrt{3} \times 0.8 = 138\%$. The effectively grounded threshold of 138% differs from that obtained by the criteria presented in IEEE Std. 142 [13], which translate to roughly about 125%. This has led to utilities adopting one or the other threshold to accept a system grounding characteristic, especially when interconnecting DERs.

8.4 Grounding Practices When Integrating DERs

DER interconnection standards, such IEEE 1547–2018 [6] and the Canadian Standards Association CSA C22.3 No. 9:2020 [15], address the several possible grounding conditions when interconnecting DERs. However, no standard provides a definite prescription of which transformer winding configurations are necessary for interconnection, allowing the electric utility freedom on how to achieve effective grounding. As explained in Vukovejic and Lukic, some utilities do not allow a DER transformer connection configured as a Δ–Yg (low side Δ) because this transformer provides a low impedance ground path, effectively reducing the ground current flowing through upstream protective devices due to the infeed effect (refer again to [12]. Systems with high DER penetration can face an unmanageable situation if this configuration is predominant.

For the reasons above, distribution utilities often require DER step-up transformers to be configured as Yg-Δ (low side Yg) or as Yg-Yg. The Yg-Δ configuration has the obvious effect of disallowing any ground fault current to flow into the distribution system, effectively eliminating the infeed effect, as described by Vukojevic et al. [16]. As explained in the previous section, however, this contributes negatively to the *Degree of Grounding* and *Coefficient of Grounding*. It is also important to point out that string inverters and central inverters used for photovoltaic generation applications are oftentimes constructed in delta or wye, but they do not supply zero-sequence current as they are strictly built as balanced current sources. As a result, unless the Δ–Yg configuration is used, photovoltaic generators will not contribute any ground current to ground faults. This is a normal practice adopted by distribution utilities to DERs connected to a feeder supplied by the BES.

Microgrid applications are different, however. As discussed earlier, a microgrid interconnected to the BES or a microgrid supplied by an isolated generation plant may become isolated from the substation grounding reference and will need to provide a ground source to supply line-to-ground connected loads while in islanded operation. As a result, a ground reference is needed. A workable option is to incorporate this ground reference in the grid-forming asset, which can be a BESS when the microgrid is islanded. This can be achieved by either using the Δ–Yg configuration as the BESS step-up transformer, or by installing an additional grounding transformer (addressed in the next section).

Using the Δ–Yg configuration offers the following advantages:

– It reduces K, improving the coefficient of grounding in weak systems.

– Reduced fault currents for faults in the inverter terminals of the BESS, leading to reduction in arc flash incident energy for ground faults.
– Allows protective devices installed on the high voltage side of the step-up transformer to operate on overcurrent sensing, since the configuration amplifies any ground fault current.

Hence, the electric utility has a choice to provide a grounding reference on the distribution feeder, either to employ a Δ-Yg transformer or to install a grounding transformer.

8.5 Grounding Transformer Design

Grounding transformers can come in several configurations. In distribution system applications, a grounding transformer is typically a Zig-Zag-Δ or an Yg-Δ (low side Δ winding can be kept unloaded). The grounding transformer provides a ground source by providing a very low impedance zero-sequence path. Figure 12 illustrates the its design. In this conceptual design, a grounding transformer with Z_{T1} and Z_{T0} is installed in a system with Z_{S1} and Z_{s0} impedances.

The new zero sequence system impedance Z_{0_New} can be calculated as (given the typical high *X/R* ratio of the transformer, it is assumed it does not alter the system positive-sequence impedance to a noticeable extent):

$$Z_{0\_New} = Z_{S0}//Z_{T0} \tag{7}$$

Utilizing the criterion for effective grounding ($K = Z_0/Z_1 < 3$), Z_{T0} can be obtained by solving the following equation:

$$K = \frac{Z_{0\_New}}{Z_1} = \frac{(R_{S0} + jX_{S0})(jX_{T0})}{R_{S0} + j(X_{S0} + X_{T0})} \times \frac{1}{(R_{S1} + jX_{S1})} \leq 3 \tag{8}$$

The required transformer rating, in KVA, can then be calculated by

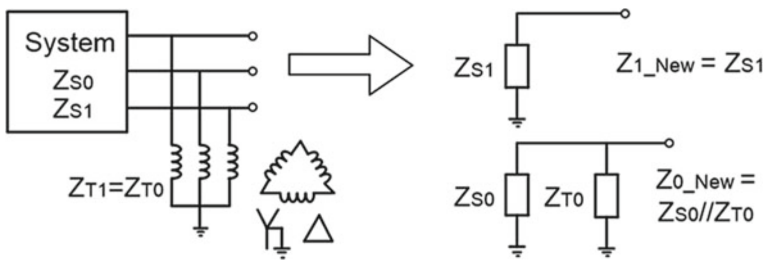

Fig. 12 Illustration of a grounding transformer connection and impact on the zero-sequence equivalent network

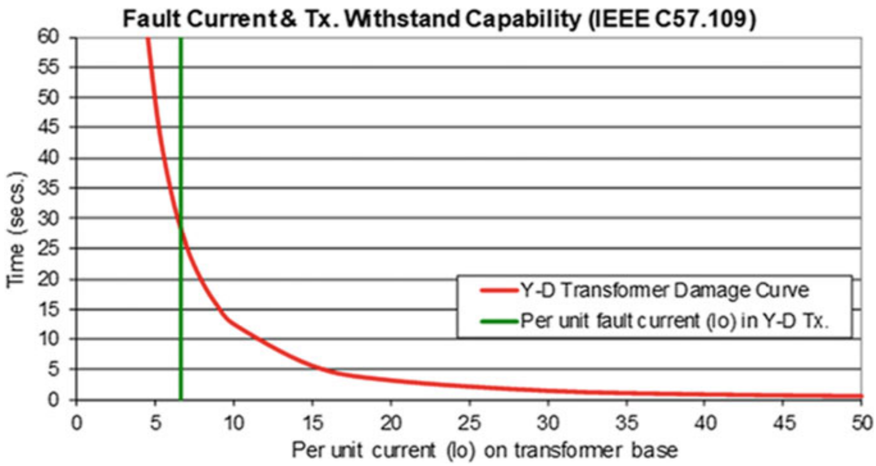

Fig. 13 Transformer damage curve vs. per-unit ground current supplied by the transformer during fault

$$S = \%Z_{base} \times V^2 / Z_{T0} \tag{9}$$

Furthermore, the transformer needs to be properly rated and verified not be damaged during system faults, as per IEEE Std. C57.109 [17], which prescribes minimum requirements for through-faults of oil-filled transformers (damage curve). This is the minimum manufacturing requirement and results in a decaying curve that relates fault current ($3I_{T0}$) and clearing times. The calculations following the procedures contained in IEEE Std. C57.109 [17] are plotted and displayed in Fig. 13 (decaying curve). The fault contribution of a sample grounding transformer (obtained from short-circuit software) is shown in the vertical line. In this example, which is only used for illustration and not intended to be representative, the transformer contributes about 7 times its rated current to the ground fault, and it will suffer damage if the fault persists longer than 28 s.

9 Case Study: Remote Off-Grid Microgrid—Protection and Grounding Characteristics

The same remote off-grid microgrid presented in the last section is being further retrofitted in 2020 with a much larger photovoltaic system and a BESS. As most microgrids with high penetration of inverter-based generation, the system under study has many of the same limitations experienced in other similarly sized microgrids. The case study used to explain the concepts of performance grounding and protection is the same system presented in Fig. 7, in the first part of this chapter.

This area has a very rocky and sandy soil, with very high soil electric resistivity. To improve ground fault detection, both feeders have a continuous Multi-Grounded Neutral (MGN), a common practice also found in other microgrids as described by Vukojevic [18]. This is a common practice in systems where the grounding resistance is high. The MGN has an expected effect of reducing the overall ground fault resistance due to the combined effect of the various installed electrodes. The practice often involves installing a grounding plate if the measured soil resistance at the electrode installation does not meet design standards. This effort generally results in increased ground fault current, enabling conventional protective devices to operate upon a ground fault.

Figure 14 shows a single-line diagram of the real microgrid system used to investigate the application of protection and grounding techniques. This is the same

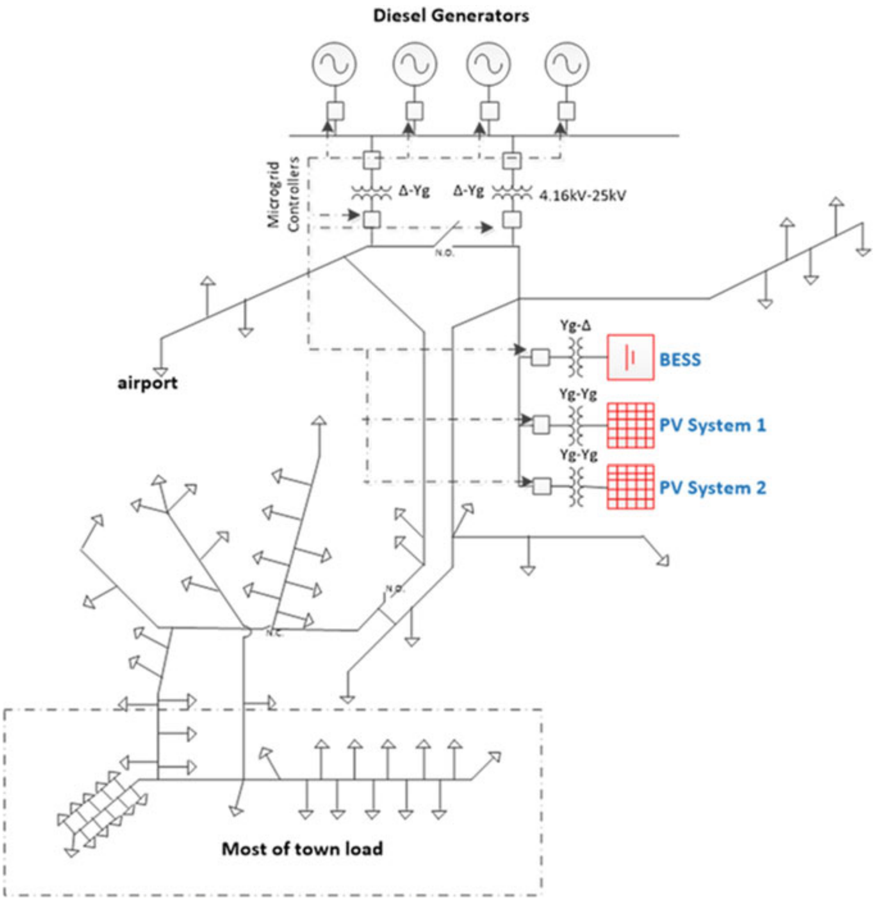

Fig. 14 Remote off-Grid microgrid fitted with DERs and a microgrid controller

system shown in Fig. 7, but with the deployment of the second phase of photovoltaic generation, sized 1.9MWac/2.2MWdc, and the addition of the BESS, sized 1.6 MW/1.6MWh, and a microgrid controller. The generators and their step-up transformers were described in previous sections.

The architecture of the microgrid controller is as follows. Each of the indicated components in Fig. 14, namely each of the four diesel generators, the main feeder breakers and reclosers, the photovoltaic systems and the BESS, were fitted with a decentralized microgrid controller, represented by the dot-dashed lines. This allows a high degree of system visibility and controllability. The optimization to arrive at these DER sizes and topologies was presented in Nejabatkhah et al. [8] and is outside of the scope of this chapter.

9.1 Available Short-Circuit Current in Islanded Mode

The off-grid microgrid is being equipped with a 1.6 MWh BESS and an aggregate 1.9 MWac photovoltaic system. Their inverter short-circuit capabilities, as provided by the manufacturer, are 1.13 p.u. and 1.0 p.u., respectively. This is maximum line-line-line (LLL) fault contribution. Conversely, the BESS is coupled through a Δ-Yg (Δ low side) transformer, resulting in substantial line-ground (LG) fault contribution (due to the transformer, not the BESS). Hence, it is not possible to use overcurrent protective elements to adequately protect the system for LLL faults, and only possibly to protect for LG faults. Tables 2, 3, and 4 show the fault current contributions of each component (diesel plant, photovoltaic farm, and BESS) for LLL, LG, and impeded LG (20 Ω) faults placed at the end of the feeder when the microgrid is grid-connected. When operating under grid-connected mode, the medium-voltage fault interrupters installed at the BESS and photovoltaic Point of Common Coupling (PCC) should not trip, as these do not have auto-reclosing enabled (for obvious reasons). In these tables, DiG stands for diesel generator and I_Plant denotes the current detected at the feeder head emanating from the diesel powerplant. The overcurrent protection for an LLL fault at the diesel powerplant is not significantly affected by the addition

Table 2 Short-circuit results for an LLL bolted fault at the end of line

LLL $I = I_P$ [A]	1 DiG	1 DiG + BESS	1 DiG + BESS + PV	2 DiG	3 DiG	3 DiG + BESS + PV
I_total	123	160	214	214	282	357
I_Plant	123	121	117	214	282	269
I_BESS	–	39	38	–	–	34
I_PV	–	–	46	–	–	42
V_DiG	380 V	480 V	600 V	720 V	1000 V	1080 V
V_BESS	–	50 V	60 V	–	–	100 V
V_PV	–	–	70 V	–	–	120 V

Table 3 Short-circuit results for a LG bolted fault at the end of line

LG_0Ω $I = 3I_0$ [A]	1 DiG	1 DiG + BESS	1 DiG + BESS + PV	2 DiG	3 DiG	3 DiG + BESS + PV
I_total	192	223	278	291	348	407
I_Plant	192	137	167	291	348	245
I_BESS	–	86	104	–	–	153
I_PV	–	–	6	–	–	9
V_DiG	900 V	1000 V	1000 V	1240 V	1470 V	1530 V
V_BESS	–	100 V	110 V	–	–	140 V
V_PV	–	–	130 V	–	–	280 V

Table 4 Short-circuit results for an impeded LG fault at the end of line

LG_20Ω $I = 3I_0$ [A]	1 DiG	1 DiG + BESS	1 DiG + BESS + PV	2 DiG	3 DiG	3 DiG + BESS + PV
I_total	176	199	235	242	272	299
I_Plant	176	123	141	242	272	180
I_BESS	–	76	88	–	–	112
I_PV	–	–	6	–	–	7
V_DiG	1000 V	1100 V	1270 V	1500 V	1700 V	1830 V
V_BESS	–	110 V	130 V	–	–	180 V
V_PV	–	–	210 V	–	–	270 V

of the DERs and can be just as effective as it was prior to their interconnection. For ground faults, however, the fault sensed at the feeder head can reduce as much as 30% due to the apparent effect. However, it is still possible to work with the existing protection philosophy.

Table 5 show the short-circuit results for islanded operation (when the BESS forms the grid). In a stark contrast to the results shown in Tables 2, 3, and 4, overcurrent no longer works.

Table 5 Short-circuit results for a fault at the end of line (islanded mode)

	LLL ($I = I_P$)	LG_0Ω ($I = 3I_0$)	LG_20Ω ($I = 3I_0$)
I_total [A]	102	140	132
I_Plant [A]	0	84	80
I_BESS [A]	40	52	50
I_PV [A]	48	3	3
V_DiG [V]	220	930	740
V_BESS [V]	30	110	90
V_PV [V]	40	70	120

9.2 Voltage Excursions and Undervoltage Protection

The voltage envelope was obtained through short-circuit studies. The calculated voltages for the grid-connected operating mode are shown in Tables 2–4, and those for the islanded mode are shown in Table 5. To note, the nominal voltage of the DiG, BESS and photovoltaic plants are 4.16 kV, 480 V, and 600 V. These calculations reveal that the voltage drop at the BESS and photovoltaic plants (measured in their low voltage bus) are somewhat, under either grid-connected or islanded modes, in the same order of magnitude of each other.

9.3 Performance Grounding Assessment

Table 6 shows the system parameters when grid-connected (first 5 columns), and when islanded (last column and denoted as BESS + photovoltaic), calculated by using the same short-circuit software. To note, the diesel powerplant step-up transformers are not removed from the system, as the entire station service remains energized. This results in the step-up transformers effectively functioning as sources (and essentially being grounding transformers to the system).

These results allow us to draw some observations:

1. The zero-sequence impedances do not vary significantly among the multiple operation modes. The reason being the fact the system always operates with the diesel plant step-up transformers energized. Because of their Δ-Yg configuration and size (4MVA each), they are the major system ground sources. The additional ground source provided by the BESS step up transformer (which is a 2MVA Δ-Yg transformer) reduces X_0 by only about 17%. Finally, the system multi-grounded neutral contributes to reduced degree of grounding.

Table 6 System characteristics for grid-connected and islanded modes

	1 DiG	1 DiG + BESS	1 DiG + BESS + PV	3 DiG	3 DiG + BESS + PV	BESS + PV
R_0	16	15	15	16	15	15
R_1	12	11	11	12	11	13
X_0	24	20	20	24	19	20
X_1	116	89	66	49	38	141
X_0/X_1	0.2	0.2	0.3	0.5	0.5	0.14
R_0/X_1	0.14	0.17	0.24	0.3	0.4	0.1
K	0.25	0.28	0.6	0.6	0.6	0.18
TOV	0.8	0.9	0.94	0.9	0.97	0.94
COG	0.45	0.5	0.54	0.5	0.6	0.54

2. The positive sequence impedance depends very substantially on the system configuration. Naturally, the stronger the source (more synchronous generators), the smaller will X_1 be. To note, the equivalent model of the BESS and photovoltaic results in very large X_1 when the system is operating in islanded mode. This relies on the assumption the generic BESS and photovoltaic inverter models are correct.
3. The system is effectively grounded under all operating scenarios. $K < 3$ under both microgrid operating modes.
4. The calculated TOV is less 125%, guaranteeing effective grounding under both microgrid operating modes. In fact, TOV < 100% under all operating scenarios, resulting in a fully grounded system with no healthy phase swelling at all during grounding faults. The calculated COG is less than 80%, the condition for effectively grounded as per IEEE Std. 142 [13].

10 Microgrid Operation, Protection Philosophy, and Restoration Strategy

The integration of the photovoltaic and BESS installations in the system and its conversion to a microgrid requires new protective devices and protection philosophy. Even though the topic of microgrids has been in vogue for over two decades, most deployments have been either proof-of-concept or demonstration projects. An example was presented in Vukovejic, 2018, which suggested employing a separate grounding transformer and not allowing the DER step-up transformers to introduce ground sources. There have been a few isolated microgrid implementations backstopped by similar drives, but so far there is no consensual recommendation on how to manage performance grounding. Hence, there is no “traditional” or “baseline” topology. This section introduces a strategy to manage performance grounding that was suited to the unique conditions of this system. The following items were important decisions made leading up to microgrid energization.

10.1 BESS Transformer Configuration

The 1.6 MW BESS is being coupled with a 2MVA, 25 kV-480 V isolation transformer. Much thought was put towards determining the transformer winding configuration and a Δ-Yg configuration was chosen. This configuration for the BESS transformer has the following advantages:

– This step-up transformer is suitable for supplying single phase-to-ground loads. It adds a ground source and allows feeder restoration even if the diesel plant is completely removed from the system, even though this is not a planned scenario.
– This configuration removes the need to install a grounding transformer in the microgrid when operating in islanded mode.

– This transformer reduces the degree of grounding, TOV, and COG, improving performance grounding.
– The disadvantages of this configuration are:
– The additional ground source de-sensitizes the main feeder interrupter. As seen in Table 2, I_Plant reduces from 192A, when the BESS is disconnected, to 137A when the BESS is connected, or about 29%. The original ground overcurrent pick-up value is 50A, which is suitable to detect LG faults, but with a longer time delay. A similar conclusion can be extracted by analyzing Table 3, which shows the results for an impeded fault. The de-sensitization effect was analytically characterized in [12].
– There will be a large infeed from the BESS for LG faults (see I_BESS in Tables 2 and 3). For proper operation, the BESS overcurrent protection needs to be torque controlled by voltage (polarized).

Overall, the flexibility of allowing operation with the feeder isolation from the diesel plant (a scenario deemed not to be needed now but may be in the future) led to the choice of a Δ-Yg configuration, even considering the above disadvantages.

10.2 Overcurrent and Reclosing Settings at BESS and Photovoltaic Fault Interrupters

The proposed settings for the photovoltaic and BESS distribution fault interrupters are based on their fault contribution and intended purpose. For foreground, below are the existing feeder fault interrupter settings:

– Main feeder (where the BESS and PV, as well as most of the load, are connected to): Phase pick-up 100A, ground pick-up 40A. The first trip is a fuse-saving fast trip that does not coordinate with downstream fuses; subsequent reclosing enables a slower curve, with the same pick-up values.
– Adjacent feeder (which mainly supply the town airport): Phase pick-up 80A, ground pick-up 40A. As in the case of the main feeder, this feeder also has a fuse-saving fast trip in the first activation of the interrupter.

10.2.1 Autoreclosing Philosophy

Both fault interrupters are protecting DERs. As such, in no case, they are protecting the distribution system, but rather the equipment beyond the PCC (on the DER side). For this reason, no autoreclosing is enabled. Having said that, the microgrid controller has the capability of closing them without human intervention, as required by the operational and restoration algorithms.

10.2.2 Voltage Polarization (Torque Control)

As discussed earlier and presented in Table 4, the PV fault contribution is about the same as its steady-state current output (see I_PV for an LLL fault). Hence, it was determined that voltage polarization for the PV interrupter is not needed and the pick-up values chosen were 80A phase and 40A ground, with the same curves as those of the feeder slow settings.

However, for the BESS, while the short-circuit contribution is only slightly higher than the rated output for an LLL fault (but still below the proposed pick-up value, see I_BESS in Table 4), it is much higher for a LG fault (see I_BESS in Table 4 for the LG cases), where it does exceed the proposed ground pick-up value. The latter is due to the transformer winding configuration, as discussed in the previous section. Hence, the settings chosen for the BESS interrupter are the same as those used for the PV interrupter, but with voltage polarization to avoid tripping on an upstream fault on the distribution system, which is to be cleared by the main feeder fault interrupter.

For a faulted system, and upon tripping the main feeder breaker, it is deemed that the PV inverters will detect the fault by sensing low voltage at their terminal, as well as their active anti-islanding scheme. The same is deemed for the BESS, and this is further discussed in the next section.

10.3 PV and BESS Inverter Voltage Settings and Other Elements

To determine the undervoltage settings to allow detecting faults in the system, the worst-case scenario, namely a fault at the end of the adjacent feeder, was simulated. The fault currents supplied by the BESS and photovoltaic are zero because it is in series with the two plant transformers that contain a Δ in the low side, discontinuing the zero-sequence path. The results are shown in Table 7. This table also reveals that the current supplied by the photovoltaic and BESS is insignificant and incapable of activating any protection element. Hence, other elements need to be used, in this

Table 7 Short-circuit results for a fault at the end of the adjacent feeder (islanded mode)

	LLL ($I = I_P$)	LG_0Ω ($I = 3I_0$)	LG_20Ω ($I = 3I_0$)
I_total [A]	88	124	120
I_Plant [A]	88	124	120
I_BESS [A]	35	0	0
I_PV [A]	42	0	0
V_DiG [V]	244	1,070	860
V_BESS [V]	60	135	118
V_PV [V]	70	90	121

case undervoltage (27). The table also reveals that, even for an impeded fault in the adjacent feeder, the voltages at the BESS and PV drop to less than 50% of nominal, triggering energization cessation at the PV plant in 160 ms (as required by IEEE Std. 1547 [6]) and being easy to set up in the BESS settings.

10.4 Islanded Configuration (Grounding Transformer)

Much of the load supplied by the microgrid is single-phase. This requires a ground source for steady-state operation, as well as to enable ground fault detection under fault condition. Hence, it was decided to install the BESS in the system with a Δ-Yg (Δ low side) transformer. This configuration provides flexibility as it would allow, if desirable, to operate the right-hand side feeder to operate islanded from the adjacent feeder.

Furthermore, as it will be described in the next subsections, the diesel plant step-up transformer will always be in the circuit when the microgrid operates in islanded mode, as the entire plant station service must remain energized. This results in the step-up transformers acting as strong ground sources (and essentially being grounding transformers to the system). This is further illustrated in Fig. 15.

To allow supply of the adjacent feeder, reclosers R1 and R2, as well as low voltage breakers B1 and B2, must always be closed. This results in the plant transformers serving as ground sources for both feeders. In fact, this configuration results in very effective grounding, which would not be possible should these transformers not be connected.

10.5 Interlock-Based BESS Operation

To increase system security, the microgrid controller logic sends a signal to disconnect the BESS from the system in case any of the breakers B1-B2, and reclosers R1-R2, have their status off. This control decision is based on the following logic:

- Breakers B1 or B2 will only trip if there is a fault in the plant step-up transformer, requiring human intervention for diagnostics and troubleshooting. Service continuity will then be restored manually.
- Recloser R2 trip and auto-reclosing can result in out-of-synch closing between the diesel plant and the BESS.
- Recloser R1 (adjacent feeder) trip and auto-reclosing can result in reclosing out-of-synch with a fifth generator (see next subsection).

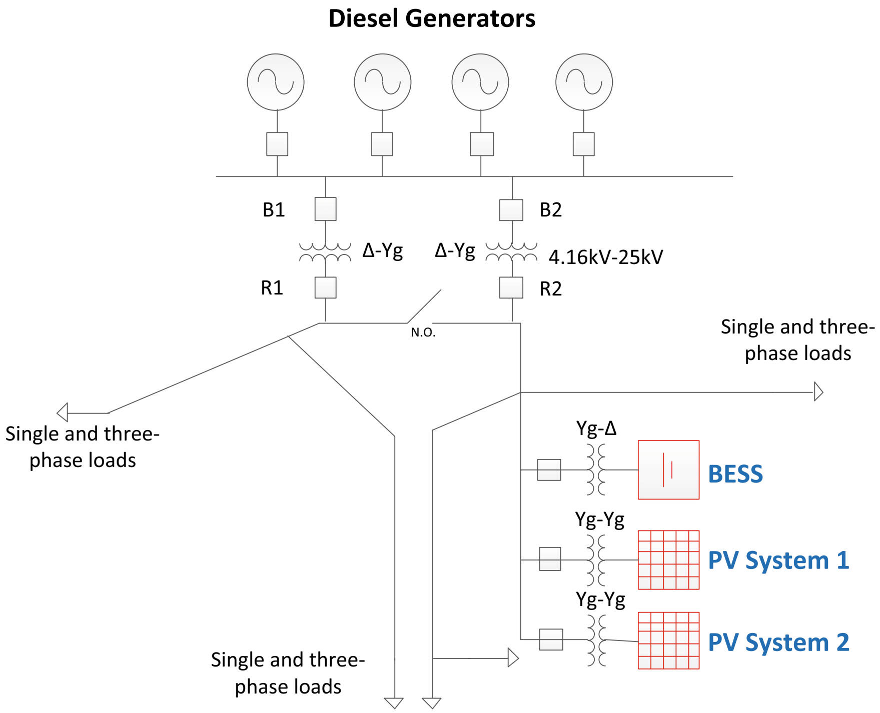

Fig. 15 Microgrid topology showing the grounding sources

10.6 Fifth Generator and Microgrid Controller Interlock

Given the load growth in the area, a fifth generator has been interconnected during the winter to cater for N-1–1 contingency. This is because there are times where three generators are needed to support the community, which result in only one generator being a spare. If this generator is under temporary maintenance, the system will experience a system-wide blackout, as all load in the community is critical.

As per the ISO, the isolated supply is a proxy for transmission and availability must be to the same standard. Therefore, the fifth diesel generator is required. This unit is normally connected downstream of recloser R1. To avoid potential out-of-synch reclosing, the microgrid controller directs the BESS offline if R1 trips.

This generator will be necessary even after the large renewable plant and the BESS installation.

10.7 Recloser Logic at BESS

Reclosing in the BESS fault interrupter is never enabled. These are the reasons:

1. Under grid-connected mode, reclosing should not be enabled as the interrupter only protects the BESS step-up transformer and any fault is likely to be permanent.
2. To simplify and avoid two settings groups, it was decided not to have it enabled under islanded mode.
3. Even if reclosing was enabled under islanded mode, the BESS would be unable to ride through its trip and reclose anyways, as the entire photovoltaic plant would trip upon experiencing an outage and would not return to service for 5 min, requiring entering the plant restoration procedure.

10.8 Restoration Procedure and Blackstart

It is not expected the microgrid configuration will noticeably disturb the system stability and reliability. It is also expected it will not require modifying the blackstart procedure from what is in place prior to the microgrid implementation. Currently, if a system-wide blackout occurs, the following are the steps followed to restore the system:

1. Plant operators initiate a start of all available diesel generators. The microgrid controller directs the BESS and photovoltaic offline.
2. Generator breakers are closed, energizing the plant 4.16 kV bus.
3. Breakers B1 and B2 are closed with a 1-min time-delay in between.
4. Recloser R2 is closed. If there is a system fault, the normal fault finding, isolation and restoration is followed by servicemen. If there is no system fault, proceed to next step.
5. Recloser R1 is closed. If there is a system fault, the normal fault finding, isolation and restoration is followed by servicemen. If there is no system fault, proceed to next step.
6. After a settable time delay (set to 3 min), if the system voltage and frequency are normal, the BESS is started in grid-following mode.
7. After a settable time delay (5 min by default, as described in IEEE Std. 1547 [6]), if the system voltage and frequency are normal, the PV starts production in grid following mode (this is the only mode the PV inverters can operate).

11 Summary and Lessons Learned

This chapter has covered the subjects of both inverter-based hosting capacity and grounding requirements in microgrids.

The presented hosting capacity method has proposed a method to determine the maximum penetration level of utility-scale inverter-based renewable generation that can be integrated in islanded mode prior to the deployment of a BESS. The recommendations are based on frequency response and frequency protection elements.

Any further installation of renewable generation can only be accepted if a BESS and microgrid controller are also installed. The chapter suggested using a set of practical charts to make this determination. By knowing frequency relay settings, these charts provide an answer to the amount of hosting capacity. If other small scale, residential renewable generation units are present, these do not need to be included in the charts for two reasons:

1. These are generally small and likely to be ignored as compared to the nameplates of utility-scale renewable generation systems.
2. These are unlikely to experience the exact same rate of energy output cessation, due to not being disconnected by the exact same protective device.

Protection and grounding are among the most complex and important subjects of a microgrid. It is imperative to ensure the distribution system is effectively grounded and protection is sufficiently sensitive. While experiences from real microgrid deployments have presented different ways of managing performance grounding, no consensual strategy has constituted a baseline to be followed. In response, a performance grounding strategy was developed. Very importantly, it was noted a grounding source is required under islanded operation, which was supplanted by the BESS step-up transformer itself being configured as Δ-Yg. In addition, it was proposed to keep the feeder supply transformer, which has the same configuration, always connected to further reduce COG and TOV. The protection behavior also changed because of the consequential reduction in short-circuit levels, especially those of line-to-line contacts, an expected effect of high penetration of inverter-based generation. A frequency and voltage-based scheme is necessary and an example of how to achieve this was presented. Conversely, the protection philosophy had to be adjusted to ensure conventional overcurrent protection would remain effective when connected to the main grid supply. This paradigm shift is a new reality in microgrids dominated by DERs.

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Smart Metering in Distribution Systems: Evolution and Applications

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Abstract The costs of smart metering deployment are directly related to capital investments in smart metering devices, communication infrastructure, and associated operational expenses. On the other hand, one of the main challenges refers to the capitalisation of the respective potential benefits. Because of the complexity to understand and quantify all the gains of a large-scale rollout of smart meters, most countries and distribution companies do not take full advantage of this technology. In this context, the main objective of this chapter is to discuss the benefits of using smart meters for operation and planning of modern distribution systems. It presents potential applications of smart meter data, which are not yet widely explored by the Distribution System Operators (DSOs) and often not considered in decisions for a large-scale smart meter rollout. Additionally, this chapter also summarises the evolution of energy meters, from the electromechanical equipment to the most advanced electronic devices, which permits the practical implementation of the discussed applications. These applications allow DSOs to better quantify the potential increase in their revenue by adding smart meters to their systems. This means that by expanding the available applications that use smart meter data, not only a wide deployment of smart meters but also the improvement or implementation of additional structures, such as the Advanced Metering Infrastructure (AMI), become financially feasible.

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1 Introduction

Smart meters emerge as key components of smart grids, allowing more observability by means of a high number of installed meters (usually one per consumer unit) and a wide range of measurement capabilities. In addition to the measurement capability, smart meters allow the increase of the automation level in distribution systems. The automation level is improved not only directly, by add-in functions, but also indirectly by being integrated into advanced management and control solutions. Obtaining full advantage from this new scenario involves a paradigm shift from the perspective of the consumers and Distribution System Operators (DSOs).

The member states from the European Union are recommended to conduct a long-term cost–benefit analysis on the implementation of smart metering systems. In case of positive results, a large-scale rollout of smart meters (at least 80% of penetration) is recommended. Otherwise, the cost–benefit analysis should be updated every 4 years. In [53], results of the cost–benefit analyses conducted by the European member states are described. These countries pointed out non-technical loss (NTL) mitigation (fraud detection and correct meter reading) as one of the main benefits of smart meter rollout. Operational savings obtained by the remote access to meter data and the remote control of power supply are another example of relevant benefits. As reported by countries that have already experienced large-scale deployment, the success of smart meter rollout also depends on consumer engagement.

In this sort of cost–benefit analysis that precedes decisions for a large-scale smart metering rollout, a major challenge is to understand and quantify the various benefits enabled by this technology, as part of them is indirect and strongly depends on the reality of each DSO. In order to help identify the potentiality of such devices, this chapter presents the evolution of energy meters, depicting the current status of smart meters, followed by their potential application in important operation and planning tasks. Indeed, by developing more applications to smart meter data, more value is aggregated to this technology, improving the return on associated investments.

2 Evolution of Energy Meters

The first patent of an AC ampere-hour meter to describe a watt-hour meter of the modern electromechanical form dates back to 1888, developed by the Westinghouse Electric Corporation [49]. Electromechanical meters operate through an electromagnetic induction mechanism to record the amount of energy consumption from consumer units. Energy consumption data must be manually collected by a meter operative or even by the consumer who submits the data to the electricity supplier for billing purposes. Because of their limited capabilities, electromechanical meters have been replaced by electronic meters worldwide.

Electronic meters were developed after the first analog and digital integrated circuits became available in the 1970s [50]. These meters capture and digitise current and voltage signals by means of a digital processor. They are able to register different electrical quantities, such as voltage magnitude, active and reactive power, and to support advanced tariffs, such as time-of-use energy rates and peak usage charges that depend on the measured power demand. Metering data can be collected remotely if a communication channel is available.

The smart meter is a category of electronic meters with more advanced functionalities. Although there is no single set of features to define it, the smart meter is characterised by having two-way communication capability, which enables meter reading, on/off control of the power supply, and software update to be remotely performed. In addition, smart meters are expected to provide information on the metering points, such as steady-state voltage magnitude, voltage sag and swell, consumed and exported energy, active and reactive powers with enough granularity and reading rate. This information can support dynamic tariffs, assist in the operation and planning of distribution systems, as well as allow consumers to manage their energy usage.

The European Commission lists a set of minimum requirements for smart metering systems to ensure useful functionalities for different market actors, as shown in Table 1.

Based on the potential benefits, in recent years, various electricity companies worldwide have initiated or even finished their large-scale rollout of smart meters. They are mainly driven by the need to reduce the carbon emission and to enable new market mechanisms, advanced rate designs, energy efficiency and the integration of distributed energy resources. From the perspective of system operation and planning, smart meters are a key component of the Advanced Metering Infrastructure (AMI), by which a large amount of data from distribution systems is acquired, improving the observability. By using smart meters and data analytics, several applications in the context of Advanced Distribution Management Systems (ADMS) can be implemented. From the consumers' perspective, smart meters provide relevant information on consumption habits and a digital link to DSO, allowing consumers to actively participate in the energy market and benefit from new services.

Table 1 Smart meter functionalities recommended by the European Commission [13]

Market actors or purposes	Meter functionalities
Consumers	To provide updated data on a frequent basis to be used by consumer solutions, allowing load-shifting and energy savings
Metering operator	To enable two-way communication, remote reading of metering data with adequate reading rates to provide information for system planning (there is a consensus that metering data should be updated at least every 15 min)
Commercial issues	To support advanced tariffs, remote on/off control of the power supply, or power limitation on consumers' units
Data protection	To permit secure data communication and fraud detection
Distributed generation	To provide consumed and exported energy and reactive metering

In 2018, 34% of the consumers from the European Union were equipped with smart meters. According to [53], the penetration rates of 77% and 92% of smart meters are expected by 2024 and 2030, respectively. Estonia, Finland, Italy, Malta, Spain, and Sweden have already finished their large-scale smart metering rollout. Italy was one of the first countries to implement a large-scale rollout in late 2001. It is already proceeding with the second-generation rollout. The main improvements of second-generation smart meters are related to the services delivered to final consumers and the greater granularity of data collected [3]. The new meters have two communication channels. The first channel transfers 15-min granular data to the DSO on a daily basis. After a validation process, these data are made available to consumers and retailers. The second channel provides near real-time and non-validated data directly to consumers, to be used in consumer solutions.

In the United States of America, 70% of the households were equipped with smart meters by 2018 (corresponding to 88 million metering points). By the end of 2020, deployments are estimated to attain 107 million smart meters [10]. Asia–Pacific is the largest market of smart meters in the world. China and New Zealand have almost finished their first wave deployments of smart meters and India is starting its large-scale rollout. In 2018, the penetration rate of smart meters in the Asia–Pacific was 67% and is estimated to grow to 94% in 2024 [48].

3 Potential Applications from the DSO Perspective

The AMI, which combines smart meters, communication networks, and data management systems with two-way communication, has been integrated with the geographic information system (GIS) and the outage management system (OMS). Aggregation of these structures has allowed the development of critical functions that were not previously possible and the improvement of existing functions that have been performed manually. These advancements result in the reduction of operational expenses. As previously described, examples of supportive smart meter capabilities are (a) automatic and remote meter reading, (b) remote control of power supply (connection and disconnection of consumer units), (c) automatic outage reports, (d) fraud detection, and (e) voltage monitoring. These and other smart meter capabilities can cope with advanced management functions such as voltage and reactive power control, fault location, nontechnical loss detection and location, automated determination of system topology and line parameters, and load modelling. In addition, apart from DSO solutions, consumer services are already being offered by distribution companies, such as outage communication with estimated time of restoration, bill estimation, load disaggregation, etc.

This section focuses on potential DSO-side applications of smart meter data to enhance operation and planning tasks, improving the quality of energy supply and consumer satisfaction.

3.1 Distribution System State Estimation

The state estimation procedure applied to an electrical power system aims to define the set of state variables x from a measurement model of the form:

$$\mathbf{z} = h(\mathbf{x}) + \mathbf{e} \tag{1}$$

where $\mathbf{z}$ is the vector of m measurement values, $\mathbf{x}$ is the vector of n state variables (usually defined as the voltage phasors from system nodes), h(·) is the nonlinear function relating the m measurement values with the n state variables, and $\mathbf{e}$ is the vector of measurement errors.

Despite being a consolidated tool to monitor and supervise the transmission systems, several challenges have been faced in the implementation of the state estimator to distribution systems. Among these challenges one can detach the limited number of measurements (m) compared to the number of nodes in distribution systems (and, therefore, the number of state variables, n), which results in a mathematically underdetermined problem. Traditionally, the monitoring of distribution systems was carried out only at the substation. To tackle this issue, pseudo measurements of loads (e.g., forecasted values of active and reactive powers) have been used, making the estimator performance strongly dependent on the accuracy of load modelling. Additionally, the unsymmetrical topology of distribution systems (with single and two-phase laterals, and unbalanced loads) requires a three-phase formulation, which considers all these features at the state estimation methodology. However, the accuracy of the distribution system modelling may be affected by the uncertainties related to system parameters and topology, due to errors in the DSO´s database.

Most of the mentioned challenges are overcome in the context of AMI implementation, considering the large-scale deployment of smart meters associated with other data sources from distribution systems such as: (a) substation meters; (b) reclosers; (c) automatic capacitor banks; and (d) smart inverters. Indeed, the potential data gathered from smart meters, for instance, active and reactive powers and voltage magnitude measurements, can enable the system observability, transforming the underdetermined problem into an overdetermined one. In this scenario, redundancy on measurements can be attained, allowing traditional formulations of state estimation (e.g., Weighted Least Squares formulation, WLS) to be applied for distribution systems. With this level of measurement redundancy, the distribution system state estimation (DSSE) can be used to identify metering inconsistencies, such as those caused by illegal load connections. Moreover, it allows the correction of parameter and topology errors.

In this context, the DSSE becomes an important supervision tool to be integrated to the ADMS. Although the large-scale deployment of smart meters mitigates important challenges for DSSE implementation, the expected applications of the DSSE are different from those of the transmission system state estimation which receives system measurements every 3–5 s. In distribution systems, the data granularity and communication rate are limited by technical and economic issues and consumer privacy concerns. Usually, the granularity of smart meter data varies from a few minutes to an hour and their communication to the data management centre can be done at a different rate (for instance, once a day). In some cases, a dedicated communication channel provides real-time (or near real-time) data to consumers and third parties to be used on consumer-side solutions [53].

Even though real-time and online applications of the DSSE can be limited by these issues, offline applications are less affected. In both cases, it is desirable that measurements from all meters correspond to the same time interval (which means that smart meters' clock should be synchronised). This is not always possible, as measurements can be originated from different devices, i.e., not only from smart meters but also from substation meters, smart inverters, and reclosers, which may have different data granularity. Expósito et al. [14] address the use of different sources of data in the DSSE formulation. The authors propose a DSSE using two-time scales for measurements. High frequency data, captured with latency of up to 1 min, are combined with pseudo measurements (or smart meter measurements, whether available), updated every 15 min. In [1], the lack of synchronism among smart meter data is considered in the DSSE formulation.

Approaches that tackle the problem of low observability in distribution systems are relevant when DSO opt for a selective smart meter rollout in place of a large-scale deployment and in situations where the rollout is still ongoing. To this end, a robust matrix completion state estimation (RMCSE) is proposed in Liu et al. [35], which showed to have a better performance than the traditional methods of state estimation.

When the DSSE uses time-aggregated measurements acquired every few minutes (e.g., every 15 min.), the real-time information of the measured quantity during this time interval is lost. In general, only the average value of the measured quantity is available. As output, the DSSE also provides average values of the system state for each time interval. This loss of real-time information does not compromise the value of the DSSE tool, as it can still support ADMS functions, such as detection and location of nontechnical losses and high impedance faults; asset management actions; and diagnosis of other steady-state problems such as overvoltage, undervoltage, and overload.

To provide near real-time visibility of distribution systems, an event-driven state estimation can be implemented, as proposed in [46]. In this approach, only the relevant variations of smart meter measurements trigger the data communication. Relevant variations can be characterised whether the difference (or the accumulated difference) between two subsequent real-time measurements of active power, for instance, is above a predefined threshold. Different threshold values can be assigned to system buses, according to the sensitivity relationship between the system state and the measurement data. The DSSE are then performed by using the most recent measurements sent by each smart meter.

Also aiming to provide real-time information on distribution grids, some studies suggest using PMU data in the DSSE. Liu et al. [36] propose a load estimation model to create pseudo measurements of active and reactive power of low voltage (LV) distribution systems by using real-time data from selective smart meters. According to their load pattern, consumers from LV systems are divided into clusters. Representative consumers of each cluster are identified to build a load model for the cluster and the total load of a LV system is obtained by aggregating the estimated loads of all clusters. The DSSE formulation is applied to medium voltage (MV) distribution systems considering measurements of voltage and current magnitudes from distribution supervisory control and data acquisition (SCADA), voltage phasor from PMUs and the pseudo measurements of LV systems from the proposed load model.

3.2 Fault Location in Distribution Systems

In the recent process of modernisation and automation of distribution system operation functions, one can detach the evolution on the Fault Location Isolation and Restoration (FLISR), which is a key function of the distribution management system to support self-healing. The basic idea of FLISR is to quickly detect and locate a fault, then isolate the faulted area as soon as possible. Consequently, the impact of the resulted power outage is minimised.

Fault detection and location is a requirement for all future actions of the FLISR process and, by accelerating the fault location, significant improvements can be achieved on reliability metrics. According to Snyder and Wornat [51], in systems that rely mostly on manual fault location methods, approximately 20–30% of total outage duration time can be associated with fault location. Consequently, a more effective fault location approach results in a faster service restoration—especially on underground circuits, where some sort of excavation is needed to identify the potential source of the fault. An effective fault location approach also identifies momentary outages to examine the likely causes and tackling the problem before turning into a permanent fault or guiding vegetation management.

As such, considerable efforts have been dedicated to automate distribution system fault location processes, which used to rely on trouble calls and visual inspections from the DSO crew. Permanently installed equipment at substations, such as protection relays and digital fault recorders, can provide further information to support the process. However, it is challenging to locate faults in distribution feeders relying only on information from the substation because the distribution feeders are branched and heterogeneous, often reconfigured, and may have distributed and intermittent sources to the fault.

The next generation of fault location methods depend on permanently installed line indicators that may or not have communication. Non-communication visual indicators help the DSO crew in visual inspections but do not contribute to automating the process. Communicating sensors—fault indicators or sentry devices—are more effective and faster than trouble calls, increasing the automation level of fault location.

More recently, the fault location process has been favoured by the advent and widespread of smart meters. The main advantage of smart meters is that they will unavoidably replace electromechanical and static energy meters [29] and consequently they will be installed at every consumer unit providing an amount of data never available before at DSO control centres. Weather and vegetation data, for instance, can join measurement data to comprise an even more sophisticated automated fault location method. As more information from sensors and meters is available, the less dependable the fault location method becomes from an accurate system model, representing a significant contribution to DSOs.

Three functionalities of smart meters can be used to support fault location. The first functionality is the last gasp outage notification that consists of sending a status message when power is lost. The second functionality is to provide the voltage magnitude measured just before the power is lost or by demand. Smart meters can be polled to inform the status or the measured voltage magnitude by demand because of the third functionality: two-way communication capability.

Based on these functionalities, new fault location methods dedicated to distribution systems emerged, as discussed below. The class of methods related to outage mapping consists of using downstream information provided by smart meters to improve the effectiveness of the traditional impedance-based methods or other fault location methods, decreasing the search space and mitigating the problem of multiple estimations. The second class explores the capability of smart meters in providing voltage and current magnitude to estimate the fault location, assuming reasonably accurate system data (topology and parameters).

3.2.1 Outage Mapping Using Smart Meters

Using downstream information provided by smart meters can improve the performance of the traditional impedance-based or more-accurate fault location methods by decreasing the search space and mitigating the problem of multiple estimations. In case of occurrence of a permanent fault, e.g., fault 1 in Fig. 1, recloser R1 acts (as it is the first protection device upstream of fault 1) and meters SM5 to SM9 must report the interruption in Zone 1. Consequently, the fault location process considers such information to reduce the search space of the algorithm. In the case of fault

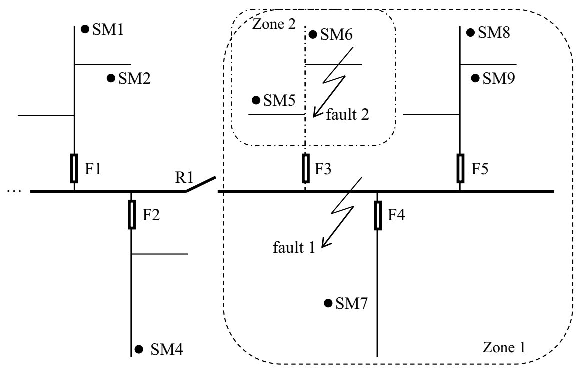

Fig. 1 Automatic outage mapping

2, assuming that this fault is eliminated when fuse F3 blows, meters SM5 and SM6 must report the interruption, restricting the search space to Zone 2.

In [40], the author proposes using smart devices at the substation to monitor and identify any unusual events in the distribution system. Then, a sequence of polling of remote devices, such as smart meters, is initiated and the interrupted devices can be identified. Considering the capacity of bidirectional communication (TWACS®), the communication address can be related to the physical location of the device in the distribution system, so that the affected area can be identified. Transponders are checked in groups of *p* devices, considering that *p* is the number of channels simultaneously available for communication. Then, each group responds simultaneously to the consultation and, subsequently, another group of *p* devices is polled immediately after the response of the previous group. Simultaneous polling can considerably reduce the duration of the identification process of the interrupted area.

In [56], the fault path is identified by searching for the nodes with the lowest voltage. The method is called "Voltage Sag State Estimation" and explores the radial topology of distribution systems and the relationship of voltage drops and interruptions with the fault occurrence. These characteristics allow the estimation of the voltage profile along the fault path, as illustrated in Fig. 2, and the identification of the affected region. One advantage of the algorithm is that there is no need to determine the fault type. Additionally, the detection of the fault occurrence can be aided by voltage meters installed throughout the system.

In [55], an impedance-based method is applied at the substation to obtain a rough estimation of the fault location. Because the result is an estimated distance to the fault, multiple branches can be indicated due to the typical distribution systems' topology. Then, to recognise the actual fault location, voltage measurements from smart meters are used to build the *Low Voltage Zones*. The proposed fault location technique decreases the multiple estimations associated with impedance-based methods applied to distribution systems and proposes a systematic approach to build the *Low Voltage Zones*, based on an adaptive threshold.

Alternatively, outage escalation methods can map the outage area by joining, for instance, information from fault indicators or weather data to smart meter status. A

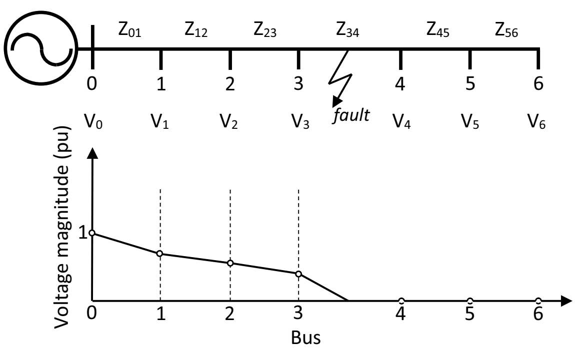

Fig. 2 Voltage profile along the fault path

knowledge-based system is designed to locate distribution system outages in [34] using data from consumer trouble calls, automated meter reading (AMR) system, and SCADA. The knowledge-based system has two major parts: an outage escalation procedure and meter-polling procedure. The escalation procedure involves searching for the outage region according to the outage information and the meter-polling part confirms the outage locations based on the meter status. A Mixed Integer Linear Programming approach is proposed in [25] to minimise the impact of lack of information and inconsistencies between the fault indicator and smart meter statuses. This condition allows the identification of the faulted line sections in cases of singular or multiple faults and malfunctions of fault indicators and smart meters. As input, it uses current measurements and unidirectional fault indicators and smart meter statuses. An enhancement of [25] is proposed in [26] including bidirectional fault indicators in a new Mixed Integer Linear Programming method.

3.2.2 Using Voltage and Current Magnitudes Measured by Smart Meters for Fault Location

Several fault location methods are based on the correspondence between measured and calculated (expected) values to identify the fault location. For instance, a method based on sparse voltage measurements dedicated to distribution systems is proposed in [45]. This method uses voltage and current phasors measured in the substation before and during the fault occurrence and voltage magnitudes measured in sparse locations of the feeder during the fault occurrence. Firstly, the algorithm uses voltage and current measurements at the substation to estimate the loading on each bus by distributing the load proportionally to the rated power of distribution transformers—load measurements from smart meters can be used instead, making the process more accurate. Then, a database is generated by storing the calculated voltage magnitude at each bus with a smart meter for scenarios of non-simultaneous short circuit at each bus of the search space (it can be the whole feeder). The calculated voltage magnitudes are compared with the respective measured values and the buses are classified according to the possibility of being located close to the fault, which is associated with the best voltage matches. This method is robust compared to other troubleshooting methods dedicated to distribution systems, as it suffers little influence from the fault type and resistance. However, the performance of the method depends on the knowledge of the loads and measurement accuracy. In [37], phasors of characteristic voltage from sparse meters installed along the feeder are used in a fault location process similar to [45].

Two other methods [5, 19] are based on the short-circuit calculation theory using bus impedance matrix. Considering that the system parameters are known, a bus impedance matrix can be built in phase components. For example, for a distribution system with *nb* buses, the dimension of the impedance matrix bus is $3nb \times 3nb$ and each element of the matrix in (2) consists of a 3×3 submatrix.

$$Z_{bus}^{(abc)} = \begin{bmatrix} Z_{11}^{(abc)} & \cdots & Z_{1k}^{(abc)} & \cdots & Z_{1nb}^{(abc)} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Z_{k1}^{(abc)} & \cdots & Z_{kk}^{(abc)} & \cdots & Z_{knb}^{(abc)} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Z_{nb1}^{(abc)} & \cdots & Z_{nbk}^{(abc)} & \cdots & Z_{nbnb}^{(abc)} \end{bmatrix} \tag{2}$$

If there are voltage meters in some buses of the system, the voltage deviation value $\left(\Delta\hat{V}_i^{(abc)}\right)$ can be obtained at each meter (using the difference between the value measured during and before the fault). The relationship between the voltage sag measured at bus i and the fault current at bus k is given by (3)

$$\Delta\hat{V}_i^{(abc)} = \hat{V}_{i,fault}^{(abc)} - \hat{V}_{i,prefault}^{(abc)} = -Z_{ik}^{(abc)} \cdot \Delta\hat{I}_{fault_k}^{(abc)} \tag{3}$$

Under the conditions described, $\Delta\hat{V}_i^{(abc)}$ and $Z_{ik}^{(abc)}$ are available while the faulted bus and the associated fault current are unknown parameters. The challenge of using this formulation is related to the value of the fault current, which in turn is associated with the fault resistance (a parameter that is difficult to estimate accurately). In [19], the fault current is approximated by the value shown in (4).

$$\hat{I}_{fault_k}^{(abc)} = \left(Z_{kk}^{(abc)} + Z_f^{(abc)}\right)^{-1} \tag{4}$$

To address the uncertainty regarding the value of the fault resistance, the use of fuzzy logic is proposed. The second method [5] considers the existence of distributed generators connected to the system and digital fault recorders installed at each generation point. The fault current is considered as the sum of the current injected by the substation and each generator. The limitation of this method is the need for synchronised phasor measurements of voltage and current in each distributed generator and in the substation, implying high costs and complexity.

In [54], a fault location method based on the *correspondence of fault current* explores the monitoring capability of feeder meters and concepts of short circuit theory. According to the short-circuit theory, the fault current at bus k can be estimated using the voltage deviation obtained at bus i as follows.

$$\hat{I}_{fault_{ik}}^{(abc)} = Z_{ik}^{(abc)} \cdot \Delta\hat{V}_i^{(abc)} \tag{5}$$

where, $\mathbf{Z}_{ik}^{(abc)}$ is the ik 3×3 submatrix from the three-phase bus impedance matrix of the feeder $Z_{bus}^{(abc)}$, and $\hat{I}_{fault_{ik}}^{(abc)}$ is the fault current calculated by using voltage measurements from meter i for a fault at bus k. The magnitude of the voltage deviation ($\Delta V^{(abc)}$) can be obtained from (5), representing a vector of dimension 3×1.

$$\Delta V_i^{(abc)} = V_i^{(abc)p} - V_i^{(abc)f} \tag{6}$$

subscript i is related to bus i, $V_i^{(abc)_f}$ and $V_i^{(abc)_p}$ are the voltage magnitudes during and pre-fault, respectively, and superscript abc represents each phase. If the voltage magnitude is measured by a feeder meter installed at bus i, the voltage deviation $\Delta V_i^{(abc)}$ can be used to estimate the fault current. Typically, feeder meters supply only voltage magnitudes. However, to calculate (6), it is assumed that the three phases are simply shifted by 120°, although distribution systems are unbalanced.

For a distribution system with N_{fm} meters, there can be N_{fm} estimated fault currents based on the assumption that the bus under fault is bus k. If the fault really occurs at bus k, the currents estimated from all meters must be practically the same, close to the real value. On the other hand, if the fault has not occurred at bus k, there will be an error on the fault current estimated based on measurements from each meter i.

Based on that, to locate the fault, a fault location index δ_k is proposed. This index is given by the total sum of the differences between the N_{fm} estimated fault current values at a given bus k and their average value (each difference is referred as d_{ik}), as shown in (7).

$$\delta_k = \sum_{ph}^{a,b,c} \sum_{i=1}^{N_{fm}} \left(\left| \hat{I}_{fault_{ik}}^{ph} - \overline{\hat{I}_{fault_k}^{ph}} \right| \right) = \sum_{ph}^{a,b,c} \sum_{i=1}^{N_{fm}} d_{ik}^{ph} \tag{7}$$

where $\hat{I}_{fault_{ik}}^{ph}$ is the fault current calculated for phase ph with measurements from the feeder meter at bus i using (8), and $\overline{\hat{I}_{fault_k}^{ph}}$ is the average of all fault current values calculated using the voltage measured at each feeder meter for bus k.

To sum up, the proposed method consists of sweeping all the buses of the feeder or the buses that are candidates of fault location and obtaining δ_k for each bus. Then, the bus associated with the minimum δ_k is selected as the faulted bus. If more than one bus (region) is pointed out as a faulted bus, automated outage mapping can be used to solve the problem of multiple estimations. The loads, represented by constant impedance models, must be included into the bus impedance matrix, as shunt elements, to improve the method accuracy.

Based on [39, 54] exploit the fact that the voltage sag vector and impedance matrix produce a current vector with a single nonzero element (that corresponds to the faulted bus) and the underdetermined nature of the problem (due to the limited number of smart meters installed at primary feeders) to solve the problem based on compressive sensing theory. Compressive sensing is an alternative technique to Shannon/Nyquist sampling for reconstruction of a sparse signal that can be well recovered by components from a basis matrix. Alternatively, [8] propose including current measurement and a refinement in the fault location process from [54].

3.3 Nontechnical Loss Detection and Location

Technical losses are inherent energy losses associated with the energy transmission and distribution system operation. All other sorts of energy losses in electrical power systems are classified as commercial losses or, in other words, nontechnical losses (NTL). NTL may be associated with meter tampering and illegal load connections (energy theft), equipment malfunctions, wrong meter reading (billing irregularities), and unpaid bills. For years, NTL has been a relevant cause of revenue loss for electricity companies worldwide, also increasing electricity costs for consumers and affecting the quality and security of power supply when irregular and unplanned loads are connected to the grid. Despite being a major problem in developing countries, NTL is also an issue for the developed ones (mainly related to illegal activities).

The energy balance is a common mechanism to estimate the level of NTL in distribution systems. By this mechanism, the amount of energy fed into the distribution system (registered at the distribution substation, for instance), for a given period, is compared with the billed energy from all consumers supplied by the distribution system. The global losses (technical and nontechnical losses) are given by the difference between these two values. To define the contribution of NTL to the global losses, a reasonable estimation of technical losses is needed, which can rely on load flow calculations or typical values assumed for distribution systems. The energy balance does not locate the consumer with NTL, but it can indicate the feeders with possible presence of NTL, as well as estimating the magnitude of NTL. This mechanism is adopted in Brazil to define the level of NTL in distribution systems. To this end, the technical losses considered at the energy balance are estimated by a load flow procedure, using information of billed energy and consumer type to model the load profiles. Part of the NTL is assumed by the consumers via tariff, according to a target value based on criteria established by the Brazilian Electricity Regulatory Agency, and the amount that surpasses the target value is assumed by distribution companies.

Traditionally, a more accurate identification of illegal loads was conducted by on-site meter inspections, that can be labour-intensive when no information on suspected consumers is available. In recent years, with the replacement of electromechanical meters by electronic meters (especially smart meters), several methods have been proposed aiming to indicate suspicious NTL locations and reduce the number of candidates for on-site inspections. Distributed and centralised solutions can be used to this end. The distributed solutions focus on preventing energy meters from fraud. One approach is the anti-fraud functionalities added to energy meters, which can notify the distribution companies by sending a signal in case of fraud detection [32]. The centralised solutions rely on NTL detection and location methodologies processed at the distribution management systems by using different data sources. The purpose of this section is to address the potential use of smart meter data in centralised solutions.

According to [17, 42], the centralised methods can be divided into two main groups: classification-based methods and system state-based methods, discussed as follows.

3.3.1 Classification-Based Methods for NTL Identification

The first group is based on the classification of load profiles gathered from smart meter data. This sort of methods, also called data-oriented methods, only depend on consumer related information, such as energy consumption profile and consumer type (residential, commercial, industrial). Abnormal consumption patterns are detected and considered to be suspected of NTL by comparing them with examples of normal and abnormal profiles in the test database or by using anomaly detection methods. Several techniques are used to classify the consumption profile, such as neural networks, fuzzy logic, optimum-path forest, and Support Vector Machine [6, 15]. In general, classification-based methods have a low detection rate and are more susceptible to false positive cases due to the mistaken association of atypical consumption behaviours with NTL, especially when examples of normal and abnormal consumption profiles are scarce or not available [42].

In [27], the authors try to overcome some of the limitations of classification-based methods. To this end, they firstly proceed with an energy balance that uses smart meter data to delimit areas with high probability of NTL. The energy consumption measurements obtained from the distribution transformers are compared with the sum of the consumption recorded by consumer smart meters. Large mismatch between these two values indicates the possible presence of NTL. Synthetic series are also used to represent NTL patterns, improving the detection rate of the algorithm.

In [20], measurements of energy consumption and voltage magnitude gathered from consumer smart meters are used to identify NTL. The method does not require information of system topology or parameters, but the connection map of consumers and service transformers is assumed to be known. A linear model relating the energy consumption with the voltage magnitude measurements is firstly created by using the training data set. The trained model and the voltage measurements are then used to estimate the energy consumption of each consumer. Large negative residual of the estimated to the measured consumption indicates NTL location. In [6], several features extracted from smart meter data and other databases are used to detect NTL at consumers with contracted power higher than 50 kW. These features are based on information of smart meter alarms, energy consumption data and other electrical magnitudes (such as voltage, active and reactive power), rate of NTL in the neighbourhood, meter location (inside or outside the consumer premises), etc. Features from consumers submitted to at least one inspection are used to train a supervised machine learning algorithm.

3.3.2 State-Based Methods for NTL Identification

The second group of centralised methods (system state-based methods) uses distribution system analysis, such as state estimation and power flow procedures, to detect and locate NTL. They combine smart meter measurements and information of the power grid (system topology and parameters). Two examples of such methods are briefly described in the sequence.

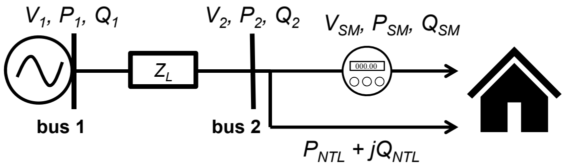

Fig. 3 Illustration of an illegal load connection (NTL) on a consumer unit

Figure 3 depicts an NTL situation resulted from an illegal load connection on a consumer unit equipped with smart meter, where a single-phase representation is used, for simplicity. In this case, the active and reactive power registered by consumer smart meter (P_{SM} and Q_{SM}) differs from the real values (P_2 and Q_2) observed at the load bus (bus number 2). On the other hand, the voltage magnitude measurement (V_{SM}) remains consistent with reality, as it records the voltage drop between bus 1 and bus 2 caused by the total power consumed in bus 2, that is, the regular load ($P_{SM} + \mathrm{j}Q_{SM}$) plus the NTL ($P_{NTL} + \mathrm{j}Q_{NTL}$). In summary, by meter bypassing, the measurements of active and reactive powers (as well as the energy consumption measurement) can be violated, but the same does not apply to voltage measurements.

The methods proposed in [16, 47] take advantage of this condition to detect and locate NTL in MV and LV systems. Despite the example of Fig. 3 depicting an illegal load connection, the methods are applicable to any case in which the meter logs lower values for the active power than the one truly consumed, including some specific cases of cyber-attack. Both methods consider the three-phase topology of distribution systems and are performed offline, without the need of synchronised smart meters. The measurements used in these methods only need to correspond to the same time interval. It is assumed that smart meters from all consumers provide active and reactive power measurements and voltage magnitude measurements per phase.

In [16], the load buses are modelled as QV buses (instead of PQ buses) on a power flow procedure (named *QV method*). This means that the load buses have specified values of reactive power, Q, and voltage magnitude, V, rather than specified values of active and reactive powers, P and Q, typically used in power flow procedures. For each load bus, the active power calculated by the load flow procedure is compared with the active power registered by the smart meter. If the mismatch between these two values (ΔP) is higher than a threshold, it may indicate possible NTL location. The threshold value, defined as the Minimum Detectable Power (*MDP*), is calculated by (8), corresponding to the active power deviation resulted from the maximum voltage measurement errors $\left(\Delta V_{\max}^{SM}\right)$.

$$\mathbf{MDP} = \left(\mathbf{J_{PV}} - \mathbf{J_{P''}} \cdot \mathbf{J_{Q\theta}^{-1}} \cdot \mathbf{J_{QV}}\right) \cdot \mathbf{\Delta_{max}^{SM}} \tag{8}$$

where $\mathbf{J_{P\theta}}$, $\mathbf{J_{PV}}$, $\mathbf{J_{Q\theta}}$, and $\mathbf{J_{QV}}$ are submatrices from the Jacobian matrix, representing the sensitivity of active and reactive power to voltage angle and magnitude, that is, $\partial\mathbf{P}/\partial\boldsymbol{\theta}$, $\partial\mathbf{P}/\partial\mathbf{V}$, $\partial\mathbf{Q}/\partial\boldsymbol{\theta}$, and $\partial\mathbf{Q}/\partial\mathbf{V}$, respectively. The vector **MDP** is obtained by applying a Kron reduction and it contains the Minimum Detectable Power for each system node. The maximum value among the phases is used as the *MDP* for a given load bus. The idea of the defined threshold is to avoid that active power deviations caused by voltage measurement errors (due to meter inaccuracy) are indicated as NTL (false positives).

As output of this method, the QV buses that violate the *MDP* are ranked from the highest to the lowest ΔP value. The load buses with the highest active power mismatches are indicated as the most probable NTL locations. Although system topology and parameters are assumed to be known, errors in line parameters do not significantly affect the method performance.

In [47], the authors propose a state estimation procedure combined with bad data analyses dedicated to NTL detection and location. As previous work, smart meters are assumed to provide measurements of active and reactive powers and voltage magnitude from all consumer buses (per phase). The NTL is treated as bad data, that is, a measurement of active power (and reactive power, when NTL has a non-unity power factor) containing gross error. A particular behaviour of measurement residuals (defined as the difference between the measured value and the estimated value of the electric quantity) is observed in the presence of NTL. This particular behaviour is characterised by positive residuals of active (and eventually reactive) power measurements and negative residuals of voltage magnitude measurements. It indicates that the estimated active and reactive powers obtained by state estimation (P_{SE} and Q_{SE}) are higher in magnitude than the measured values (P_{SM} and Q_{SM}) and that the estimated voltage magnitude (V_{SE}) is higher than the measured value (V_{SM}), as illustrated in Fig. 4. Based on this condition, an index calculated by the composition of the normalised residuals of the active (or reactive) power and voltage measurements is used to identify NTL location, described as follows.

The proposed algorithm, illustrated in Fig. 5, initiates with the distribution system state estimation using the Weighted Least Squares (WLS) formulation, followed by the inspection of active and reactive power measurement residuals from all consumer buses. The presence of NTL at the analysed system is confirmed when at least one normalised residual of active or reactive power measurement (${r_P}^N$ or ${r_Q}^N$) is higher than a defined threshold, commonly used in bad data analyses. After detecting the

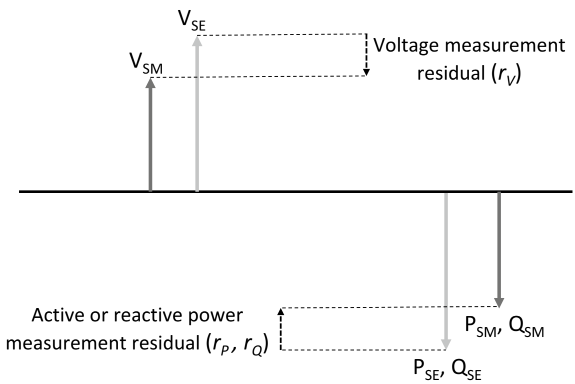

Fig. 4 Measurement residual behaviour in case of NTL in a load bus where smart meters provide active and reactive power and voltage magnitude measurements

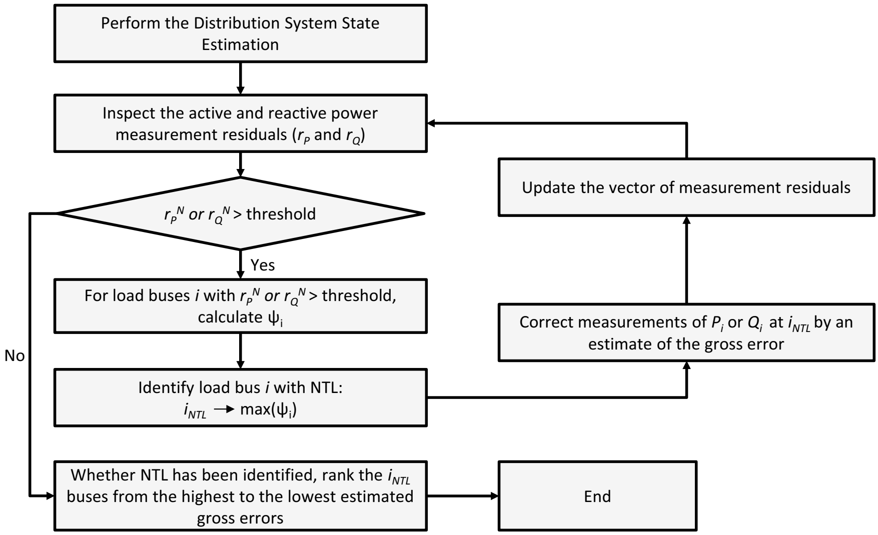

Fig. 5 Proposed algorithm to detect and locate NTL by using smart meter and data analytics

presence of NTL, the next step is to identify its location. To this end, an index ψ_i based on the particular residual behaviour depicted in Fig. 4 is calculated by (9) and assigned to each consumer bus i whose active or reactive power measurement residual has violated the threshold in the previous step.

$$\psi_i = \max\left(r_{Pi}^N, r_{Qi}^N\right) - r_{Vi}^N \tag{9}$$

The highest index value among system buses i indicates NTL location (i_{NTL}). The use of the proposed index promotes a better selectivity when compared to other methods based on traditional bad data analyses. An iterative procedure is then conducted to correct the measurements of active and reactive powers with gross errors (that is, with NTL) and to identify all suspected locations of NTL (in case of multiple illegal load connections). The algorithm result is a list of suspicious consumers in a decreasing order, from the most to the least probable NTL location according to the estimated gross errors. The tests performed on a Brazilian 1682-bus distribution feeder showed the method can detect and locate NTL as small as 2 kW for LV illegal loads and 23 kW for MV illegal loads.

The methods presented in [16, 47] can have their sensitivity increased if they are applied to a period of a day or a month, for instance, instead of a single point. The power deviation (ΔP) of [16] can be translated to the energy deviation (ΔWh) for a given period. The algorithm proposed in [47] can also be applied to each time interval of a given period. The gross errors of active and reactive power measurements estimated for each time interval can be added up to compose the total gross errors assigned to NTL suspected buses. By using the energy deviation and the aggregated gross errors, the methods are less affected by meter inaccuracy. It also improves the methods' detection, especially in cases where illegal loads are not permanently connected to the system.

It is important to note that the presence of distributed generation at the consumer unit with NTL does not affect the methods' performance, because the inconsistency between voltage magnitude and active and reactive power measurements still remains in this situation, which is the base of both methodologies for NTL identification.

3.4 Voltage Quality Monitoring

Every factor that deviates voltages from an ideal waveform is defined as a voltage quality problem. Therefore, voltage quality monitoring comprises observing one or more of the following aspects: voltage unbalance, voltage sag/swell, under/overvoltage, voltage harmonic distortion. Based on the existence of a wide spectrum of voltage quality issues, several works present surveys or results from laboratory tests to better understand the potential and limitations of the use of smart meters' capabilities to monitor voltage quality. Table 2, from 2015, presents the voltage quality monitoring capabilities of the most common smart meters in New Zealand [7].

In Palacios-Garcia et al. [43], a smart meter with the ability of detecting three types of voltage quality events are tested: long-term deviations (longer than 10 s); short-term deviations (between 1 and 10 s) and voltage outage. To perform the tests, one

Table 2 Voltage quality monitoring capability of smart meters

	Manufacturer A model 1	Manufacturer A model 2	Manufacturer B	Manufacturer C
Sampling interval	1 s–1 month	1–60 min	10/15/30/60 min	5/15/30/60 min
Voltage	Instant., min., max., average	Instant., min., max., average	Instantaneous	Instantaneous
Phase angle	Instant., min., max., average	Instant., min., max., average	Instantaneous	Unknown
Resolution	5 cycles	5 cycles	1 s	32 cycles
Voltage sag start	0–255% Vn	0–255% Vn	0–300 V	192–288 V
Voltage swell start	0–255% Vn	0–255% Vn	0–300 V	192–288 V
Hysteresis	Yes	Yes	Unknown	No
Voltage THD	Yes	Yes	Pending firmware update	No
Individual harmonic measurement	Yes (up to 50th)	No	Pending firmware update (up to 25th)	No

smart meter was connected to a grid simulator, where short and long-term deviations were generated to test the detection features. When a long-term voltage deviation is detected, three values are recorded: maximum, minimum, and average voltage for the period. In the case of short-term deviations, the start and end points are also recorded. Nevertheless, if the event is shorter than two seconds, only the extreme value is registered.

In [46], an event-driven state estimation is proposed to monitor the level of voltage magnitude and unbalance in distribution systems. According to this approach, the communication of smart meter data from consumer i is triggered whether at least one of the following two conditions is characterised: (a) the variation between two subsequent measurements of active or reactive power (ΔP_i or ΔQ_i) is higher than the thresholds values (ΔP_{lim} or ΔQ_{lim}), or (b) the accumulated variation between subsequent measurements of active or reactive power ($\sum \Delta P_i$ or $\sum \Delta Q_i$) is higher than the threshold values (ΔP_{lim} or ΔQ_{lim}). When such an event is identified by the smart meter, the following data are communicated to the DSO: instantaneous measurements of active and reactive powers and voltage magnitude (assuming that measurements are aggregated every elementary interval of 1 s). These communicated data are used as input of the DSSE algorithm, which is performed whenever an event occurs, updating the estimated state of the system.

The event-driven DSSE can also be used to detect voltage sags caused by large and fast load variations, that is, high values of ΔP_i and ΔQ_i (e.g. motor starting), besides identifying its cause. The voltage sag source detection is conducted by identifying the smart meter that sent information when the voltage sag has started.

Among the benefits of voltage quality monitoring one can highlight more accurate knowledge of voltage outage events and causes, as well as of the regions more affected by voltage quality problems. Moreover, in Watson et al. [57], voltage harmonic distortion is used to determine distribution system topology. Voltage quality problems directly affect electronic loads and motor torque and, consequently, can cause financial losses related to process trips or damage. Certainly, voltage outages and deviations are among the top reasons of consumers´ complaints to the DSO.

The following items are the most common causes of voltage quality problems:

- Arc furnaces, frequent start/stop of electric motors (for instance elevators), oscillating loads
- Permanent and temporary faults and operation of protection devices
- Unbalanced distribution of the loads over the three-phase system
- Lightning, switching of lines or power factor correction capacitors, disconnection of heavy loads

By identifying the causes, the DSO engineers can act preventing:

- Voltage unbalance by correcting the distribution of single and two-phase loads over the three-phase system
- Neutral overload in 3-phase systems, overheating of all cables and equipment, loss of efficiency in electric machines, electromagnetic interference with communication systems by mitigating harmonics

- Damage of electronic components and insulation materials, data processing errors or data loss, electromagnetic interference by alleviating the impacts of: lightning, switching of lines or power factor correction capacitors, disconnection of heavy loads
- Malfunction of information technology equipment, namely microprocessor-based control systems (PCs, PLCs, ASDs, etc.) that may lead to a process interruption, tripping of contactors and electromechanical relays, loss of information and malfunction of data processing equipment, disconnection and loss of efficiency in electric rotating machines by avoiding voltage sags or short interruptions with DSO side or consumer side solutions

Despite all the benefits voltage quality monitoring can provide to the improvement of distribution companies' services, data volume is a concern. The challenges are related with communication, storage and processing big data volumes. Halliday and Urquhart [22] affirm that a smart meter that transmits 10-min data of voltage magnitude, voltage unbalance or positive and negative sequence voltages, total harmonic distortion, sag/swell, and outage event data captures approximately 5 megabytes/year. A DSO with 1,000,000 consumers with smart meters could therefore expect 5 terabytes of data/year. In 2008, data transfer costs/meter was estimated to be $60/year, representing a total of $60 M/year for a DSO with 1,000,000 consumers with smart meters.

3.5 Automated Determination of Topology and Line Parameters

Management of an updated and correct database for distribution companies is not only an important but also a particularly difficult task. As a DSO database contains all assets from the company, its applicability ranges from financial to operation and planning activities. Adjustment of tariffs at the end of a regulatory period, energy loss compensation, expansion of the system, fault location, and power quality studies are examples of activities that rely on database information. However, most operators report that their data are scarce, patchy, or not even digitised [41]. This implicates that errors are practically inherent in such databases.

A significant part of the database errors is originated because data are included and updated manually. It means that for any line or transformer added to the system or any switch that has changed its status, a DSO worker must update or include new information in one or more databases. Because of that, it is common that different sectors on the same DSO have inconsistencies among their databases. Table 3 exemplifies common errors related to manual data entry [12], classified by topological and line parameters errors.

In order to mitigate the occurrence of such errors, automated algorithms based on data analytics have the potential to validate, complete, and correct inconsistencies on DSO databases. In the past, these methods had limited application on distribution

Table 3 Most common topological and line parameters errors in distribution systems

Topological errors	
Error	Example
Data have wrong or unknown information	No information of transformers, lines, switches parameters. An integer variable has a string value associated
Branch elements (lines, transformers, etc.) have fewer than two buses information	Buses *To* or *From* have wrong or unknown information
Elements are isolated, missing or wrongly connected	Isolated or missing lines, transformers, switches, loads. Loads connected to wrong low voltage system
Phase connectivity is wrong or unknown	Downstream line bus has three phases (*a*, *b*, and *c*) whereas upstream line bus has only two phases (*b* and *c*)
Elements have unexpected endpoints	Lines in low voltage systems without downstream connectivity (other lines or loads)
Line parameters errors	
Errors	Example
Lines have incorrect or unknown length	Service cables longer than expected (typically up to 30 m)
Spatial position of wires is wrong or unknown	Wires position do not match with mechanical structures used
Lines have wrong wire specifications	Incorrect material or diameter

systems because of the lack of sufficient data to provide reliable solutions. Nowadays, the high deployment of smart meters on consumers with capacity of acquiring measurements are the missing elements to allow the implementation of accurate and reliable data analytics solutions.

Among data analytics approaches, multiple linear regression has been investigated in the recent literature for identification and correction of topological and line parameter errors [11, 31, 38, 44, 52, 57]. The greatest attraction of this strategy is the fact that it presents a simple formulation, based on electric circuit theory. Methods that utilise common knowledge of electrical engineering tend to be well accepted in the industry sector. Another positive characteristic corresponds that the multiple linear regression can be applied in multi-phase and multi-wire systems [11]. This means that this strategy is precise even for systems with distinct topologies, such as North American, European, or South American systems. Finally, in a quantitative perspective, these methods have been reported with roughly 90% of accuracy for topology estimation and 80% of zero error impedance estimation [11].

3.5.1 Formulation of a Multiple Linear Regression Applied to Distribution Systems

A multiple linear regression is formulated based on the highlighted lines shown in Fig. 6.

Consider that the highlighted lines are three-phase four-wire. The measurements acquired in the consumers' smart meters are phase-neutral voltage magnitude, active and reactive powers per phase. The number of samples for these measurements is defined as η. The voltage drop from bus 1 or bus 2 to their upstream bus is calculated as shown in (10).

$$\hat{V}_{AN} - \hat{V}_{an} = (Z_{aa} - Z_{an})\hat{I}_a + (Z_{ab} - Z_{bn})\hat{I}_b + (Z_{ac} - Z_{cn})\hat{I}_c + (Z_{nn} - Z_{an})\hat{I}_n, \quad (10)$$

Note that the voltage drop in (10) corresponds to phase a. It can be analogously obtained for phases b and c. The terms in (10) can also be applied to other topology configurations by simply removing the current term that is not presented in the lines.

As the earth current and angular differences among buses in distribution systems are small [24], the combination of (10) for lines 1 and 2 results in (11) [11]. The terms $\mathbf{I_R}$ and $\mathbf{I_X}$ represent the real and imaginary components of the calculated currents.

$$\underbrace{\boldsymbol{V_{an1}} - \boldsymbol{V_{an2}}}_{\eta x 1} = \underbrace{\begin{bmatrix} \mathbf{1} & -\boldsymbol{I}_{\boldsymbol{R1}}^T & \boldsymbol{I}_{\boldsymbol{X1}}^T & \boldsymbol{I}_{\boldsymbol{R2}}^T & -\boldsymbol{I}_{\boldsymbol{X2}}^T \end{bmatrix}}_{\eta x 13} \overbrace{\begin{bmatrix} \beta_0 \\ \boldsymbol{R}_{\mathbf{1}}^T \\ \boldsymbol{X}_{\mathbf{1}}^T \\ \boldsymbol{R}_{\mathbf{2}}^T \\ \boldsymbol{X}_{\mathbf{2}}^T \end{bmatrix}}^{13x1} \rightarrow$$

$$\boldsymbol{Y} = \boldsymbol{U}\boldsymbol{\beta} + \boldsymbol{\varepsilon} \quad (11)$$

The least-square model is applied to solve (11), so that the estimated parameters of the lines can be obtained. These parameters refer to the positive sequence resistance

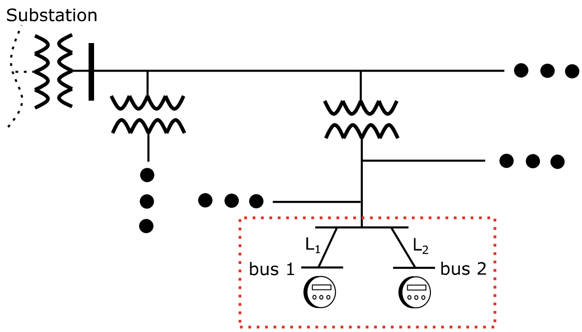

Fig. 6 Illustration of a distribution system, where part of a low voltage system (two consumers with smart meters and service cables) are highlighted for the formulation of the multiple linear regression

and reactance and an estimated neutral resistance for lines 1 and 2. They can be compared to the existing values for these elements in the DSO database. They can also be used to fill in missing data or obtain the correct type of each wire from these lines.

As shown before, the validation of the line parameters is done by analysing the estimated parameters from the multiple regression. For the topology check, the coefficient of determination is applied as shown in (12).

$$R^2 = 1 - SSE/SSTO \tag{12}$$

where:

$$\begin{aligned} SSE &= \boldsymbol{Y}^T\boldsymbol{Y} - \boldsymbol{\beta}^T\boldsymbol{U}^T\boldsymbol{Y} \\ SSTO &= \boldsymbol{Y}^T\boldsymbol{Y} - \frac{1}{\eta}\boldsymbol{Y}^T \underbrace{[\mathbf{1}]}_{\eta x \eta} \boldsymbol{Y} \end{aligned} \tag{13}$$

The coefficient of determination assesses the proportion of the variance that is explained by the multiple regression model. This parameter varies from zero to one, that is, from total unfitted to total fitted. A value close to zero means that the connection between lines 1 and 2 probably does not exist. In contrast, a value close to one means that such a connection probably exists.

3.5.2 Automated Validation Process

The validation of line parameters and line connection is achieved by using (11) and (12), respectively. The data included on the multiple linear regression model is provided by existing smart meters.

After checking the line parameters and topology, the voltage of the upstream bus (Fig. 6) can be approximately calculated by (10). Additionally, the aggregation of the calculated currents from both meters results in the approximate currents from the upstream bus. By obtaining these virtual measurements of voltages and currents for the upstream bus in Fig. 6, the downstream circuit can be replaced for an equivalent virtual meter.

Based on that, the automated validation of line parameters and topology for distribution systems starts from the consumers' smart meters towards the substation. This process consists ideally of combining all real and virtual meters until only one virtual meter has been left (on the substation location). In this case, all line parameters and the system topology are validated. However, in practical systems, one limitation that this method may face is the incompatibility of phases from two connected lines (e.g., line 1 has only phase *b* and line 2 has only phases *a* and *c*).

Figure 7 illustrates the general idea of the automated process for validation of line parameters and system topology. The distribution system diagram is reorganised by layers, which are referenced by branch elements (lines, transformers, etc.). Note that,

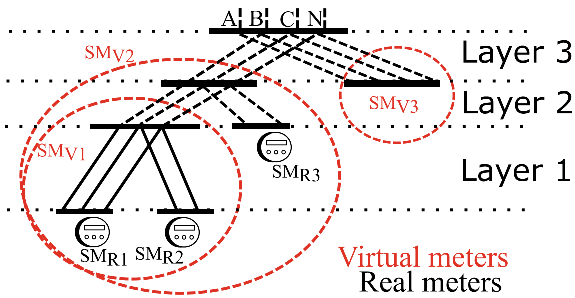

Fig. 7 Illustration of the automated process for line parameters and topology validation using real and virtual meters

in the first layer, there is a combination of two real meters, resulting in a virtual meter (SM_{V1}). Then, SM_{V1} is combined with a real meter (SM_{R3}), resulting in another virtual meter (SM_{V2}). Finally, the last virtual meter is obtained from two virtual meters (SM_{V2} and SM_{V3}). At this point, all line parameters and the system topology have been checked, corrected or completed.

Most methods applying multiple linear regression in the literature deal with offline correction and validation of databases. This means that the automated process to correct or validate a database is executed by, for example, the end of a day or a week. The online application of this approach is still a challenge to be implemented. A challenge faced in real-time applications is that multiple linear regression requires an overcompensated set of samples to retrieve a result. Depending on the sample rate of smart meters, the sampling period is impractical for applications. For example, two three-phase four-wire lines have 13 variables to be estimated in the multiple linear regression model. If the meter sample rate is one hour, it takes at least 14 h to obtain a solution by using this approach. This period may be too long for switches monitoring or fault location.

3.6 Load Modelling

Load modelling still represents source of inaccuracy to power system analyses that are crucial to DSO operation and planning tasks. Unlike the models of generators and other distribution system elements, load models are complex and have not been well-established [2]. The measurements acquired from smart meters help to better represent active and reactive power demands of loads. However, these measurements cannot reproduce precisely the voltage dependency of loads, so that load modelling is still incomplete in a power system analysis tool. In this context, methods that better describe the load behaviour are still desired by the industry.

There are basically two classifications for the approaches that cover load modelling: component-based [9, 23, 33] and measurement-based methods [18, 28, 30].

Component-based approaches create templates for loads according to their characteristics, *e.g.*, type of consumer (residential, commercial, or industrial), consumption, total demand, etc. Based on statistical information, typical appliances and equipment are assigned to certain consumer units. After defining the template of a load, patterns for individual appliances and equipment are obtained in laboratory tests (e.g., [4]) or in existing databases. The aggregation of each component provides a reasonable model for loads in power system analysis tools. The major challenge in these approaches is to determine the component set that better describes each load.

Measurement-based approaches rely on data acquired on meters to define the most suitable model for loads. Power quality meters, phasor measurement units, and consumers' smart meters can be utilised for these methods. It means that they may employ waveform, phasor [21], or magnitude [18] measurements. Particularly consumers' smart meters are an attractive option for DSO because these devices have been widely deployed to replace electromechanical meters. For instance, one measurement-based method is described below.

This measurement-based method focuses on the determination of voltage dependency model for loads. This approach is applied for static load modelling, which is suitable for steady-state studies (e.g., load flow). The measurements utilised are voltage magnitude, active and reactive powers, so that they can be acquired in consumers' smart meters.

The voltage dependency of active and reactive powers on its exponential form is formulated as shown in (14),

$$P = P_0\left(\frac{V}{V_0}\right)^{n_p}, Q = Q_0\left(\frac{V}{V_0}\right)^{n_q} \tag{14}$$

where V_0, P_0, and Q_0, are the nominal values for voltage magnitude, active and reactive powers and V, P, and Q, are real-time values for voltage magnitude, active and reactive powers for a load.

The exponent terms n_p and n_q define the voltage dependency for active and reactive powers, respectively, and are generally unknown. The idea of the proposed approach is to estimate such parameters by sampling the variation of voltage magnitude, active and reactive powers from consumers' smart meters. The estimated exponents are obtained after rearranging (14), as shown in (15),

$$n_p = \frac{\log_{10}(P_{t+1}/P_t)}{\log_{10}(V_{t+1}/V_t)}, n_q = \frac{\log_{10}(Q_{t+1}/Q_t)}{\log_{10}(V_{t+1}/V_t)} \tag{15}$$

where t represents the measurement instant.

Note, in (15), that the exponent terms are determined by variations over time on powers and voltage measurements. In this case, the challenge is to define the characteristic variations that can estimate the exponent terms. Based on that, the following rules are applied [18]:

- Voltage magnitude, active power and reactive power per phase are measured and stored in a circular memory (buffer) with 5-s capacity
- If a voltage variation higher than 0.5% is detected, the following test is executed:

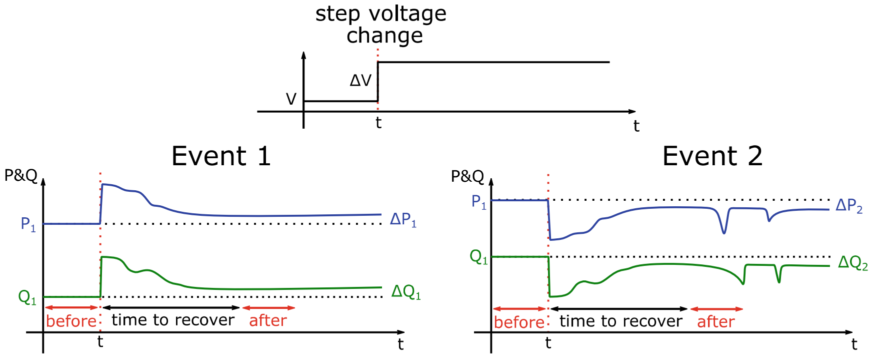

Fig. 8 Illustration of one case that is accepted (event 1) and another case that is rejected (event 2) by the imposed rules

- If voltage increased (decreased) and active and reactive powers decreased (increased), discard this event because the change may have been caused by load variation
- If other voltage or power variations are observed after the first event, discard this event because other perturbations may be evolving, which are not related to the condition the method aims to detect
- If voltage increased (decreased) and active and reactive powers increased (decreased), determine P_{t+1}, P_t, Q_{t+1}, Q_t, V_{t+1}, V_t. These measurements are averaged values for 0.5 s before the event detection (t) and 0.5 s after the event detection ($t+1$). Then, calculate the load exponents n_p and n_q by using (15)

Figure 8 illustrates two events in order to clarify the application of the proposed rules. For a given voltage rising step, active and reactive powers from event 1 also increased without having fluctuations before or after the event. This means that this event satisfies the above-mentioned conditions and can be used in the estimation of the exponents. Then, active and reactive powers are acquired and n_p and n_q are calculated. On the other hand, considering event 2, active and reactive powers decrease resulting in a voltage increase. Additionally, there are power fluctuations after the event. Any of these conditions is sufficient for this event to be ruled out.

The process of calculating n_p and n_q is repeated for each accepted event. The higher the number of accepted events, the more precise the estimated parameters. This means that the selected thresholds detect a voltage variation and determine the periods before and after playing a key role on the sampling size, and, consequently, on the precision of the method.

4 Conclusions

In this chapter, the evolution of energy meters was firstly introduced, depicting the status of smart meters with their main functionalities. Then, potential DSO-side applications of smart meter data were presented, helping to identify the benefits enabled by the large-scale deployment of such devices and the associated AMI. These new applications can maximise the utilisation of AMI capabilities, assisting distribution companies that have already implemented this advanced infrastructure or the ones that are considering implementing it. The former may mitigate the risk of having their investment recovery rejected by regulators or other authorities. The latter can better justify the implementation of AMI to their shareholders. These scenarios are possible because companies are projecting the AMI potentiality to improve the operation and planning of distribution systems, as well as to provide new consumer solutions.

As previously discussed, direct applications can be implemented by using the data from smart meters, such as those pieces dedicated to fault location, NTL detection and location, and voltage quality monitoring. In addition, multiple auxiliary applications are enabled: DSSE, automated determination of system topology and parameters, and load modelling. The auxiliary applications assist in different operation and planning tasks, providing information to be used by direct functions. For instance, NTL identification and fault location methods typically depend on the knowledge of distribution system characteristics, and benefit from a more accurate determination of system topology and parameters. The DSSE can be used as a supervisory tool to monitor the voltage quality in distribution systems and to identify NTL. Accurate representations of consumer loads, allowed by more suitable load modelling methods, are important inputs of the load flow calculations and DSSE procedures (to be used as pseudo measurements).

A particular set of measurements gathered from smart meters, composed of active and reactive powers and voltage magnitude data, reveals relevant information on consumers and distribution system characteristics. Some of the discussed methods rely on this set of measurements to detect and locate NTL, build load models, and define the system topology and parameters. Despite the fact that acquiring real-time (or near real-time) data from all consumer smart meters is still an issue, mainly due to communication constraints, it does not inhibit the application of most of the discussed methods.

Overall, using smart meter data to support distribution system operation and planning tasks integrated to the ADMS functions add value to smart meters, helping to justify the investments associated with AMI implementation.

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Communication in Active Distribution Networks

Manel Velasco, Pau Martí, Ramón Guzman, Jaume Miret, and Miguel Castilla

Abstract The use of a multi-purpose shared digital communication network to connect spatially distributed power electronic inverters provides additional capabilities for small-scale power systems to achieve higher functionality and efficiency for power management and quality. However, the use of a shared network introduces also uncertainty due to unexpected timeliness and failures that may negatively impact in the power system operation and reliability. This chapter takes an experimental point of view to analyze the operation and reliability of an islanded inverted-based low-scale laboratory micro grid (MG). The considered scenario is a set of inverters driven by digital processors that exchange control data over a shared digital communication network that inherently introduces messages delays and dropouts, and that it is subject to failures such as loss of communications. By means of communication-based distributed control, inverters goal is to ensure active power sharing and frequency regulation.

1 Introduction

The replacement of fossil fuels by various sources of renewable energy requires strategies to facilitate their integration into the energy system. One potential solution

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are microgrids (MGs) [1], which are expected to constitute a scalable power system with a high service standard by adequately combining advanced power electronics, information and communication technologies, and new control and management strategies [2]. In essence a MG consists of a combination of diverse distributed generation (DG) units (interfaced by power inverters), loads and storage systems managed by fast acting power electronics. A MG is connected to the distribution network through a single point of common coupling.

DG units can be highly heterogeneous, and can generate variable frequency AC power, e.g. wind turbines, or DC power, e.g. solar panels. The heterogeneity of generated power is interfaced with the synchronous AC MG via power electronic inverters (DC/AC or AC/AC converters). Inverters can be classified as currentsource inverters (CSIs) or voltage-source inverters (VSIs). CSIs must be continuously synchronized with the grid via phase-locked loops and their main goal is to inject current to the grid (according to the specified reference power). VSIs do not need any external reference to stay synchronized with the grid and they can be used to guarantee energy quality in islanded operation [3].

Microgrids have several specific features that make them differ from conventional power systems [4]. First, they must be able to operate despite intermittent behavior at the DG output and changes in loads. Second, they should offer a plug-and-play and scalability functionality in order to connect/disconnect the diverse units without reprogramming the control and management system. And third, when the main power grid is not available, they should operate independently, in islanded mode. The original definition of MG focuses on its islanding capability to protect itself from outages and interruptions, however, the concept and practice have evolved with an increased emphasis on generation and load management. The advanced microgrid is able to actively balance generation with demand, economically schedule and dispatch its generation resources, and attain high reliability and resiliency.

The MG islanded operational mode is significantly more challenging than the grid connected mode because the dynamics of the MG are no longer dominated by the main grid [5]. Islanded mode requires the implementation of accurate control mechanisms to achieve and maintain the demand–supply equilibrium, where MG DG units play a key role [6].

1.1 MG Scenario and Control Objectives

The presented analysis places the attention to the MG islanded operation mode where heterogeneous and physically distributed VSIs take coordinated actions following communication-based distributed control principles to ensure synchronization, voltage regulation, power balance and load sharing [7, 8].

Figure 1 illustrates a generic scheme of a MG with all the key elements that are covered in the analysis. The AC MG operates in islanded mode, and comprises two sets of elements. The first set is related to power generation and supply, loads, and transmission lines (solid lines). From left to right, battery, wind turbine, solar panel,

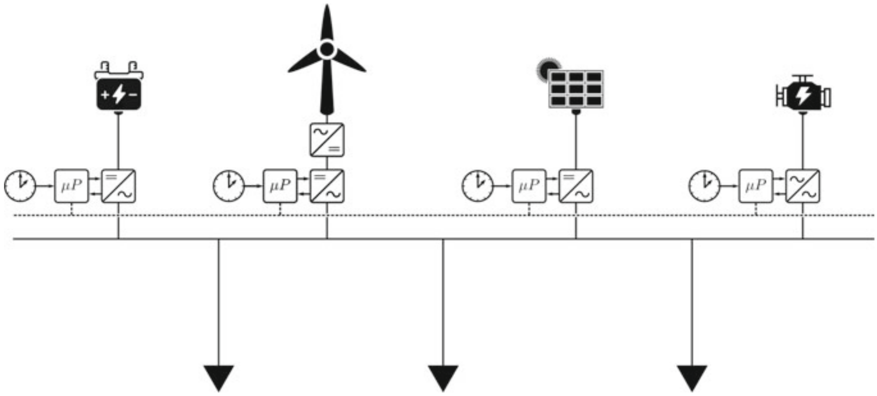


Fig. 1 Scheme of the inverter-based islanded microgrid

synchronous generator, all interfaced through power inverters, can be identified. The second set is related to computation technology and digital communication network (dashed lines), where microprocessors that execute distributed control algorithms and exchange control data can be recognized.

Within the wide number of control objectives being addressed within a MG, the focus is placed on active power sharing and frequency regulation. Hence, the control objectives of the inverters are formulated in steady-state as follows:

- To provide accurate power sharing,[1] as in

$$P_{i,ss} = \frac{P_T}{\sum_{j=1}^{n}\left(\frac{m_i}{m_j}\right)}, \tag{1}$$

  where $P_{i,ss}$ is the power supplied by each inverter in steady-state, P_T is the total power, and m_i and m_j are two parameters related to the rated power of the inverters. The total power includes the load power and the transmission losses.
- To regulate the frequency of the MG in steady-state ω_{ss} to its nominal value ω_0, which can be expressed as

$$\omega_{ss} = \omega_0. \tag{2}$$

The achievement of these control objectives, that are often addressed using a hierarchical control scheme [9], increasingly relies on a shared digital communication architecture that supports the MG operation [6]. Therefore, data exchange between inverters plays a key role, and the impact that communications have in control performance must be analyzed due to the inherent uncertainty brought by the communication network. In addition, the communication uncertainty may also

[1] The power provided by the inverter must be proportional to its power rating while guaranteeing the supply of the load.

impact on the perception that inverters have of the structure of the electrical network, which may not correspond to its real structure.

The high-level interdependency between the electrical network and the communication technology that makes the problems of reliability and operation more complex than in the traditional grid, has been identified in the literature. See [10] for a key contribution on interdependencies between infrastructures, and [11] for a recent review. Unexpected operational timeliness or failures in the communication infrastructure negatively impact power systems [12]. The particular distributed control policy that apply as well as the type of communication scenarios that may occur determine the degrees of interdependency between the electrical and communication networks. And they will lead to different levels of degradation of power quality but hopefully without causing loss of power supply nor serious damage to hardware assets [13, 14].

1.2 Communication Uncertainties

The analysis presented in this chapter covers two aspects of distributed power management applications whose operation relies on using a shared digital communication network. The first aspect is communication timeliness and the second one applies to reliability. Timeliness refers to the inherent but probably unexpected timing properties that affect the logical operation of distributed action, which are caused by message delays and dropouts. They inevitably occur and they will impact control performance when placing a network within control loops. Reliability refers to unexpected failures that lead to a loss of communications in distributed control applications. And the loss of communications implies a temporary interruption of the distributed exchange of control data between specific VSI and may also impair the distributed notification of anomalies affecting the electrical network such as damage in power transmission lines.

This chapter is organized as follows. Section 2 describes the laboratory MG where all the experiments are performed. Section 3 explains the particular aspects of the communication network that are accounted for in the experiments. Section 4 presents the control policies for power sharing and frequency regulation that are considered and Sect. 5 provides a sketch of the modeling and analysis approach that gathers together power flow principles with graph theory. Section 6 describes the experiments and Sect. 7 concludes the chapter.

2 Laboratory MG

The MG equipment used in the experiments is located in the laboratory of the Power and Control Electronics Systems Research Group (SEPIC) at the School of Engineering (EPSEVG) of the Technical University of Catalonia (UPC), in Vilanova i la

Geltrú, whose extended description can be found in [15]. It is worth mentioning that the growing interest in MG research has led to several publications describing MG laboratory setups for research and educational purposes such as [16–18].

The experimental setup is a three-phase small-scale laboratory microgrid, schematically illustrated in Fig. 2. The values of the components are listed in Table 1. The system is composed of four generation nodes $G_{1,2,3,4}$ in which the power generation of distributed energy sources is emulated. Each generation node consists

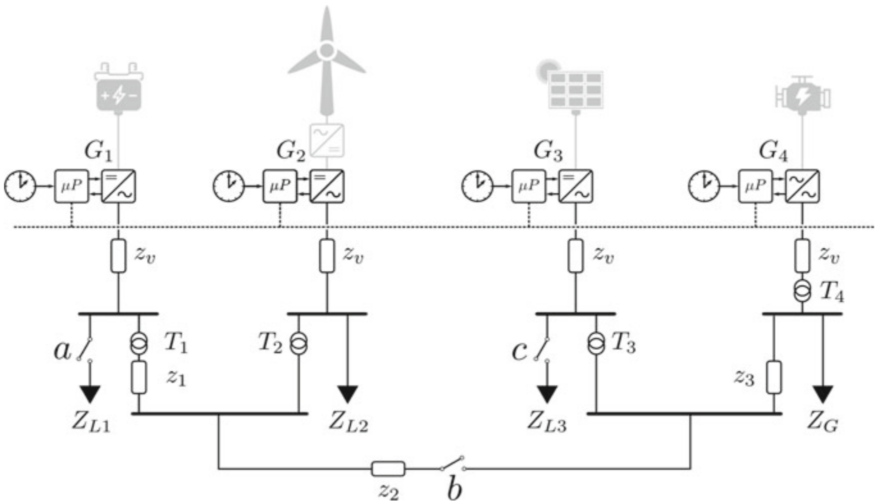


Fig. 2 Microgrid scheme

Table 1 Nominal values of the laboratory MG components

Symbol	Description	Nominal value
v	Grid voltage (rms line-to-line)	$\sqrt{3}$ 110 V
ω_0	Grid frequency at no load	$2\pi 60$ rad/s
Z_1	Line impedance 1	0.75Ω@90°
Z_2	Line impedance 2	0.30Ω@90°
Z_3	Line impedance 3	0.30Ω@90°
T_1	Transformer impedance	0.62 Ω@37.01°
T_2	Transformer impedance	0.62Ω@37.01°
T_3	Transformer impedance	1.31Ω@9.87°
T_4	Transformer impedance	1.31Ω@9.87°
Z_v	Virtual impedance	3.76Ω@90°
P_G	Nominal global load power	1.5 kW
Z_G	Global load impedance	22Ω@0°
$P_{L1,L2,L3}$	Nominal local load power	0.5 kW
$Z_{L1,L2,L3}$	Local load impedances	88Ω@0°

of a 2 kVA three-phase full-bridge IGBT power inverter MTLCBI0060F12IXHF from GUASCH and a damped LCL output filter. For the energy supply an AMREL SPS-800-12 DC power source is used. The tested controller strategy (enabled with virtual impedance Z_v) of each inverter is implemented on a dual-core Texas Instruments Concerto board. It consists in a C28 floating point digital signal processor (DSP) that implements the control algorithms, and an ARM M3 processor that is used for communication purposes, both using a hardware clock that has a drift rate upper bounded by 1.00002 [19], that is, each inverter clock accuracy error is lower than ± 20 parts per million (ppm). The MG uses the User Datagram Protocol over a switched Ethernet to allow communication among the four inverters. In the diagram, the circle with small arrows at the bottom represent the Ethernet switch that has a point-to-point ethernet cable to each generator (M3 processor). Timelines properties are inherent to the use of the Ethernet network but they are also sometimes explicitly magnified whenever required to provide a better view of the impact that they have in application performance. The baseline transmission rate is set to 0.1 s. Three-phase inductances in series with resistors are implemented to emulate the wires of the distributed lines, termed as $Z_{1,2,3}$. The diagram also includes isolation transformers $T_{1,2,3,4}$ connected at the output of each inverter. The MG feeds a global load with impedance Z_G and three local loads with impedance Z_{L1}, Z_{L2} and Z_{L3}. Resistive heaters are used as loads, connected in wye configuration with a floating neutral node. The scheme in Fig. 2 also includes two interruptors *a* and *b* in the form of electronic relays governed by a digital board. Interruptors *a* and *c* are used to connect or disconnect the local loads Z_{L1} or Z_{L3} respectively, while *b* allows the electrical partitioning of the MG. They are used for forcing unexpected failures in transmission lines. Communication failures are performed at the Ethernet switch level by disabling specific communication ports.

The main components of the laboratory MG are given by the pictures shown in Fig. 3. The MG is organized in four shelfs, see the left picture, each one containing an inverter and both control and sensing boards, detailed in the right picture.

Figure 4 provides a complementary view of the laboratory MG stressing the communication and electrical network, organized into two levels. It will be used for the analysis of different operational scenarios regarding MG performance. In particular it shows the MG in terms of connectivity where nodes labeled by 1, 2, 3 and 4 correspond the four VSI and vertex reflect connectivity between nodes. The top graph corresponds to the electrical connectivity between the four generators. In this case the existence of a vertex between two nodes indicates that there is, physically, a transmission path between the two VSI and therefore that they can exchange power flows. The bottom graph corresponds to the communication connectivity involving also the four generators. The existence of a vertex between two nodes indicates that, from a logical operation, these two VSIs can exchange control data. Therefore, the interpretation of vertex in each graph is a little bit different. By comparing the laboratory MG scheme given in Fig. 2 with the nodes connectivity shown in Fig. 4 it can be concluded that the electrical connectivity corresponds to the case when all interruptors are closed, while the communication connectivity corresponds to a traffic scheme where all nodes can exchange data with the rest of the nodes (following an

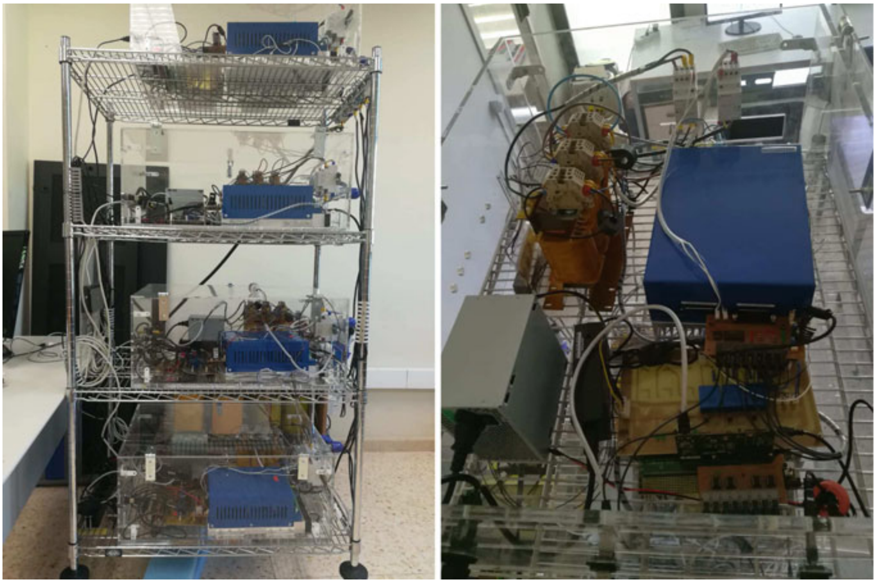


Fig. 3 Laboratory MG: 4-VSI structure (left), and detail of VSI and control and communications hardware (right)

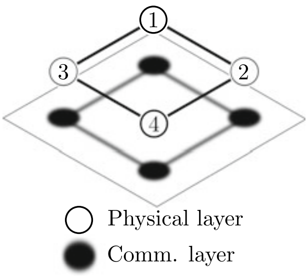


Fig. 4 Characterization of the MG in terms of electrical (top) and communication (bottom) connectivity, illustrated by means of two layers, where nodes represent generators in both layers, and lines between pairs of generators in both graphs represent the existence of connectivity

all-to-all communication scheme). This type of figures will be used for illustrating different type of communication failures that will impair the exchange of control data between VSIs (and illustrated in the communication connectivity) or will impair the exchange of supervisory data between VSI upon detection of damage in power links (and illustrated in the electrical connectivity).

3 Communication Timeliness and Reliability

From a platform point of view, MGs are distributed systems consisting of a collection of physically dispersed computation devices, communicating with each other to accomplish collective goals. The MG distributed control necessitates the communication of sensor information towards a controller and of information about the control input from the controller towards the actuators, architecture known as networked control system (NCS) [20]. The implementation of this communication can be done using the large variety of digital networks that are becoming available everywhere and can be used for the implementation of feedback loops without additional installation cost. Some properties of digital communication networks (such as being open and inhomogeneous with changing topology and nodes, and behaving non-deterministically in dependence upon the number of nodes, the used links and the traffic) influence the overall MG behavior.

In general, communication-based policies for frequency regulation and active power sharing were designed considering ideal conditions. That is to say, the theoretical logics of these control approaches are supposed to be not affected by the way in which the platform comprising communication devices, communication network and power grid works. In a realistic world, ideal conditions no longer hold and many sources of unpredictability arise due to imperfections in the communication and transmission networks. As previously stressed, the current analysis covers two aspects.

The first one refers to timelines and in particular focuses on time delays and dropouts. Varying transmission delays arise because sampling and transmitting data, and executing the control algorithm take a certain (nonzero) amount of time. Besides the fact that these operations cannot be performed infinitely fast, the network and the computation resources can also be partially occupied by other tasks and the data can be routed differently at every transmission. This introduces nonzero and time-varying transmission delays. Message dropouts occur because transmissions may fail, due to collisions of messages with others or because the data get corrupted in the physical layer of the network, causing a message to never arrive or to become unreadable. Although a large body of control theory of NCS is available that take into account communication constraints with respect to timing, information loss, variable communication topology, etc. (see e.g. [21, 22]), this research is not fully reflected in the power systems theory in practice. In most of the literature relating to power systems, it is assumed that the transmission of signals to and from the central control unit or between inverters occur over an ideal, lossless and delay-free communication network. However, this tendency is starting to change, and several results do put emphasis on the networking system in terms of communications infrastructure [23, 24], in terms of communication technologies [25], and in terms of the impact that communications have in distributed power applications [26, 27]. The analysis presented next unifies and complements previous works. An effort is made for explaining, from a qualitative point of view, the effect that unexpected timeliness have in the behavior and performance of active power sharing and frequency restoration control policies.

The second aspect being considered refers to reliability and covers the problem of loss of communications. On the one hand, the loss of communications implies a temporary interruption of the distributed exchange of control data between specific VSI. This is typically caused by a failure in a communication link. On the other hand, the loss of communications may also impair the distributed notification of anomalies affecting the electrical network such as damage in power transmission lines. Both problems of loss of communications can be also due to physical faults or cyberattacks, and they can be tightly related. For example, communication failures can be caused by sophisticate attacks on exchanged data leading to immediate physical misbehavior of power systems [28]. These attacks can be, for example, in measurements to disrupt awareness of the situation, or in control signals for components of the power grid, including generation units and loads. But communication failures can also be caused by vegetation and extreme climate conditions that also causes physical faults in terms of electrical failures. The most severe are power outages because they disrupt the electricity supply for an extended time resulting in the loss of critical services (e.g. [29, 30]) such as communications. Power blackouts may be triggered by a single power line failure that triggers consequent failures along the grid. Power lines carry electric flows, which cannot be freely determined but follow the laws of physics. Once a power line fails, the energy flowing over the remaining lines is automatically redistributed, and these changes can cause one or more operating lines to exceed their capacity. Power lines can carry excessive flows for some period of time before they are heated up to a certain level and become inoperable. Cascading failures can be initiated once one or more power lines fail. Hence, fast and accurate detection and localization of power line outages are among the most important monitoring tasks in power grids [31]. The goal of reliable distributed control approaches of MGs is to ride-through electrical and communication failures providing graceful degradation of power quality.

Looking at the reliability aspect, and in order to limit and give structure to the generic problem of loss of communications, the analysis will cover failures that can be understood as damage in power links (physically) and unavailability of communication links (logically). Moreover, these two type of failures are supposed to occur in such a way that the MG is partitioned, electrically and also from a communications point of view. Hence, the lack of reliability will lead to disconnected electrical/communication partitions, that co-exist within the MG. Hence, an electrical partition generates isolated sub-MGs that are controlled by a single (and distributed) control algorithm. A communication partition results in several (and distributed) control algorithms working in parallel on the same physical MG. Figure 5 illustrates for example the case that an electrical failure occur (by opening the *b* interruptor) which leads to physical partition of the electrical network and power flows can only be exchange among nodes 1 and 2 or among nodes 3 and 4. In addition, it also illustrates a communication failure that leads to two communication islands, one where

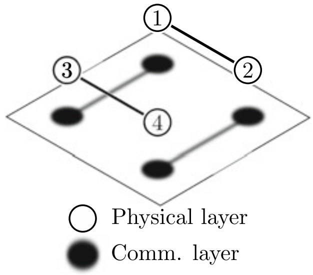


Fig. 5 Partitions: communication and electrical failures that lead to partitions where two sets of nodes become isolated each other (electrically and in terms of communications)

nodes 1 and 3 can exchange control data and the other where only nodes 2 and 4 can exchange control data.

4 Active Power Sharing and Frequency Regulation

Islanded MGs should meet certain required reliability and adequacy standards, which demand all controllable units to be actively involved in maintaining the system voltage and frequency within acceptable ranges. However, due to the low system inertia and fast changes in both the output of distributed power sources and loads, the MG frequency can experience large excursions and thus easily deviates from nominal operating conditions [32], even when there are sufficient frequency control reserves. Hence, it is challenging to control the frequency around the nominal operating point [33]. Control strategies ranging from centralized to completely decentralized have been proposed to address these challenges [34], and some of them have subsequently been aggregated into a hierarchical control architecture. This control hierarchy consists of three levels, namely primary, secondary and tertiary control.

The primary control is the first level in the control hierarchy and it is used to interconnect VSIs working autonomously in parallel for regulation of voltage frequency and amplitude. Its main goal is to compute the set-point frequency $\omega_i^*(t)$ and amplitude $V_i^*(t)$ for each inverter current and voltage internal control loops. For power sharing, a common control approach is to apply the droop method [35], which is based on the principle that the inverter frequency and amplitude can be used to control active and reactive power flows for load sharing in MG islanded operation. This controller depends only on local sensed variables and it is based on dropping[2] the output-voltage frequency and amplitude regarding the active and reactive power supplied by the source, respectively. This causes the divergence of frequency and amplitude with respect to their nominal values. Its basic formulation is given by

$$\omega_i^*(t) = \omega_{0i} - m_p pi(t), \tag{3}$$

[2] Dropping the output voltage emulates a conventional synchronous generator.

$$\nu_i^*(t) = \nu_{0i} - n_q qi(t), \tag{4}$$

where ω_{0i} and ν_{0i} are the inverter nominal voltage frequency and amplitude, $pi(t)$ and $qi(t)$ are the inverter output active and reactive power, m_p and n_q are the proportional control gains. Equation (3) is called frequency droop control and Eq. (4) is called voltage droop control. In the standard definition of droop, control actions are done relative to desired set-points for active and reactive power, p_{0i} and q_{0i} respectively [35], which are determined by long-term objectives, e.g. tertiary control. In (3) and (4) these power set-points have been omitted but their inclusion would not alter the presented results. In addition, the measured rather than the normalized values for active and reactive power are used because working with dimensionless values could hide the real impact of the non ideal conditions affecting the supporting platform. Hence, without loosing generality, all inverters are assumed to have the same nominal power.

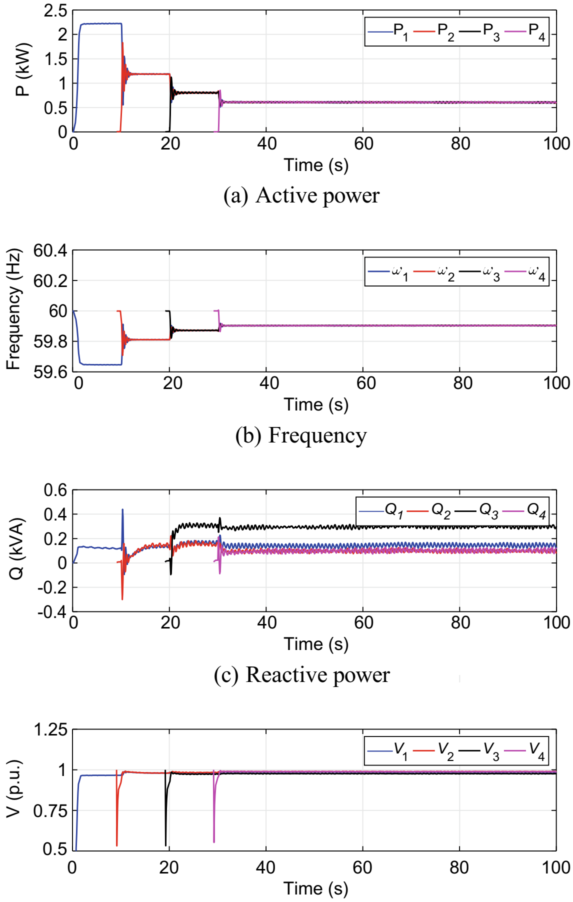
Both droop Eqs. (3) and (4) introduce deviations in the frequency and amplitude to be corrected by the secondary control [36]. Since the chapter investigation restricts the focus on frequency regulation and active power sharing, the considered droop method is the frequency droop control (3), that may be complemented with a corrective term for frequency restoration, thus leading to different secondary control policies. The standard voltage droop control (4) will not be further complemented nor discussed because it targets reactive power control which is another subject of research by itself. However Eq. (4) is implemented in all the experiments to have reactive powers and voltages within given ranges. By considering this policy in all the scenarios, a common comparison framework is stablished for performance evaluation. In addition, to solve the negative performance effect on droop-based control caused by interconnecting mainly resistive line impedances [37], a popular approach also included in the MG set-up, is the virtual impedance technique [38]. However, it is not formalized explicitly because it does not play any significant role in the analysis being presented.

4.1 Experiment #1—Droop Control

For illustrative purposes, Fig. 6 shows the operation of the laboratory MG used in the experiments when droop control (3) and (4) is implemented with $m_p = 1$ mrad/(Ws) and $n_q = 0.5$ mV/(VAr). The experiment has the following pattern. At times $t = 0$, 10, 20 and 30 s, each inverter implementing the droop control is activated, respectively. The first generator starts and fixes MG frequency and voltage to feed loads with an approximate power demand of 2.2 kW. The activation of the second, third and fourth inverters is done by means of a phase-locked loop for synchronizing them to the MG voltage phase, and also they start contributing to feed the loads.

Figure 6 shows the active power delivered by each inverter (Fig. 6a), as well as the frequencies (Fig. 6b), reactive powers (Fig. 6c) and voltage amplitudes (Fig. 6d).

Fig. 6 Experimental result: 4VSI-MG dynamics for droop-only control



(a) Active power

(b) Frequency

(c) Reactive power

(d) Voltage amplitude

The obtained dynamics are assumed to be acceptable although some performance features could be improved. As it can be observed, looking at the active power Sub-figure, after each inverter new connection, active power sharing is achieved with the expected transient dynamics. In addition, looking at the frequency Sub-figure, the droop control introduces a deviation in frequency (Fig. 6b). For the sake of completeness, Fig. 6c and d show the dynamics of the reactive powers and voltage amplitudes. It is worth noting that at each connection, the voltage transient dynamics (Fig. 6d) exhibits a sag. These dynamics could be enhanced by a fine tuning of the control parameters and/or by a smarter soft-start of each VSI. Additionally, the frequency droop observed in Fig. 6b could violate existing standards if a proper tuning of the droop control strategy is not applied. However, the chapter does not deal with these issues and its focus is on the system dynamics whenever non-ideal conditions in the MG operation appear, once all inverters have been connected.

Secondary control is the highest hierarchical control level in MGs operating in islanded mode and aims at guaranteeing that frequency and voltage deviations are eliminated after every load or generation change inside the MG. Apart from a few autonomous control approaches that avoid exchanging control data over a communication network, e.g. [39–41], many existing solutions have considered the use of some sort of communication channel among VSIs in order to meet the frequency and voltage restoration goals, see [42–46] to name a few. In general, the secondary control operates on a slower time frame as compared to the primary control. This allows achieving a decoupling between primary and secondary levels which helps easing the control design.[3]

Although not considered in the current analysis, tertiary control is a management level in grid-connected operations and adjusts long term set-points for the entire power system. It is responsible for coordinating the operation of multiple MGs and for communicating needs or requirements from the host grid, see e.g. [47, 48].

Among the great variety of cited works on control policies for active power sharing and frequency restoration, this chapter selects several prototype methods that are analyzed when non-ideal conditions arise. A generic frequency regulation policy (including (3)) will take the form of

$$\omega_i^*(t) = \omega_{0i} + \lambda_i(t) + \varphi_i(t), \tag{5}$$

where $\lambda_i(t)$ is the specific control algorithm taking different forms, and the perturbation term $\varphi_i(t)$ models bounded uncertainties such as measurement errors or disturbances. Regarding the control algorithm $\lambda_i(t)$, some approaches are based on the hierarchical control approach and built on top of the frequency droop method (3).

They are termed as droop-based policies, and follow the equation logics

$$\omega_i^*(t) = \omega_{0i} - m_p p_i(t) + \delta_i(t), \tag{6}$$

where $\delta_i(t)$ is a corrective term that operates as an integral-like control of the frequency error, and its particular structure and operation determines the features of the complete control scheme, resulting in

$$\textit{Local integrals} \quad \omega_i^*(t) = \omega_{0i} - m_p p_i(t) + k_{Il} \int_0^t \big(\omega_{0i} - \omega_i^*(t)\big) dt, \tag{7}$$

$$\textit{Centralized} \quad \omega_i^*(t) = \omega_{0i} - m_p p_i(t) + k_{Ic} \int_0^t \big(\omega_{0m} - \omega_m^*(t)\big) dt, \tag{8}$$

[3] The difference in time frames also reduces the communication bandwidth since the sampled measurements exchanged over the network are minimized, regardless of the different traffic schemes that may apply, ranging from the one-to-all to the all-to-all.

$$Decentralized \quad \omega_i^*(t) = \omega_{0i} - m_p p_i(t) + k_{Id} \int_0^t \left(\omega_{0i} - \omega_m^*(t)\right) dt, \tag{9}$$

$$Averaging \quad \omega_i^*(t) = \omega_{0i} - m_p p_i(t) + k_{Ia} \int_0^t (\omega_{0i} - \frac{1}{n} \sum_{j=1}^{n} \omega_j^*(t)) dt, \tag{10}$$

$$\begin{aligned} Consensus \quad \omega_i^*(t) = \omega_{0i} - m_p p_i(t) + k_d \int_0^t \omega_{0i} - \omega_i^*(t) \\ + \frac{c_i}{n} \sum_{j=1}^{n} a_{ij} \left[\delta_j(t) - \delta_i(t)\right] dt. \end{aligned} \tag{11}$$

The first policy termed *Local-integrals* (7) is the straightforward extension of the frequency droop (3) because each corrective term is an integral controller of the frequency error locally computed at each VSI, not requiring the exchange of control data. The next four policies rely on a communication infrastructure.

In the policy termed as *Centralized* (8) [9] the corrective term is only calculated and sent by the MG central control unit (MGCC). This term is the integral of the error between the nominal frequency ω_{0m} and the MGCC frequency $\omega_m^*(t)$, which is then used by each VSI to apply the droop-based control (6). In terms of communication scheme, the centralized control policy will require sending the correction term δ_i periodically to all inverters. Hence, it applies a broadcast traffic pattern where a node sends data to all the other nodes in the network, following a one-to-all communication scheme on a master/slave paradigm.

In the *Decentralized* control policy (9) (see the overview given in [8]) the frequency error between the nominal frequency and the MGCC frequency, $\omega_m^*(t)$, is locally integrated at each VSI. In terms of communication scheme, the decentralized control policy will require sending the MGCC frequency error periodically to all inverters, thus following the same communication one-to-all pattern as in the centralized policy.

In the *Averaging* control policy (10) (see [44] for DC MG) the corrective term is calculated at each VSI using the averaged set-point frequency where $n - 1$ frequencies have been received from the other MG VSIs. The averaging control may increment the traffic exchange compared to the previous two policies. For this case, all inverters have to send the measured frequency to the rest of inverters in the MG. Hence a broadcast scheme is also used, but for all inverters, implying an all-to-all communication scheme.

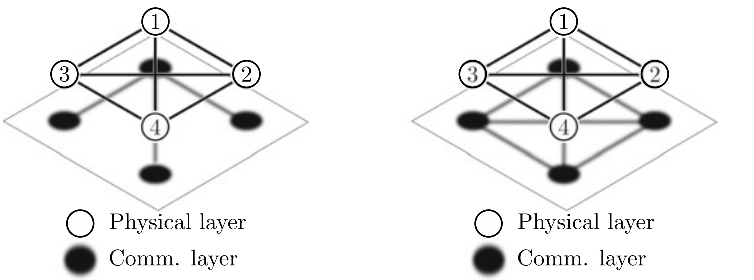
The *Consensus* control policy (11) (see for example [42]) is characterized by a correction term that considers the frequency error and the correction term error, The operation of the consensus policy requires each inverter to communicate with their neighbors the droop correction term δ_i. Therefore, the communication scheme is the same as in the previous policy.

Recent approaches propose different strategies for active power sharing and frequency regulation where the hierarchical approach is avoided or where modifications on the primary droop control are investigated, e.g. [49, 50]. Thus, an additional policy named *Droop-free* [49] not following the hierarchical structure but still following the form given in (5) is also selected. In this case, the nominal frequency is modified by a proportional function of the inverter output active power $P_i(t)$ and the rest of n 1 MG inverters active power P_j t, provided that communications are available. It has the form.

$$\omega_i^*(t) = \omega_{0i} + c_i\left(\left(\sum_{j=1}^{n} a_{ij}\, p_j(t)\right) - np_i(t)\right) \tag{12}$$

where c_i is the control gain and $a_{i,j}$ are communication weights as design parameters to specify the connectivity structure of the MG. The communication requirements of the droop-free control policy are the same as in the case of the consensus, but each inverter has to send its active power $p_i(t)$.

Figure 7 illustrates a possible communication scheme for the analyzed policies that require the use of a communication network. Clearly, the first two policies, *droop-only* and *local integrals*, do not require communications and the concept of communication paradigm is not applicable, while the rest of policies require communications. Within them, the *centralized* and *decentralized* policies follow a master/slave (M/S) communication paradigm characterized by the fact that the integral of the frequency error is computed at the master node or at each slave node, respectively. Figure 7a illustrates this case when node 1 acts as master and nodes 2, 3 and 4 act as slaves The three last policies, *averaging*, *consensus* and *droop-free* follow a cooperative communication paradigm in the sense that all participating nodes exchange control data to their neighbors, where in this case, all nodes are set to be neighbors



(a) Centralized and Decentralized (b) Averaging, Consensus, and Droop-free

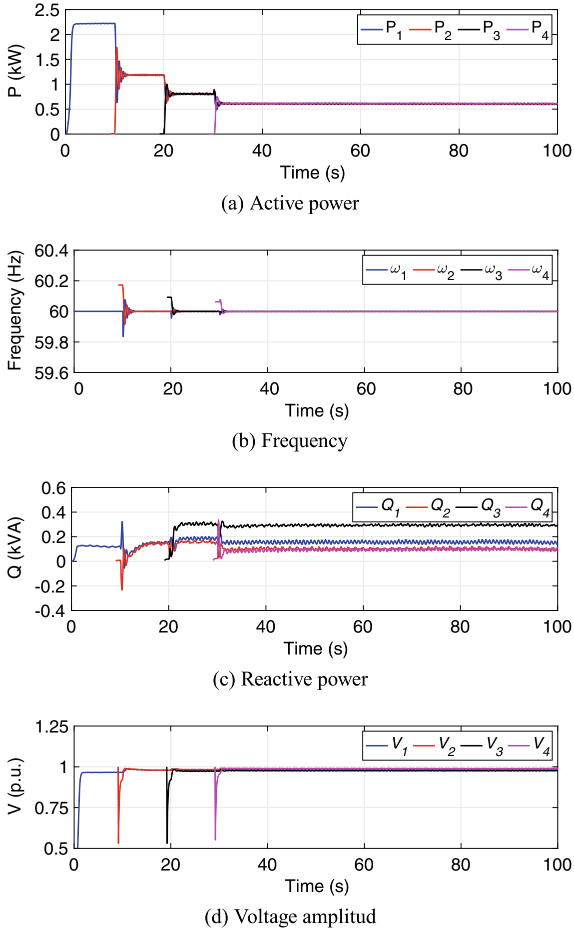
Fig. 7 Secondary control policies in terms of communication connectivity

4.2 Experiment #2—Droop-Free Control

Again, for illustrative purposes, Fig. 8 shows the operation of the laboratory MG when the droop-free control (12) is implemented. The experiment has the same pattern as in Example 1. At times $t = 0$, 10, 20 and 30 s, each inverter implementing the droop-free control is activated, respectively; all inverters exchange control data among them.

Figure 8 shows the active power delivered by each inverter (Fig. 8a), as well as the frequencies (Fig. 8b), reactive powers (Fig. 8c) and voltage amplitudes (Fig. 8d). As outlined above, the obtained dynamics are assumed to be acceptable although some performance features could be improved. In this case, it can be observed that the droop-free control is able to regulate the frequency at the set-point 60 Hz (Fig. 8b) while all inverters share the active power demand (Fig. 8a).

Fig. 8 Experimental result: 4VSI-MG dynamics for droop-free control



(a) Active power

(b) Frequency

(c) Reactive power

(d) Voltage amplitud

5 Modeling and Analysis

The modeling approach combines power flow analysis with graph theory to allow developing model-based analysis design techniques that go beyond the classical simplified linearized models, i.e. the so-called small-signal models, that may not capture fundamental aspects of the problem [51]. Both electrical and communication networks are modeled as graphs, where nodes correspond to VSIs interfacing DGs. Nodes actively control frequency, voltage and power, and they may exchange control data over a communication channel. Graph Laplacian matrices provide the characterization of electrical and communication connectivities. See e.g. [42, 50] for MG control approaches where the electrical network is modeled as a graph. It is important to note that the majority assume lossless networks, unlike the approach proposed here. And see e.g. [42, 49] for MG control approaches where the communication network is modeled as a graph.

None of the previous works have evaluated partitions of the considered graphs. Specific control policies such as consensus algorithms with changing graphs in terms of switching topologies or connectivity robustness have been previously considered, see [52] for a generic study, or [45] for an analysis with application to MGs. Only in [49] it is studied the resiliency of the droop-free control to a single communication link failure when it does not alter the connectivity of the communication graph, and in [53] it is presented a robust secondary control to restore the voltage and frequency to their nominal values with a novel feature that ensures the performance continuity during a communication failure.

The MG electrical network is modeled as a generic connected grid where loads are modeled by balanced three-phase constant impedances. Although richer configurations including for example non-linear and time-varying loads could be considered, keeping a simplified model helps gaining understanding and reaching results that will permit dealing with more complex MGs. A Kron reduction is performed which allows obtaining a lower dimensional dynamically-equivalent model described by ordinary differential equations [54]. The reduced network is modeled as a connected undirected graph $\mathcal{G}_e = \{\mathcal{N}_e, \mathcal{E}_e\}$ where the n_e nodes $\mathcal{N}_e$ represent DGs interfaced with VSIs and edges $\mathcal{E}_e \subseteq \mathcal{N}_e \times \mathcal{N}_e$ represent the power lines. Nodes are characterized by a phase angle θ_i and a voltage amplitude v_i. Edges represent line admittances between nodes i and j as $\mathrm{y_{ij}} = \mathrm{g_{ij}} + j\mathrm{b_{ij}} \in \mathbb{C}^+$, where $g_{ij} \in \mathbb{R}^+$ is the conductance and $b_{ij} \in \mathbb{R}^+$ is the susceptance. The electrical network is represented by the symmetric bus admittance matrix $Y \in \mathbb{C}^{ne} \times \mathbb{C}^{ne}$, where the off-diagonal elements are $\mathrm{Y_{ij}} = \mathrm{Y_{ji}} = -\mathrm{y_{ij}}$ for each edge $\{i, j\} \in \mathcal{E}_e$, and the diagonal elements are given by $Y_{ii} = \sum_{i=1}^{n_e} Y_{ji}$. It is assumed that the reduced MG is connected.

The communication network can also be represented by a connected undirected graph $\mathcal{G}_c = \mathcal{N}_c, \mathcal{E}_c$ where the n_c nodes $\mathcal{N}_c$ represent VSIs that implement de communication-based policies, and edges $\mathcal{E}_c \subseteq \mathcal{N}_c \times \mathcal{N}_c$ represent communication links. Parameters a_{ij} whenever apply form the adjacency matrix of $\mathcal{G}_c$ such that $a_{ij} = a_{ji} = 1$ if nodes i and j can exchange their information and $a_{ij} = 0$ otherwise.

It is considered that nodes in the electrical and communication graph are the same, i.e. $\mathcal{N}_e = \mathcal{N}_c$, hence $n_e = n_c = n$, which is the habitual situation in MGs, e.g. [55].

For balanced AC microgrids, the active power injected by each ith node of the n-node MG is described as

$$p_i(t) = \nu^2 \sum_{j=1}^{n} g_{ij} + \nu^2 \sum_{j=1}^{n} b_{ij}(\theta_i(t) - \theta_j(t)) \tag{13}$$

assuming that nodes phase angles are similar while voltages are constant and equal, as often assumed in power systems modeling, e.g. [56], and also in MG modeling, e.g. [57]. By considering the matrix $G \in \mathrm{R}^{n\times n}$ formed by the line conductances w. hose entries are. given by $G_{ij} = g_{ij}$, denoting the set of phase angles by $\Theta_.\ (t) =$ active power of the Kron-reduced network (13) becomes

$$P(t) = \nu^2 G\mathbf{1}_{n\times 1} + \nu^2 B\Theta(t) \tag{14}$$

where $\mathbf{1}_{n\times 1} \in \mathrm{R}^{n\times 1}$ denotes a vector of ones, and $B \in \mathrm{R}^{n\times n}$ is the Laplacian matrix of the power system given by

$$B = \begin{bmatrix} \sum_{\substack{j=1 \\ j\neq 1}}^{n} b_{1j} & -b_{12} & \cdots & -b_{1n} \\ -b_{21} & \sum_{\substack{j=1 \\ j\neq 2}}^{n} b_{2j} & \cdots & -b_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ -b_{n1} & -b_{n2} & \cdots & \sum_{\substack{j=1 \\ j\neq n}}^{n} b_{nj} \end{bmatrix} \tag{15}$$

and formed by the line susptances.

Each node $i \in \mathcal{N}_e$ is modeled as a control algorithm implemented at each VSI driven by the frequency regulation and voltage droop givenz in (5) and (4), respectively. By denoting the set of VSI local frequencies by $\Omega(t) = [\omega_1(t) \ldots \omega_n(t)]^T$ the set of desired frequencies by $\Omega_0 = [\omega_{01} \ldots \omega 0n]^T$, the set of frequency regulation algorithms by $\Lambda(t) = [\lambda_1(t) \cdots \lambda_n(t)]^T$, and the set of perturbations by $\Phi(t) = [\varphi_1(t) \cdots \varphi_n(t)]^T$ the per-node frequency control algorithm given in (5) can be compactly written for the entire MG as

$$\Omega(t) = \Omega_0 + \Lambda(t) + \Phi(t) \tag{16}$$

where $\Lambda(t)$ will be probably characterized by $L \in \mathbb{R}^{n\times n}$ that is the Laplacian matrix of the communication graph $\mathcal{G}_c$ given by

$$L = \begin{bmatrix} \sum_{\substack{j=1 \\ j \neq 1}}^{n} a_{1j} & -a_{12} & \cdots & -a_{1n} \\ -a_{21} & \sum_{\substack{j=1 \\ j \neq 2}}^{n} a_{2j} & \cdots & -a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ -a_{n1} & -a_{n2} & \cdots & \sum_{\substack{j=1 \\ j \neq n}}^{n} a_{nj} \end{bmatrix} \tag{17}$$

where a_{ij} are the entries of the adjacency matrix of $\mathcal{G}_c$. The compact form of voltage droop (4) that would accompany (16) is omitted because it is not further used in the analysis. For example, for the consensus-based policy, Eq. (16) takes the form.

$$\Omega(t) = \Omega_0 - MP(t) + K \int_0^t \left(\Omega_0 - \Omega(t) - \frac{1}{n} CL\Lambda(t) \right) dt + \Phi(t) \tag{18}$$

while for the droop-free (12) it is

$$\Omega(t) = \Omega_0 - cLP(t) + \Phi(t) \tag{19}$$

In both cases, (18) and (19), the communication Laplacian matrix L appears in the control algorithm.

The goal of the control (16) is shaping the active power and frequency dynamics. The active power dynamics can be obtained by computing the derivative of (14) that leads to

$$\dot{P}(t) = \nu^2 B \dot{\Theta}(t). \tag{20}$$

By being $\omega_i = \dot{\theta} i$, the active power variation (20) is written as

$$\dot{P}(t) = \nu^2 B \Omega(t). \tag{21}$$

By substituing (16) into (21), the closed-loop dynamics can be written as

$$\dot{P}(t) = SP(t) + U\Omega_0 + R\Phi(t) \tag{22}$$

where the closed-loop system matrix $S \in \mathbb{R}^{n \times n}$, input matrix $U \in \mathbb{R}^{n \times n}$, and perturbation matrix $R \in \mathbb{R}^{n \times n}$ are

$$S = \left[\nu^2 B \Lambda \right] \tag{23}$$

$$U = \left[\nu^2 B \right] \tag{24}$$

$$R = \left[\nu^2 B \right]. \tag{25}$$

Summarizing, a closed-loop model (22)–(25) has been built, which integrates the power flow equations and the two graph Laplacian matrices that characterize the MG electrical structure and the communication requirements of the distributed control that applies. Observe also that communication delays and dropouts have not be yet included. Considering a message dropout as a prolongation of a communication delay [21], the inclusion of delays and dropouts in (22)–(25) can be done by introducing control algorithms characterized in $\Lambda\ t$ in (16). This would lead to a time-varying closed loop matrix $S\ t$ in (23) that can be treated by a variety of approaches, see for example [58, 59] and references there in for both recent theoretical results and their application to MG control.

The reliability analysis treating the electrical and communication partitions can be done using the zero eigenvalue analysis. This technique has been also used in the stability analysis of power systems of critical lines [60] and in the stability analysis for partitioned MGs controlled by cooperative-based secondary control approaches [61, 62]. The main logics of these approaches are the following. First, the closed-loop dynamics (22)–(25) must be complemented with the system restriction imposed by the power balance equation,

$$\forall t, \quad \sum_{i=1}^{n} p_i(t) = P_T \tag{26}$$

that indicates that for a given load, the total power P_T (that includes the power losses) that is injected by the MG nodes is always the same. With this restriction and by knowing that each partition adds a 0 eigenvalue in the Laplacian matrices and thus to the system matrix S (23), the analysis of the ranks of the system matrix S (23) and the input matrix U (24) permit to infer MG stability. In short, whenever a communication partition occurs, and reminding that the closed-loop system is multiple-input/multiple-output, the additional 0 eigenvalue becomes an integrator of each input/output relation (from input ω_{0i} to any of the outputs). Then, the system operation corresponds to n integrators working in parallel, which puts the MG into risk [63], and implies unstable dynamics for the perturbed system. Whenever an electrical partition occurs, the additional 0 eigenvalue does not have the destabilizing effects as in the case of the communication partition. However, power flows can not be transferred between the isolated MGs and cascading failures could occur if each sub-microgrid supply–demand would not be able to reach the equilibrium [30]. However, the adopted model assumes that the MG capacity has been dimensioned and control gains have been designed such that this equilibrium can be always reached. Hence, after the electrical partition, each MG will reach different steady-state equilibrium points.

6 Experimental Evaluation

The experiments have been performed on the laboratory MG described in Sect. 2. The experiments covering the timeliness analysis only use the first three inverters G_1, G_2 and G_3. Those covering the reliability.

6.1 Timelines Evaluation

Each experiment in the timeliness analysis lasts 80 s. From the beginning, the global load with impedance Z_G is connected. Then, the set of events that characterize the experiment progress as follows. At time $t = 0$ s the first pair of generator/load ($G_1 - Z_{L1}$) is activated, at time $t = 10$ s the second pair of generator/load becomes active ($G_2 - Z_{L2}$), and at time $t = 20$ s the third pair of generator/load becomes active ($G_{3\_}Z_{L3}$). Finally, at time $t = 60$ s the global load is disconnected. The control parameters for the experiments are given in Table 2.

Before evaluating the impact of delays, Fig. 9 shows the experiment corresponding to the ideal case, where the top subfigure shows the active power P_i and the bottom subfigure the frequency ω_i for the three VSI during 80s. Looking at the control strategy, which in this case corresponds to the *Averaging*, up to time $t = 40$ s, only

Table 2 Control parameters

Strategies	Equations	Control parameters
Centralized	(8)	Integral gain $k_{Ic} = 1.2$
Decentralized	(9)	Integral gain $k_{Id} = 1.2$
Averaging	(10)	Integral gain $k_{Ia} = 0.7$
Consensus	(11)	Integral gain $k_d = 4$, proportional gain $c_i = 0.005$
Droop-free	(12)	Proportional gain $c_i = 0.005$

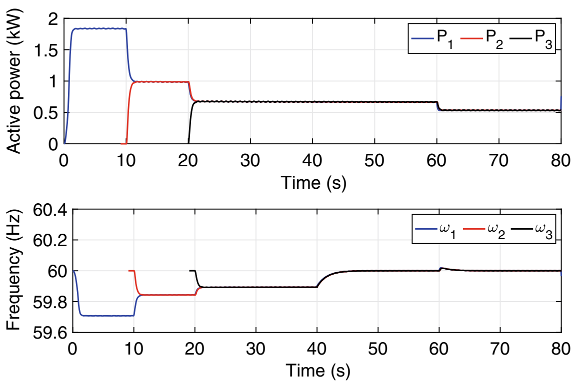
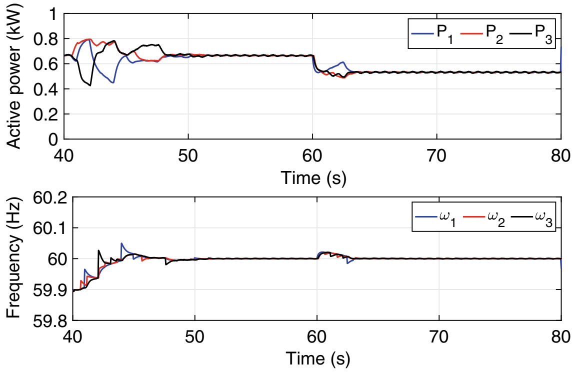


Fig. 9 Experimental result: Active power and frequency for an example policy (averaging) in a 3-VSI MG configuration with no losses and a transmission interval of 0.5 s

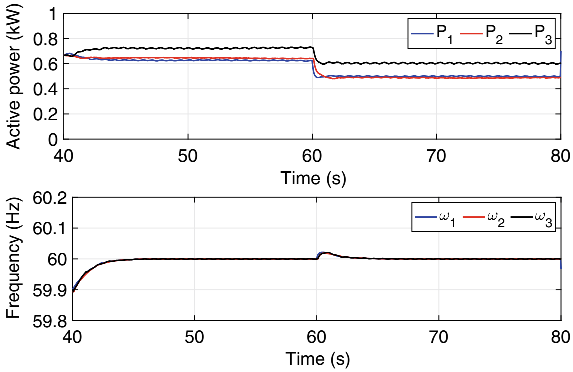
primary droop control applies, and from $t = 40$ s to the end, droop plus secondary control applies. This can be observed at the left-bottom subfigure, where frequency restoration starts at $t = 40$ s. The other policies give the same type of figures, and therefore, they are not shown here.

Figures 10 and 11 show the impact of the communication parameters for each policy based on data exchange in terms of power sharing (top subfigures) and frequency restoration (bottom subfigures). Hence, the case of *droop method* and *local integrals* do not apply in this analysis because their operation is local and not data exchange takes place. In particular, the scenario shown in these figures is characterized by a transmission interval of 0.5 s and a loss percentage of 30%. It is important to note that these figures only show the last 40 s of each experiment run. The first observation is that frequency restoration is accomplished by all policies. The second observation is that power sharing is only achieved by the *centralized* and the *consensus* policies while the *decentralized* and *averaging* fail. This reveals that the *decentralized* and *averaging* policies are more sensitive to delays, indicates their lack of robustness. It is also interesting to stress that although these two policies

Fig. 10 Experimental result: Active power and frequency for Centralized and Decentralized policies in a 3-VSI MG configuration with 30% of losses and a transmission interval of 0.5 s

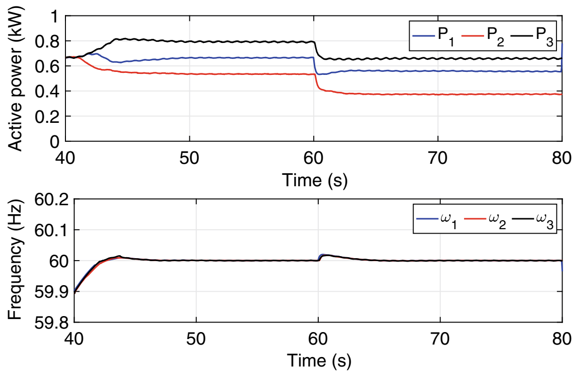


(a) Centralized

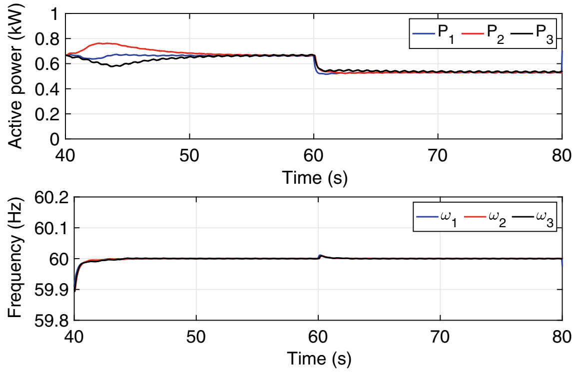


(b) Decentralized

Fig. 11 Experimental result: Active power and frequency for Averaging and Consensus policies in a 3-VSI MG configuration with 30% of losses and a transmission interval of 0.5 s



(a) Averaging



(b) Consensus

do not meet the power sharing goal, they reach different equilibrium points, thus avoiding unstable dynamics that would put the MG operation into risk. The *droop-free* policy results are not shown because they are very similar to the ones given by the consensus policy.

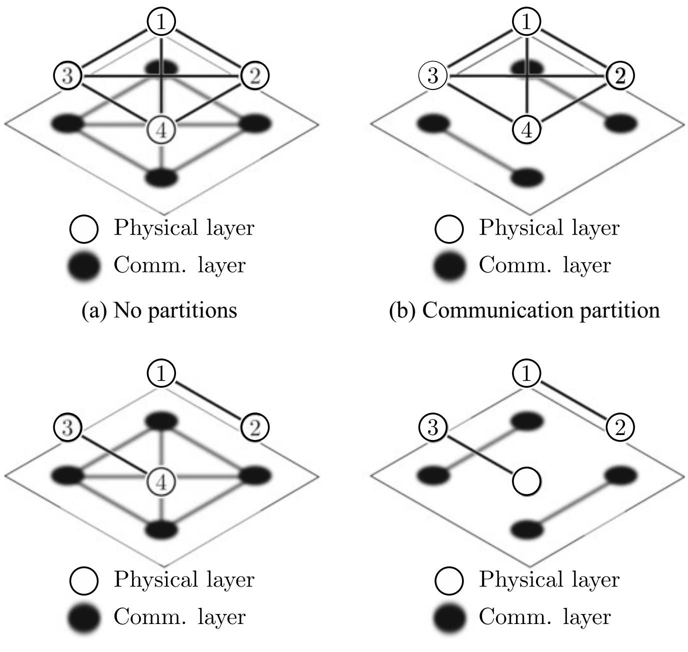
Looking at the results of the *centralized* and *consensus* policies, it can be observed that the transient dynamics of the active power are quite different. The *consensus* policy outperforms the *centralized* because it provides smoother dynamics at each transition. In addition, in the assessment of these two policies, there are known facts that can be considered related to fault tolerance or communication bandwidth.

In terms of fault tolerance, it is known that for master–slave configurations, as in the centralized case, the MGCC represents a single point of failure and replicas are required. In terms of communication bandwidth, the consensus requires a more intense data exchange. In this case it is also known that reducing the number of considered neighbors implies less communication demands at the cost of probably longer transients.

It is important to stress that the experimental results shown in Figs. 10 and 11 correspond to a feasible scenario different than the ideal one: worser scenarios can not be reproduced because security protections automatically disconnect overloaded VSIs while better scenarios give results that provide closer curves to the ones shown in Fig. 9.

6.2 Reliability Evaluation

By considering the loss of communications problem caused by a failure in a communication link that leads to a communication partition or to a electrical partition, three main scenarios can be identified: only communication partitions, only electrical partitions, or both, as illustrated in Fig. 12. Regarding the set of control policies described in Sect. 4, partitions in the electrical network could be analyzed for all policies while communication partitions should be analyzed for those policies based on data exchange. However, partitions in the electrical network when the control algorithm is local (case of *droop method* and *local integrals*) are not relevant because this is the same as analyzing two separate stable MGs. Indeed, after the electrical decoupling of the partition happens, power flows can not be transferred among the isolated MGs. It is important to point out that cascading failures could occur if each sub-microgrid



(a) No partitions (b) Communication partition

(c) Electrical partition (d) Both partitions

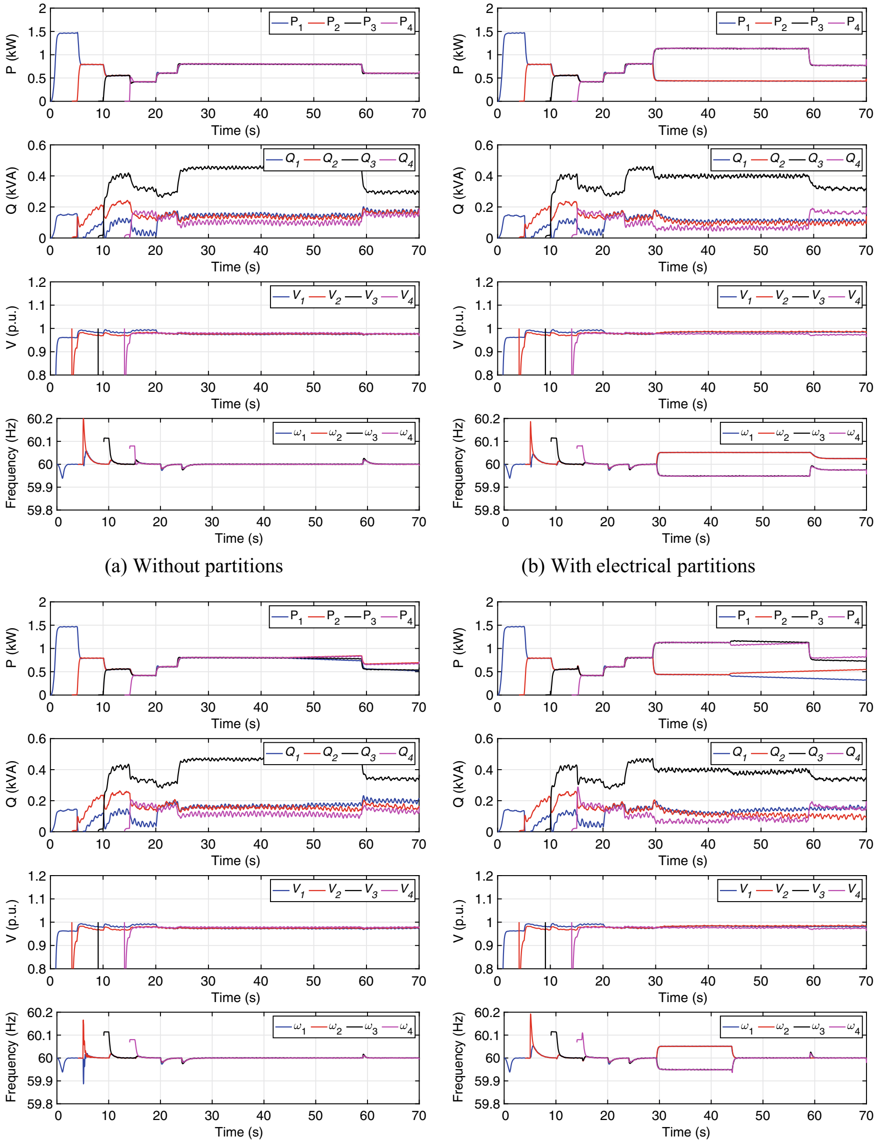
Fig. 12 MG graph connectivity scenarios supply–demand would not be able to reach the equilibrium. However, if the assumption that the MG capacity has been dimensioned as well as control gains have been designed such that the equilibrium can be always reached for all the analyzed policies, this problem would not appear. Hence, after the electrical partition occurs, each sub-MG will reach different steady-state equilibrium points for both *droop* and *local integrals* depending on DGs and loads.

All the experiments that cover the reliability problem follow the same pattern. In the MG start-up, every 5 s, each one of the four inverters enabled with a specific control algorithm connects to the MG to feed both the global and local loads. The global load is connected throughout all the experiment. In order to introduce different type of load changes, the local load L_1 (attached to G_1) is connected at time $t = 20$ s, and the local load L_3 (attached to G_3) is connected and disconnected at times $t =$ 25 s and $t = 60$ s, respectively. In addition, the partitions indicated in Fig. 12 are also applied to the experiment. In particular, at time $t = 30$ s, whenever required, an electrical partition occurs, leading to the scenario illustrated in Fig 12c, where two separate MGs start working in parallel, one involving $G_1 - G_2$, and the other involving G_3 G_4, but governed by a single control algorithm. Regarding communications, at time $t = 45$ s, whenever required, a communication partition occurs leading to the scenario illustrated in Fig. 12b, where two control algorithms start acting in parallel, one involving $G_1 - G_2$, and the other involving G_3 G_4. The last scenario involving the two type of partitions as illustrated in Fig. 12d is also analyzed. In this case, first at $t = 25$ s two separate MGs start working in parallel, one involving G_1 G_2, and the other involving G_3 G_4, and at $t = 45$ s, the communication partition implies that two control algorithms start acting in parallel, one involving G_1 G_3, and the other involving G_2 G_4.

For example, Fig. 13 provides a complete overview of the performance of the *consensus* (11) policy under different partition scenarios. Figure 13a shows the "normal" operation (i.e., no partitions), Fig. 13b shows the case of the electrical partition, Fig. 13c shows the case of the communication partition, and finally Fig. 13d shows the case of both partitions.

For the normal operation, Fig. 13a, it can be observed that after each inverter connection, active power sharing is achieved while the frequency droops but it is quickly restored at the desired set-point, $\omega_{0i} = \omega_{0j} = 60$ Hz. In addition, voltages and reactive power obey the voltage droop policy (4). The load changes can also be seen in the figure, in particular, in the active power curves.

For the electrical partition, Fig. 13b shows the dynamics that correspond, from time $t = 30$ s, to two separate sub-MGs working in parallel. But both sub-MGs are governed by a "single" *consensus* control algorithm, meaning that the algorithm operates without knowing that active power can not be transferred between the two sub-MGs. In this case, the steady-state behavior of the active power changes compared to the normal operation of the MG, and the injected P_i's reach different equilibrium points, organized in pairs and that differ among partitions. That is, $G_1 - G_2$ feed the single local L_1 load thus sharing its power demand ($P_1 = P_2$), and G_3 G_4 feed the global load and the local L_3 load, thus sharing also its power demand ($P_3 = P_4$). If the newly reached active power values were beyond VSIs rated power,



(a) Without partitions (b) With electrical partitions

(c) With communication partitions (d) With both partitions

Fig. 13 Experimental result: Consensus control for 4-VSI MG under different partitions scenarios they will trip due to an over-current situation. Looking at the frequencies, the same type of dynamics can be observed: $\omega_1 - \omega_2$ and $\omega_3 - \omega_4$ reach different equilibrium points.

When a communication partition occurs, Fig. 13c, “two” control algorithms start acting in parallel at $t = 45$ s, one involving $G_1 - G_2$, and the other involving $G_3 - G_4$. In fact, the algorithm executed in each VSI is the same, but they only consider for their computations the exchanged power that is available. Both generators G_1 and G_2 use p_1 and p_2 while both generators G_3 and G_4 use p_3 and p_4. Note that in this case, the four generators are still sharing the power demand of all loads. In this scenario, the injected active powers show a slow but unstable dynamics where active powers do not settle, and are grouped in pairs. In particular, P_1 and P_2 increase and P_3 and P_4 decrease. Hence, the inherent (and distinct) perturbations entering in the system (22) through the input matrices U and/or R such as measurement errors [64], effect of drifts [65], etc., become very important up to the point that make the dynamics unstable, that is, the MG crashes. Note also that the difference between frequencies $\omega_1 - \omega_2$ and $\omega_3 - \omega_4$ can not be appreciated.

Finally, Fig. 13d shows the case of multiple overlapped partitions, and the described effects for each type of partition can be observed. When the electrical partition occurs, the active power reaches different equilibrium points, organized in pairs. And when the communication partition occurs, each pair of active power start to diverge, leading to the undesirable scenario of a MG failure.

Complementary to Fig. 13, the rest of communication-based policies, *centralized*, (8), *decentralized*, (9), *averaging* (10), and *droop-free* (12), are also tested in the laboratory MG using the same type of experiment, and the main results are gathered in Fig. 14. Each policy corresponds to a Sub-figure that only shows the active power dynamics for each of the partitions scenarios displayed in Fig. 12. From top to bottom, each subfigure shows the case of no partitions, and then it shows the case of electrical partition, the communication partition, and finally, both partitions. The dynamics of the reactive power, as well as the dynamics of the voltage frequency and amplitude are omitted because they do not provide additional information than the one already provided by the active power.

The main conclusion that can be extracted for these set of Sub-figures of Fig. 14, which is coincident with the results already observed by the *consensus* policy (Fig. 13), is that all policies that are based on communications can not meet the given control objective whenever a loss of communication occurs. If no loss of communication occurs, which corresponds to the first plot of each Sub-figure, control objectives are meet such as achieving perfect power sharing. If the loss of communication impairs the notification of an electrical damage, such the case illustrated by the electrical partition (second plot of each subfigure), no active power sharing is accomplished and inverters injected active power settle to different equilibrium points. Whenever the loss of communications implies a temporary interruption of the distributed exchange of control data between specific VSI, such as the case illustrated by the communication partition (third plot of each Sub-figure), all policies show unstable dynamics that will lead the MG to a crashing situation if emergency procedures are not available. The type of unstable dynamics differ depending on the

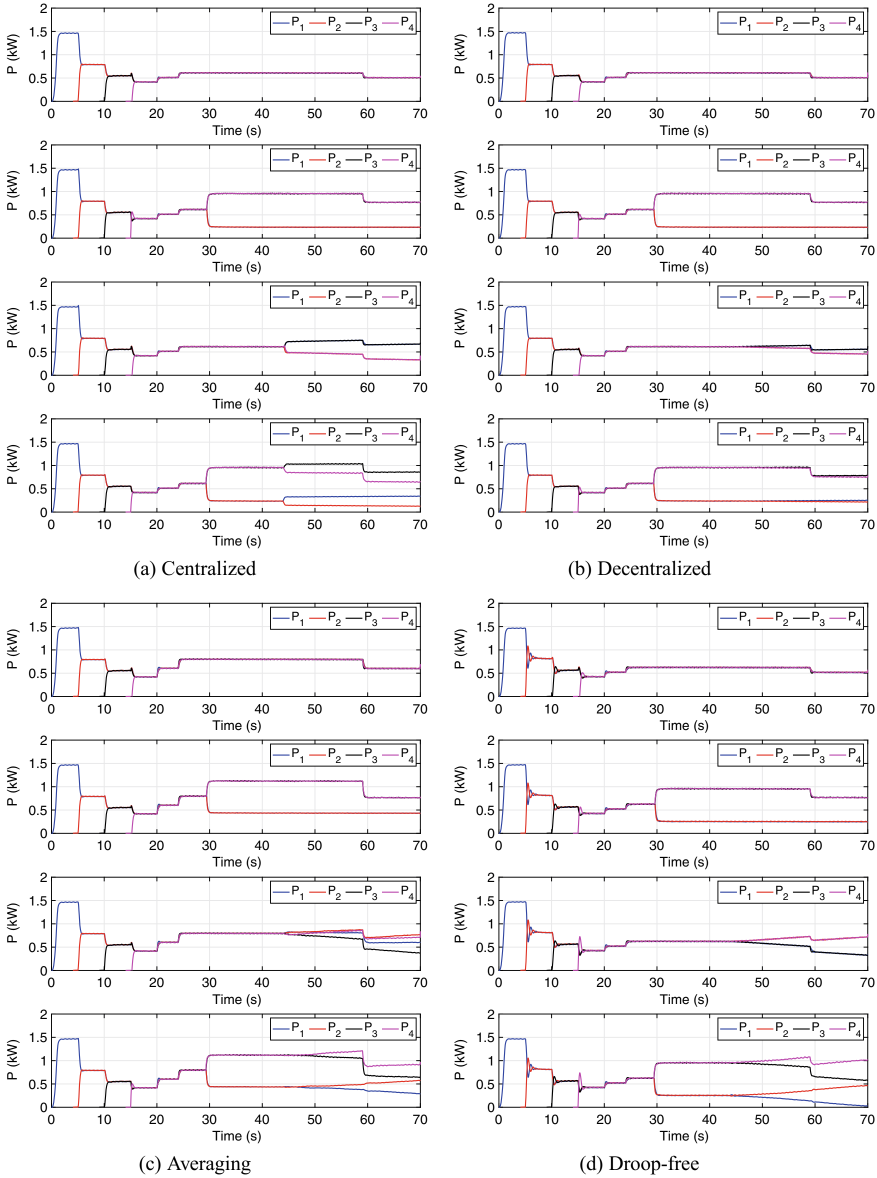


Fig. 14 Experimental result: active power dynamics for 4-VSI MG with the rest of communications-based control policies under the different partitions scenarios.

particular policy, but all become dangerous. And finally, when the loss of communication induces an overlapping of an electrical and a communication partition (fourth plot of each Sub-figure), the individual negative effects become visible together.

7 Concluding Remarks

Communication infrastructure can be used to coordinate MG control actions to improve energy management and quality. However, inherent properties of the communication infrastructure may also impair meeting these objectives. Properties in terms of timeliness such as message delays and dropouts, and properties in terms of reliability such as loss of communications should be considered in the analysis, design and implementation of efficient and reliable MG. This chapter, using an experimental approach on a laboratory MG, has tested state-of-the-art MG control policies for active power sharing and frequency regulation. The main lesson learned from all the experiments is that timeliness and reliability issues may lead the MG operation to unacceptable risking situations involving a MG crash. Therefore, the identified problems poses new challenges to the design of future trends such as the Internet of Energy (IoE) that applies the Internet of Things (IoT) technologies to energy control systems.

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Renewable Sources Complementarity

Pedro Bezerra Leite Neto, Osvaldo Ronald Saavedra, and Denisson Queiroz Oliveira

Abstract The presence of renewable sources in modern power grids is a means of supplying greener and more sustainable energy to the final customers. However, this inherent variability of energy sources requires the addition of resources for grid flexibility. This variability depends on the availability of the primary energy source, which varies in time and space. However, it is possible to take advantage of an energy mix due to the complementarity effect. This chapter aims to review the concepts regarding the complementarity of renewable energy sources, by describing some of the existing indexes from the literature so that they can be evaluated in different time and space scales. Larger network and geography are considered here. The reason being, when the active network concept is expanded, additional techniques and technologies are required to broaden the scope of active networks for provincial, state-wise and/or country-wide active networks. In this sense, complementarity becomes crucial for different microgrids working in connected modes. This chapter provides this bridge.

Keywords Complementarity · Variability · Renewable sources of energy

1 Introduction

In an electrical power system, the electricity supply must maintain an instantaneous balance to achieve a safe, reliable, and stable operation. Renewable Energy sources (RES) have an intermittent feature that does not match the requirements of power

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systems, such as power balance between demand and generation, continuity, and high generation availability.

The extensive connection of distributed energy resources to the grid is required to consider it as an active distribution grid, allowing bidirectional flows of energy at different levels. Although there is a current trend to connect renewable-based distributed generators at distribution level, a careful investigation is required to evaluate its effects on the grid operations to be able to exploit the benefits of energy diversification.

Most of the sources of renewables that are applied, such as wind and solar energy, have large variations throughout the day, sometimes with a lack of generation at intervals ranging from a few minutes to hours. This variability leads to power balance loss when demand and generation do not match. For instance, solar power output may fall more than 50% in a few minutes due to passing clouds.

In modern power systems, an additional attribute is needed to compensate for the variability in supply and demand and keep the balance—flexibility. As the penetration of intermittent renewable sources increases in the network, there is an increased need for flexible resources to mitigate its effects.

Historically, variability and uncertainty in the system have been linked to demand. This variability was offset by having flexible conventional plants and a reliable network. Today, continuous changes in energy production and consumption—creating more variability and uncertainty—require other means of flexibility than conventional ones. This pressure arises from the increasing share of renewable energy sources, both on a large scale and a distributed level, and the increase in energy consumption and demand variability caused by the electrification of sectors such as transport, heating, and cooling systems, as shown in DNV GL Group Technology and Research [11].

Several factors involved in the optimization in power grid planning and operations, the grid topology, and operational strategies are being further investigated in modern power systems. However, generation optimization has only recently attracted more attention owing to the increase of RES with high variability. This kind of investigation is essential so that ways can be found of taking advantage of their variability for power system operations.

This approach has some benefits. Since it is possible to deploy an electrical generation system that is able to appropriate different features of RESs, traditional flexibility solutions like spinning reserve and energy storage systems, have become less necessary.

According to Jurasz et al. [16], there are two key ways to harness the variability of RES: (a) hybridizing the power supply, e.g., PV-wind systems, or PV-Hydro systems, and, (b) spatially distributing the generation of the resulting power through a smoothing method. This last solution depends on the complementarity in the generation of different sources.

Since the changing rates of renewable supply vary over a wide interval, the response rates of flexible devices also vary, resulting in high-cost operations. The exploitation of complementarity of renewable sources is an excellent opportunity to reduce these needs and facilitate the penetration of renewable sources in the grid.

This chapter sets out the concepts of variability and complementarity for renewable sources. Its objective is to review recent investigations of these subjects and describe the most widely used indexes to assess the degree of complementarity between different renewables.

2 Concepts and Background

2.1 Variability of Renewable Power Sources

Hydroelectric power is the most well-known renewable source of energy. Its supply is subject to uncertainty owing to factors related to seasonality with fluctuating wet and dry seasons, which means large reservoirs are required to regularize the power supply. However, environmental concerns are constraining the reliance on hydroelectric power plants with large reservoirs.

The current trend is to deploy run-of-the-river power plants with small reservoirs so that the generation can be regulated for some hours each day. In this new scenario, there is an increase in the level of hydropower variability and, thus greater uncertainty concerning this source.

The variability of renewable-based power supply is related to its primary energy source. Wind power, for instance, depends on the wind speed in a particular region and the associated factors of seasonality. Hence, the availability of wind power depends on the region, climatic conditions, and seasons. All these points result in a significant degree of uncertainty. With regard to wind power forecasting, mid-term and short-term intervals give rise to a lower degree of uncertainty than long-term conditions. However, the problem of uncertainty over wind power can be overcome by deploying power plants with complementary features that are connected to the same grid in different regions. Wind farms with several turbines can benefit from local complementarity and assist in smoothing out the variability and providing a greater firm power.

Despite these possibilities, wind power is still susceptible to unforeseen reductions in power called ¨wind ramps¨, which may upset the power balance. It is necessary to use compensatory devices to respond to these sudden drops in supply and prevent these kinds of events.

When these devices are available in large numbers, nominal capacity, and speed response, and are distributed in a suitable way, it can be claimed that the grid complies with flexibility requirements and is able to react quickly and efficiently to the wind speed variability of wind farms.

In its turn, photovoltaic power is affected by daily and yearly seasonality. In addition, the solar day varies in different geographical locations. Regions near the Equator have a higher insolation than others in wide latitudes and produce more energy. However, passing clouds in different seasons can cause abrupt falls in power generation, and thus harm the grid operations.

As photovoltaic energy penetration increases in more favorable regions, larger ramps in power leading to falls in supply are expected, which requires more flexibility services. The deployment of devices to respond appropriately to these ramps is necessary to mitigate the problem of solar power intermittency across many temporal scales. Energy storage devices, open-cycle gas power plants, and hydro units are natural candidate technologies.

In addition, ocean energy exploration is increasing around the world. Of the alternative systems available, tidal power using currents and tidal barrages stand out. Both have intermittent features, but unlike previous sources of energy, they are smooth and predictable. Thus, it is possible to determine how much, and when, the power generation occurs. The slow and predictable intermittency of these sources is their main advantage.

All the previous renewable sources are subject to seasonality factors in space and time. How then should they be combined in a positive way to improve the power system? It should be noted that generation and load are asymmetric. While the power generation accepts uncertainty in load control, the load does not accept an uncertain generation of power.

Hence, from the standpoint of the power system, we are concerned with sources that allow energy-related controllability to match the load requirements with regard to frequency and voltage. Thus, as far as it is possible to make full use of the complementarity of these sources, the requirements for grid flexibility can be met.

In modern power systems, flexibility is an ancillary service. As long as the complementarity is effectively exploited, it is possible to reduce the costs incurred by flexibility and offer cheaper energy tariffs.

In light of this, complementarity can be considered as an opportunity to reduce the need for flexibility services in interconnected power systems. In addition, it is possible to improve energy security and contribute to grid decarbonization.

2.2 Complementarity

Complementarity can be defined as the relationship between two or more independent phenomena, that leads to a better result than when they are separate entities. Concerning power systems, complementarity occurs when different power sources operate together to behave like one equivalent source with lower variability.

According to Jurasz et al. [16], complementarity can take place in the following ways:

- **Spatial complementarity:** this refers to a situation where a particular energy source is abundant in one region but scarce in others. Such a problem is common in large power systems. The coordinated operation of these sources allows demand to be supplied homogeneously. Figure 1 shows an example of the spatial complementarity of photovoltaic generation in subsystems North and South of the Brazilian Power System;

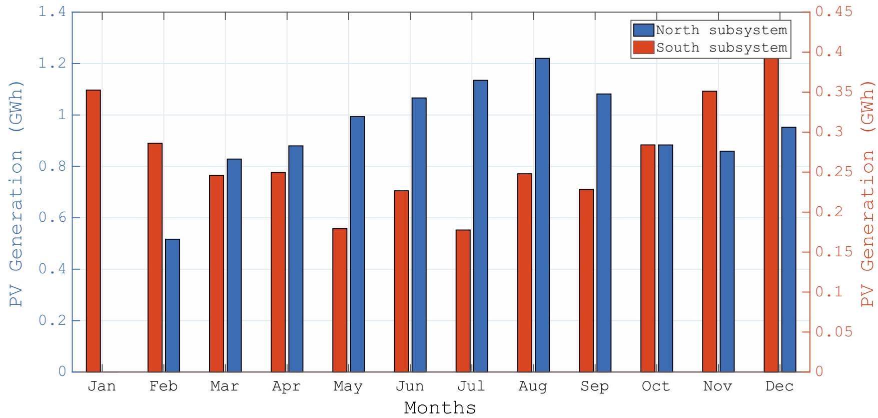

Fig. 1 Spatial complementarity in the Brazilian North and Northeast subsystems in 2019 (Data from National Operator of the Brazilian Electric System (ONS) (2020))

- **Temporal complementarity:** this occurs when two or more sources display complementarity in one region. For instance, in the subsystem North of the Brazilian Power System, hydroelectric power generation is higher from January to June, and wind power generation is higher from May to December. The occurrence of this kind of complementarity may arise from a single source. Photovoltaic plants with modules assembled in different positions (inclination and azimuth angle) or wind farms with distinct turbine models. Figure 2 shows an example of temporal complementarity between hydroelectric and wind sources in the North subsystem in the Brazilian Power System;

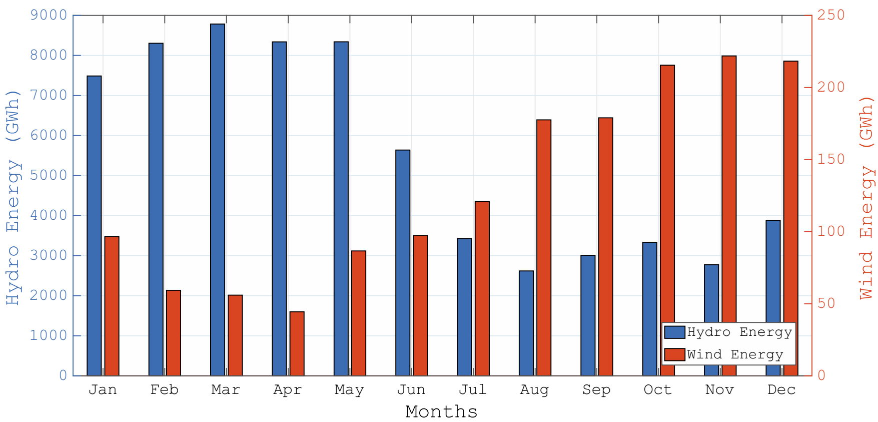

Fig. 2 Temporal complementarity between hydro and wind power in the North subsystem in the Brazilian Power System. (Data from National Operator of the Brazilian Electric System (ONS) (2020))

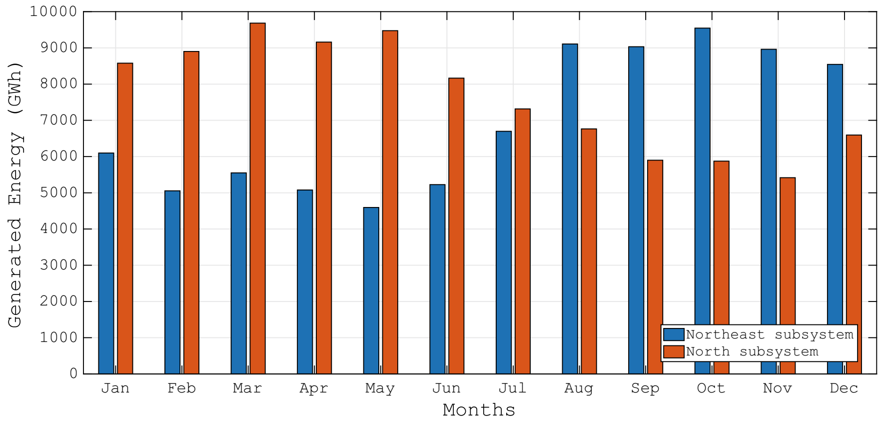

Fig. 3 Spatiotemporal complementarity in the Brazilian power subsystems North and Northeast. (Data from National Operator of the Brazilian Electric System (ONS) (2020))

- **Spatiotemporal complementarity:** this has features from both spatial and temporal types. Figure 3 provides an example of spatiotemporal complementarity in North and northeast subsystems in the Brazilian Power System.

2.3 Benefits of Complementarity

In the last few years, several investigations have been carried out to evaluate the effects and benefits of complementarity between power sources. This results from the increasing participation of renewables and makes it necessary to know how the different sources interact.

From a negative perspective, the increasing proportion of renewables in the power grid is causing greater uncertainty with regard to power generation. In light of this, flexible devices able to respond to energy intermittency are needed to make the operation of an interconnected power system more complex and sometimes more expensive due to the costs of these devices' services.

The complementary features of renewables and their correct exploitation can lead the power system further away from this adverse situation. Spatiotemporal complementarity, for instance, can increase the firm power of wind farms. In interconnected networks, the more expensive sources of flexibility can be significantly reduced, and thus bring down global costs.

The authors in de Oliveira Costa Souza Rosa et al. [9] investigate the degree of complementarity between solar, wind, and hydro sources in the southeast and western regions in Brazil using the Pearson correlation coefficient. They noted that the correlation index values suggest there is complementarity between the sources, and state that the solar source share must be approximately 50%.

In the same way, in Araujo and Marinho [1], the authors have evaluated the complementarity between wind and hydraulic energy sources in the State of Pernambuco (Brazil) through the Pearson correlation coefficient. A high degree of complementarity degree between both sources was observed over a period of a year, to such an extent that it was possible to save water in the *Sobradinho* reservoir.

The authors in Zhu et al. [28] designed a dynamic economic dispatch model based on a multi-scale complementarity between wind, solar, hydro, and thermal sources. The complementary is achieved by adjusting the generated power to reduce the imbalance between generation and demand. In this investigation, the load tracking index is used as a complementarity index.

In reference Zhou et al. [27], the complementarity in a microgrid with biogas, solar, and wind sources is investigated. The authors showed there was a possible means of mitigating the intermittency problem and improving the storage system and operations as well. The complementarity between sources lowered the battery charging/discharging parameters and degradation costs, as well as improving renewable energy penetration.

In Silva et al. [22] the authors applied the correlation coefficient to evaluate spatiotemporal complementarity between hydro and offshore wind sources. The results have shown a robust seasonal complementarity in the wind regimes between the North and Northeast regions in Brazil. Moreover, it demonstrated that there is a strong complementarity between offshore wind and hydro sources in different areas of the country.

In François et al. [12], there is an investigation of complementarity between solar and run-of-river hydro in Italy. In this case, the temporal complementarity was evaluated by taking account of different shares between energy sources and applying two indexes: (a) standard deviation of power balance and (b) the energy storage capacity required to keep power balance. When taking account of a small-time interval (hours), the results showed the run-of-river source has a more significant impact on the energy balance, whereas, in longer intervals (days or months), the solar source is mainly responsible for keeping energy balance. According to the authors, this is due to the smaller variability of the solar source that arises from a larger time scale.

Figure 4 brings together the main factors related to the complementarity-based approaches and quantifiers. *Table* provides an overview of the recent investigations of different power sources (Table 1).

Complementarity in Isolated Microgrids

Since energy scarcity is a more critical factor in isolated microgrids, RES complementarity is a good solution in these kinds of situation. This means there is an incentive to deploy hybrid energy systems in geographical areas with climatic limitations, and that are restricted to the spatial complementarity of a specific source. In these situations, a local complementarity must be sought by combining different kinds of RES located near each other to form a smoother power generation curve, rather than considering each source individually.

The energy scarcity problem in isolated microgrids can be mitigated through the complementarity between RES for the following reasons:

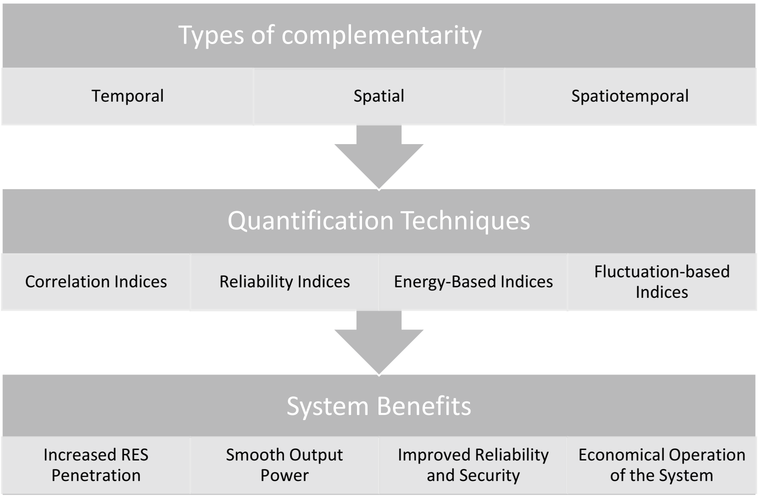

Fig. 4 Characterization of the investigation into complementarity

(a) a reduction in the amount of surplus energy, which is usually due to the inability of the storage system to absorb it;
(b) a decrease of energy deficits, which requires the use of a diesel generator or energy storage systems.

In view of this, complementarity between RES can provide an increased penetration of clean sources, since a smaller portion of this energy will be wasted. It also assists in reducing fossil fuel consumption and preserving the storage system, as its O&M costs can make the entire project financially unfeasible Bezerra et al. [3].

Reference Bezerra et al. [4] shows that solar, wind, and tidal current sources, which can be found in abundance in remote maritime islands, have some degree of complementarity with each other, (with the source of tides being highlighted), which despite variable patterns of behavior, is highly predictable. Owing to its smoother profile, tidal current generation is a good candidate source for isolated microgrids, however, its use as a single source is less attractive, since there are wide variations in the amount of energy generated because of the alternation between spring and neap tides. One solution to this problem is hybridization with other sources, such as solar and wind. This type of hybrid system can increase firm power, as shown in Bezerra et al. [4].

3 Quantification Techniques

Several authors outline methodologies for assessing the degree of complementarity between energy sources. Some general approaches, like the use of the correlation factor, are good preliminary indicators. Other more specialist methods have been recommended in the literature that take account of the peculiarities of power systems. These seek to quantify the complementarity and its benefits to the grid operation. In the following section, this range of approaches is reviewed.

3.1 *Quantifying the Variability of Generation Sources*

The quantification of complementarity requires an evaluation of the sources of variability. This evaluation should include the features of the source. For instance, in the case of a solar source, a temporal scale of seconds is appropriate due to the speed of the clouds' horizontal movement David et al. [8], while for a wind source, a temporal scale ranging from minutes to several hours is acceptable Ikegami et al. [15].

3.1.1 Ramp Rate

The ramp rate is a useful index of speed variability. A ramp can be defined as a variation in power generation or primary source, in the interval t to $t + \Delta t$, such that the variation is higher than a defined threshold. Some authors give slightly different definitions of ramp rates, including different threshold values and time intervals (Δt). These parameters change in accordance with the energy source in question.

Mathematically, the ramp rate can be defined according to Eq. (1).

$$RR = \frac{(P(t + \Delta t) - P(t))}{(\Delta t)} > RR_{val} \tag{1}$$

The ramp rate is considered when it is higher than a threshold RR_{val}; $P_{t+\Delta t}$ and P_t are the power output at time $t + \Delta t$ and t, respectively.

Note that the ramp rate may have positive or negative values. In general, negative ramp rates have a harsher effect since other power sources with fast response times must compensate for the sudden drop in generated power without load shedding. Figure 5 shows an example of a positive ramp rate.

3.1.2 Coefficient of Variation

The coefficient of variation is a statistical measure of dispersion defined as the ratio between standard deviation and a mean value Brown [5]. In power systems, it is a good indicator of the degree of variability in the generation sources.

Consider a wind farm where, for a time interval Δt, let the mean power generated be $\overline{P_{\Delta t}}$, and the standard deviation be σ_P. The coefficient of variation (CoV) is:

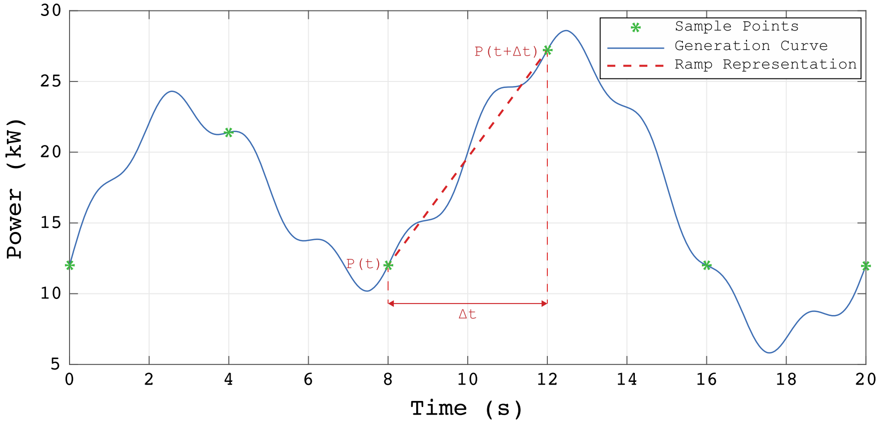

Fig. 5 A positive power ramp

$$CoV = \frac{\sigma_P}{P_{\Delta t}} \times 100\% \tag{2}$$

3.1.3 Average Fluctuation Magnitude (AFM)

The AFM can be defined as the average of absolute values of difference of power at time t and $t + \Delta t$, in an evaluation interval T Zhang and Liu [26]. Expressed in mathematical terms:

$$AFM_N = \frac{1}{T}\sum_{t=1}^{T}|P(t+\Delta t) - P(t)| \tag{3}$$

where T is the time interval considered. For example, the discretization used can be on the minute scale and $T = 60m$. $P(t)$ represents the power output at time t.

3.1.4 Reverse Fluctuation Count (RFC)

According to Zhang and Liu [26], RFC detects the inflection of the generation curve in two successive discretization intervals. The inflection is detected when:

$$\frac{P(t+\Delta t) - P(t)}{P(t) - P(t-\Delta t)} < 0 \tag{4}$$

When the RFC is zero, the generation has a continuously increasing or decreasing pattern. When RFC is higher than zero, the generation curve does not show inflection, but has an unknown variation rate. The higher the RFC value, the greater this uncertainty.

3.1.5 Moving Fluctuation Intensity (MFI)

In Zhang and Liu [26], the authors combine the previous quantifiers by defining MFI as the product of the Average Fluctuation Intensity and Reverse Fluctuation Count:

$$MFI_T = AFM_T \times RFC_T \tag{5}$$

MFI shows the combination of AFM and RFC. The bigger the MFC valuer, the higher is the frequency and magnitude of inflections in the power curve Yan et al. [24].

3.1.6 Maximum Fluctuation Width (MFW)

According to Yan et al. [24], the MFW indicates the worst case scenario of variability in a given period. It quantifies the difference between the highest and the lowest value of the generation curve in the period. A large MFW suggests a high variability of generation in the period. In mathematical terms:

$$MFW_T = (P_{max} - P_{min}) \times \frac{t_{max} - t_{min}}{|t_{max} - t_{min}|} \tag{13.6}$$

where t_{min} and t_{max} are the occurrence intervals of minimum power (P_{min}) and maximum power (P_{max}), respectively. The quotient of time intervals indicates whether this variation was upwards (positive) or downwards (negative).

3.2 Assessing the Source Diversification

The assessment of the effects of the renewable energy sources of diversification requires indexes to quantify the degree of complementarity between them. Several techniques to quantify the fluctuation of generation sources, and their complementarity are proposed in the literature. Some techniques are outlined below.

3.2.1 Correlation Coefficient (CC)

The CC is a standard statistical tool for assessing to what extent two time series resemble each other. When two temporal series have a similar pattern of behavior, there is a considerable similarity; otherwise, there is a strong complementarity.

The Correlation Coefficient is a number in the interval -1 to 1. The closer to 1, the stronger the similarity, while the closer to -1, the higher the complementarity.

The CC can evaluate the spatial–temporal complementarity in different time scales: minutes, hours, days, or months. Thus, it is a useful tool for assessing complementarity between energy sources.

The Pearson correlation is one of the best-known coefficients. It assesses the degree of correlation between two variables that are linearly associated. The Pearson correlation is the ratio between the covariance of two variables and the product of their standard deviations. In the case of two sources, a and b, with a nominal output $P_a(t)$ and $P_b(t)$, respectively, the Pearson correlation ρ_P is given as:

$$\rho_P = \frac{cov(P_a, P_b)}{\sigma_{P_a}\sigma_{P_b}} \tag{7}$$

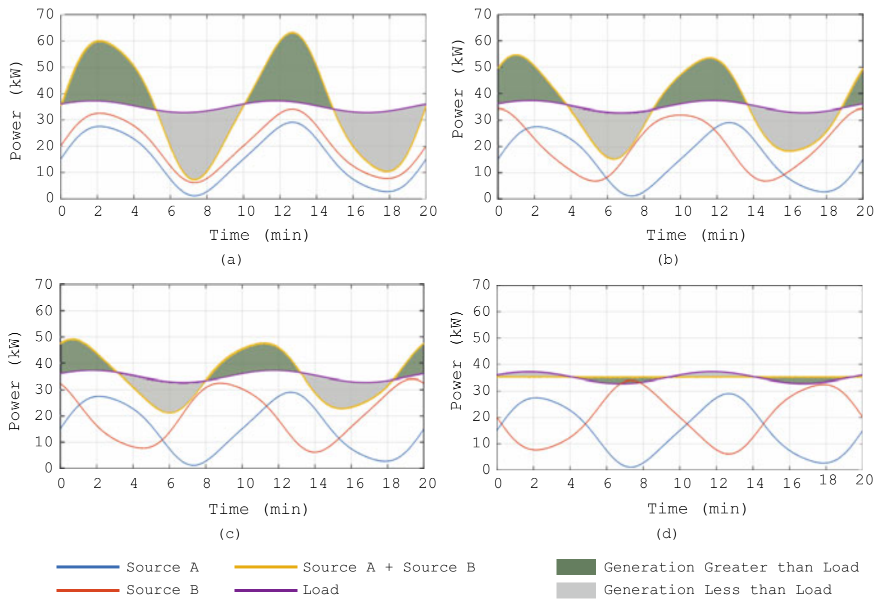

Fig. 6 Examples of a correlation between two different power sources A and B, where the total generation is compared with load curve, when: **a** Correlation coefficient is 1; **b** Correlation coefficient is 0; **c** correlation coefficient equals -0.5, and **d** correlation coefficient equals -1

As well as the Pearson correlation, Kendal and Spearman rank correlation coefficients are also widely used. Figure 6 shows the application of the Pearson coefficient in different generation-load cases.

3.2.2 Relative Fluctuation Rate (RFR)

The Relative Fluctuation Rate has a particular feature which involves considering both power sources and patterns of demand Diab et al. [10].

Consider a system formed of two different power sources, *a* and *b.* The RFR is:

$$RFR = \frac{\sqrt{\frac{1}{T}\sum_{t=1}^{T}(P_a(t) + P_b(t) - P_{load}(t))^2}}{\overline{P}_{load}} \tag{13.8}$$

where $P_a(t)$ and $P_b(t)$ are the power supplied by sources *a* and *b,* respectively at time *t*; $P_{load}(t)$ is the load power at time *t,* and $\overline{P}_{load}$ is the mean load power. T is the analytical period. Low RFR values indicate a closer proximity between the generation and demand curves.

3.2.3 Dispersion Factor (DF)

Renewable sources with extensive modularity, such as solar and wind, can reach a great generation capacity though their aggregation in power plants within a large geographical area. As a result, a non-uniform distribution of the primary source, caused by the Earth's relief and cloud movements, in large regions serves to homogenize the profile of total equivalent generation. This feature is stressed as far as new devices are installed in power plants.

In the case of the solar source, the dispersion factor includes the density of the geographic distribution of PV units. Consider the distance between the first and the last PV unit in the direction of the displacement of the clouds as l, the clouds speed v, and the time interval t_c for the clouds to pass through the solar plant Hoff and Perez [14, Yan et al. 24]. The solar dispersion factor is defined as:

$$DF = \frac{l}{v \times t_c} \tag{9}$$

Observe that the higher the solar plant, the greater the DF is. With regard to the cloud speed, the higher the speed, the lower the DF. Hence, the Dispersion Factor is a spatial complementarity index in a local context.

3.2.4 Load Tracking Index (LTI)

The Load Tracking Index (LTI) assesses the ability of a set of generating sources to follow the load demand curve. It measures the deviation between the total generation and the demand curve. Thus, the lower the LTI value, the greater is the ability to track the load demand curve Zhu et al. [28]; Jurasz et al. [16].

This index was designed in Zhu et al. [28] to assess a Virtual Power Plant (VPP) complementarity with solar, wind, and hydro sources. The LTI can be evaluated as:

$$LTI = D_t + D_s + D_c \tag{10}$$

$$D_t = \frac{1}{\overline{P}_{load}} \sqrt{\frac{1}{T} \sum_{t=1}^{T} (P_{VP}(t) - P_{load}(t))^2} \tag{11}$$

$$P_{VP}(t) = P_w(t) + P_p(t) + P_h(t) \tag{12}$$

$$D_s = \sqrt{\frac{1}{T-1} \sum_{t=1}^{T} \left(P_r(t) - \overline{P}_r\right)^2} \tag{13}$$

$$P_r(t) = P_{load}(t) - P_{VP}(t) \tag{14}$$

$$D_c = \frac{P_{r,max} - P_{r,min}}{T} \tag{15}$$

where D_t is the VPP fluctuation rate regarding the load demand; D_s is the standard deviation of the load demand fluctuation; D_c is the load demand fluctuation rate; these two last parameters represent the fluctuating features of power balance P_r; P_{rmin} and P_{rmax} are the minimum and maximum values of P_r in an interval T.

3.2.5 Daily Physical Guarantee (DPG)

This index assesses the local complementarity of many renewable sources. The DPG has been suggested in Bezerra et al. [4] as a means of determining the complementarity between sources in an isolated microgrid. It is assessed as the mean equivalent power for which the daily energy from sources is less than, or equal to, a given value during at least 90% of the year.

The DPG is defined as:

$$DPG = P_{90}(P_D) \tag{16}$$

$$P_D(d) = \frac{E_W(d) + E_P(d) + E_T(d)}{24h} \tag{17}$$

where $E_W(d)$,$E_P(d)$, and $E_T(d)$ are the energy supplied by wind, solar, and tidal currents source at day d, respectively; $P_D(d)$ is the constant equivalent power corresponding to total generation at day d; $P_{90}(P_D)$ is the 90th percentile of the P_D values. Figure 7 shows an example of how to assess the daily physical guarantee.

3.2.6 Comments

Several quantification techniques have been employed in different complementarity investigations. Some indexes, such as the correlation coefficient, are widely employed, as seen in Table. Other indexes have more specific applications, e.g. the Daily Physical Guarantee (DPG).

According to Bezerra et al. [4], complementarity investigations in isolated microgrids require some prudence. Although Indexes like the Relative Fluctuation Rate or Load Tracking Index incorporate the effects of variability and complementarity, they fail to describe the instantaneous power of the generation and load correctly. This means it is not possible to distinguish intervals, whether the generation exceeds the load or not.

In addition to renewable sources, isolated microgrids also include diesel generators and/or energy storage systems. These sources are dispatched based on their costs when the renewable energy generation is lower than the load. However, the frequent use of these sources may increase fossil fuel consumption and cause premature aging of the energy storage system. The authors in Bezerra et al. [4] show that Daily Physical Guarantee, based on the concept of firm power, may incorporate features of these kinds of isolated microgrids. Through an example, they demonstrated that DPG is a suitable index to assess the complementarity in remote microgrids and their impact on the backup diesel generator and energy storage system.

4 Applications

These kinds of indexes can be applied to different systems, from microgrids to bulk power systems by highlighting the complementarity benefits from different standpoints:

a. Complementarity between hydrographic basins has been investigated in hydrothermal systems to improve the use of reservoirs. One way to take advantage of this is to deploy an interconnected power system to make the energy exchanges feasible.
b. The seasonal complementarity can increase the penetration of renewables in the grid and contribute to grid decarbonization. When this kind of seasonal generation occurs in different regions, it is necessary to raise the transmission

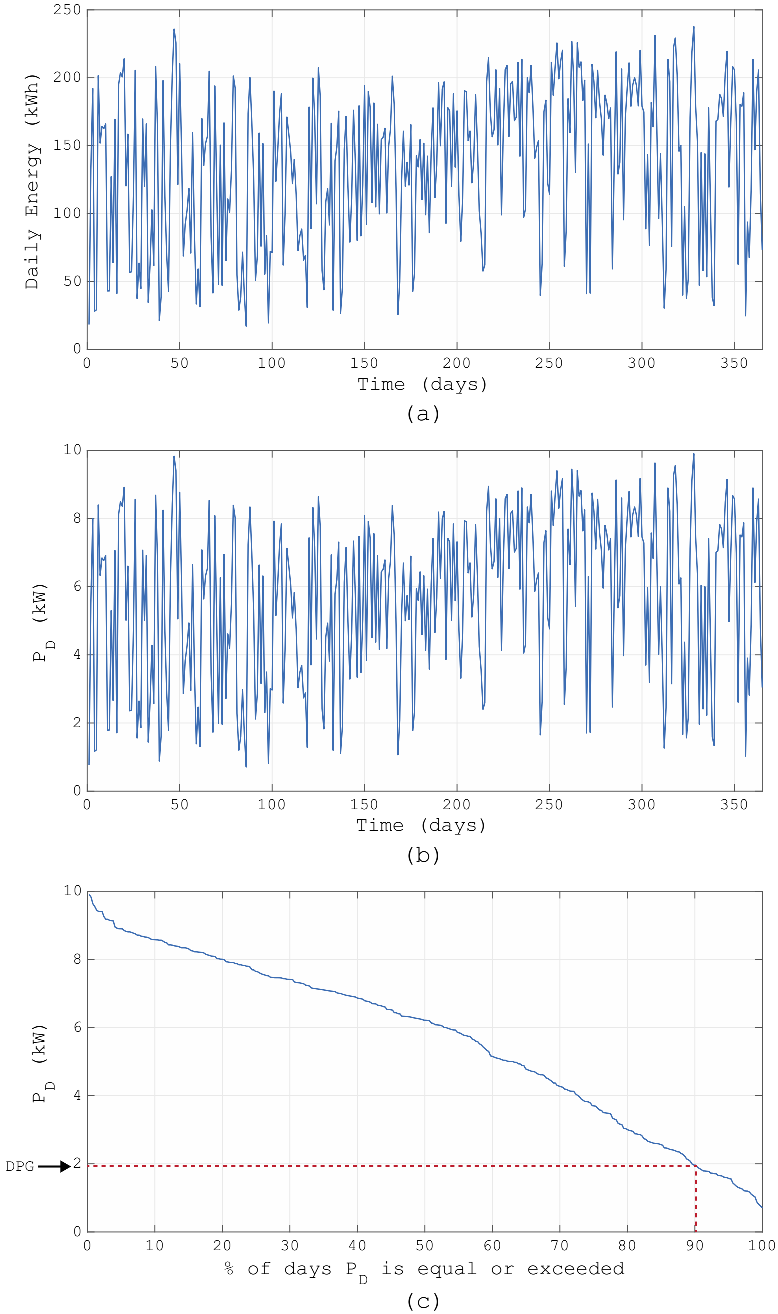

Fig. 7 Example of an assessment of the DPG: **a** the daily energy produced by renewable sources in one-year interval; **b** equivalent constant power corresponding to respective daily energy produced; **c** duration curve of P_D, highlighting the percentile Q_{90}, which represents DPG

capacity. Further energy storage options, like hydrogen, are alternatives to be considered in the future to avoid clean energy waste DNV GL Group Technology and Research [11].

c. The local complementarity of renewables can increase the firm power of a renewable energy hub Bezerra et al. [4]. The combination of these sources creates an equivalent source with lower intermittency than individual ones. In isolated microgrids, it helps reduce the requirements for energy storage and make the grid operation simpler.
d. Taking advantage of the complementarity of renewable resources can significantly reduce the need for power reserves to balance generation variability.
e. Taking advantage of complementarity brings economic and environmental benefits and contributes to a higher participation of renewables in the energy mix that is leading to a carbon-free power system.

5 Conclusion

Energy from wind, solar, and tidal sources has different degrees of variability due to the primary source features. Wind energy is influenced by weather conditions involving air masses with different temperatures and affected by seasonal factors. Solar energy is limited to the hours of daily solar irradiation. Although this irradiation varies smoothly during the day, passing clouds have an impact on power generation. Finally, tidal energy depends on the lunar cycles, and has a predictable behavior. However, the energy potential falls sharply in neap tides, thus creating a seasonal cycle linked to the lunar phases.

When dealing with such renewables, two types of quantifiers have been examined. The first measures the renewable variability with some approximations, and the second is based on indexes of complementarity. In light of certain hypotheses and simplifications, the application of these indexes needs to be treated some caution. A good practice is to compare several indexes.

Exploiting complementarity can bring many benefits to modern power grids and contribute to the flexibility and decarbonization of interconnected power systems. With regard to microgrids, the local complementarity can be attained by increasing firm power, ensuring a longer energy storage lifespan, and eventually being dependent on lower initial financial investments. The combination of these factors leads to the reduction of O&M costs and increases the technical and economic viability of these types of projects.

Each renewable source has its intermittency profile. Further investigation is mandatory in light of the prospect of forming joint applications to generate electrical power and ensure a continuous and reliable power supply. Deploying hybrid power generation is one way of mitigating their variability and benefiting from their complementarity.

Table 1 Review of investigations into the sources of complementarity

References	Sources	Type of complementarity	Quantification technique	Benefits	Comments
Cao et al. [7]	[W] [PV]	[STC]	• Complementarity coefficient • Coefficient of variation • Improved coefficient	• Smooth power output • Reduces ramp reserve capacity	• Different temporal scales are investigated to maximize the sources of complementarity
Bezerra et al. [4]	[W] [PV] [TI]	[TC]	• DPG	• Reduces fossil fuel dependency • Preserving battery bank lifetime	• Shows the sources of complementarity in an isolated microgrid, improves the storage system operation significantly, and reduces fossil fuel dependency • The addition of ocean energy to the energy mix improves the microgrid operation
Naeem et al. [20]	[W] [PV]	[STC]	• Correlation coefficient	• Reduces energy exchange cost	• Results show that the optimal RES mix can lead to considerable reductions in energy exchange costs
Canales et al. [6]	[W] [PV] [H]	[TC]	• Complementarity vector • Compromise programming • Total temporal complementarity index	• Maximum average daily outputs • Maximum cumulative production	• The results show a relation between timescale selection and the energetic complementarity index value

(continued)

Table 1 (continued)

References	Sources	Type of complementarity	Quantification technique	Benefits	Comments
Kougias et al. [17]	[PV] [H]	[TC]	• Correlation coefficient	• Maximum energy output	• In the studied location, a 10% compromise in the energy output of the small PV system results in a significant increase in the complementarity between small hydro and small PV systems
Diab et al. [10]	[PV] [W] [H]	[TC]	• Relative fluctuation rate	• Minimum energy cost	• The best configuration of a grid-connected PV/Wind/pumped storage system is achieved, by taking account of the loss of power supply probability (LSLP), low fluctuation of injected energy into the external grid, and full utilization of solar and wind resources

(continued)

Table 1 (continued)

References	Sources	Type of complementarity	Quantification technique	Benefits	Comments
Sun and Harrison [23]	[PV] [W]	[TC]	• Aggregated PV-wind-demand combinations	• Improves the network's capacity to absorb a greater amount of renewable generation • Increases total energy exports	• It is shown that the complementarity between different RES improves the exploitation of the available capacity of distributed generation • It is also shown that complementarity between different RES enables them to connect more renewable generation to the distribution grid
Berger et al. [2]	[W]	[STC]	• Criticality indicator	• Lower occurrence of system-wide low wind power generation events • Potential benefits of Interconti-nental Electricity Interconnection	• Generation sites across continents can benefit from high-quality resources simultaneously • Complemen-tarity between RES reduces the occurrence of simultaneous low power generation in intercontinental grids

(continued)

Table 1 (continued)

References	Sources	Type of complementarity	Quantification technique	Benefits	Comments
Li et al. [18]	[PV] [H]	[TC]	• Correlation coefficient	• Maximum total energy production • Maximum guaranteed rate	• Results show that complementarity in PV-Hydro systems is essential • The efficiency of the complementary operations is improved when account is taken of the uncertainty of streamflow and PV sources
Zhang et al. [25]	[PV] [W] [H]	[STC]	• Autoregressive moving average (ARMA) • Improved vine-copula method	• Improve the system's coordinated operation to fully utilize complementary characteristics between large-scale hydro, wind, and solar sources	• Results show that the coordinated operational strategy of the sources can improve the transmission availability in the dry season
Han et al. [13]	[PV] [W] [H]	[TC]	• Complementary rate of fluctuation (CROF) • Complementary rate of ramp (CROR)	• Optimize the system scheduling, making the output power of the system more stable • Improve the capacity design of the • PV–WP–H system	• The optimal level of complementarity can be obtained by changing the photovoltaic/wind power generation ratio

(continued)

Table 1 (continued)

References	Sources	Type of complementarity	Quantification technique	Benefits	Comments
Luz and Moura [19]	[PV] [W][H] [B]	[STC]	• Correlation coefficient	• Optimal energy mix and the water flow of hydropower reservoirs • Maximum reservoir operations • Minimum curtailment or loss-of-load	• Results show the benefits of complementarity in Brazilian regions and renewable energy sources

PV: photovoltaic
W: wind
H: hydro
Th: thermal
Ti: tidal
B: biomass
TC: temporal complementarity
STC: spatiotemporal complementarity

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State Estimation and Active Distribution Networks

Madson Cortes de Almeida, Thiago Ramos Fernandes, and Luis Fernando Ugarte Vega

Abstract Active Distribution Networks (ADN) are distribution systems containing advanced monitoring and communication infrastructures and efficient functions to remotely and automatically manage Distributed Energy Resources (DERs) and network topology. In an ADN, the Distribution Management System (DMS) collects and processes data, filters errors inherent to the meters and communication issues, and determines the network operating condition. Based on the operating condition, the DMS controls voltages, power flows, and system topology from the management of various devices, allowing the system to operate according to standards of power quality and energy efficiency. A state estimation function properly designed is required to filter errors inherent to the monitoring infrastructure. The state estimator provides the most likely network operating condition, which is the basis for the application functions of the DMS. This chapter presents an overview of some Distribution System State Estimation (DSSE) approaches available in the literature. Four well-established approaches are presented, and their advantages and disadvantages are discussed. Aspects such as state estimation modeling and solutions are included. The chapter also presents the main challenges for enabling DSSE in ADNs and briefly discusses a set of application functions usually available in a DMS that can benefit from DSSE, focusing on how state estimators can aid these functions.

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1 Introduction

The proliferation of Distributed Energy Resources (DERs), including distributed generators, energy storage systems, and controllable loads, and the high standards for power quality and energy efficiency have changed how distribution systems are designed, planned, and operated [26]. While these changes provide opportunities for improvements in the overall efficiency, reliability, and flexibility of distribution systems, they also pose operational challenges, such as bidirectional power flows, overcurrents, overvoltages, increased voltage unbalances, etc. [21]. The need for an effective management and control of distribution networks requires their evolution from passive to Active Distribution Networks (ADNs).

The CIGRE C6.11 working group defines ADNs as distribution networks with systems ready to remotely and automatically control DERs and network topology to efficiently manage and utilize the network assets [13]. Active management enables the optimization of distribution networks by taking full advantage of generation dispatch, on-load tap changers, voltage regulators, reactive elements, and topology reconfiguration in an integrated way. As a result, it reduces the negative impacts of the integration of DERs into the network, minimizes network reinforcement requirements, maintains the system stable, and improves its reliability [49]. Table 1 summarizes the main features of ADNs.

Figure 1 illustrates an idealized ADN. It consists of a distribution network with different DERs, advanced monitoring and communication infrastructures, and a Distribution Management System (DMS). The DMS is the brain of the ADN. It collects and processes real-time and forecasted data (e.g., the status of switches, on-load tap changers positions, DER power outputs, load and voltage profiles, power flows, etc.) to control voltages and power flows from the management of devices such as DER units, FACTS, on-load tap changers, reactive elements, and power electronic converters. The control is performed based on the network operating conditions determined by a state estimator, considering standards of power quality and energy efficiency.

Table 1 Main features of active distribution networks (Adapted from [13])

Infrastructure requirements	Application functions	Benefits
• Advanced protection schemes	• Data collection	• Improved reliability
• Communication upgrades	• State estimation	• Efficient utilization of assets
• Integration into existing systems	• Power flow congestion management	• Improved integration of DERs
• Flexible network topology	• Volt/VAr control	• Minimizes network reinforcement requirements
	• DER and load control	• Network stability
	• Topology reconfiguration	

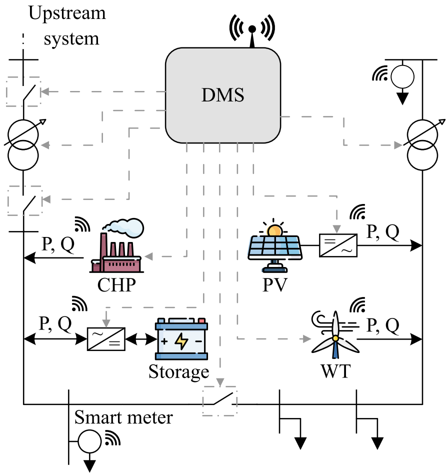

Fig. 1 Idealized active distribution network (Adapted from [49]. Icons designed by Freepik from www.flaticon.com.)

State estimation is a data processing tool that determines the most likely operating condition of a power system (i.e., the system state) for a given measurement set, system topology and parameters. In the ADN, the state estimator is mainly responsible for (i) supporting and increasing system visibility and (ii) filtering measurement noise and gross errors resulting from meter malfunction and communication issues. Therefore, it is the basis for the management and control functions of the DMS and is crucial for the real-time monitoring of the ADN. This fundamental role of the state estimation in ADNs can be verified by the increasing number of publications related to Distribution System State Estimation (DSSE).

Figure 2 shows a timeline of publications concerning DSSE. The number of publications was obtained from the Web of Science [11], considering journals with the highest impact factors in electrical power engineering. The figure also highlights some important events that impacted the interest in DSSE throughout the years. The first studies considering DSSE were published in the early 1990s [6, 7, 41, 52]. During the 1990s and early 2000s, DSSE was not a subject of great interest, probably due to its infeasibility in distribution systems as a consequence of the lack of metering and communication infrastructures. However, after the first half of the first decade of the 2000s, the number of publications involving DSSE has considerably increased, coinciding with the advancements and cost reductions in metering and communication technologies [55], the increase in the renewable generation capacity [31], and the definition of the ADN concept [13].

Given the vital role of state estimation in ADNs, this chapter presents four well-established distribution system state estimators and the challenges to be overcome to enable DSSE in ADNs. Additionally, the chapter briefly describes some DMS functions that can benefit from state estimation. The remainder of this chapter is structured as follows. Section 2 presents the state estimation approaches devoted to distribution systems. Theoretical aspects of state estimation, modeling, and numerical solutions

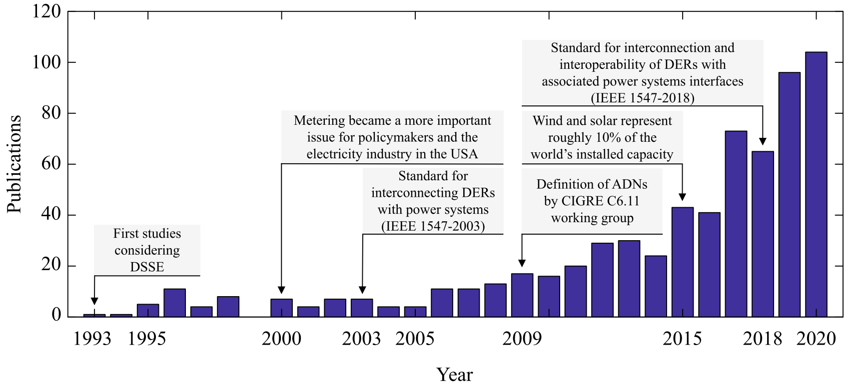

Fig. 2 Timeline of publications involving DSSE

are also discussed. Section 3 discusses the main challenges to be circumvented to enable DSSE in ADNs. Section 4 briefly outlines how some basic DMS functions relate to state estimation. Finally, Sect. 5 concludes the chapter.

2 Distribution System State Estimation

State estimation will constitute the backbone of the ADNs, acting as a filter between measurements and the DMS application functions that require the most reliable database for the system state. This section presents the concepts behind well-established state estimation approaches, focusing on the ones dedicated to distribution systems.

2.1 State Estimation Approaches

Due to the typical features of distribution systems, well-consolidated state estimators developed for transmission systems may require improvements before being applied to distribution systems [18]. Therefore, considerable efforts have been made to the development of state estimators devoted to distribution systems. The Weighted Least Squares (WLS) solution is the most popularly adopted. The main differences among the proposals lie in the choice of the state variables and how the measurements are considered. Concerning the state variables, DSSE approaches are generally classified as node voltage or branch current based. Both can be formulated in polar or rectangular coordinates, each with its advantages and disadvantages [26]. This section presents four state estimators well-established in the DSSE literature.

2.1.1 Traditional State Estimator

The Traditional State Estimator (TSE) is widely used in transmission systems and was found to be suitable for distribution systems concerning statistical properties and accuracy in [54]. The TSE adopts the bus voltage phasors in polar coordinates as state variables (i.e., $\boldsymbol{x} = [\boldsymbol{v},\ \boldsymbol{\theta}]$). It uses the available measurements, including power flows and injections, bus voltage magnitudes, etc., to estimate the system state. The relationship between the state variables and measurements is nonlinear. Thus, the resulting Jacobian matrix, $\boldsymbol{H}(\boldsymbol{x})$, depends on the state variables and has to be updated at each iteration of the state estimation process. Accordingly, the resulting Gain matrix, $\boldsymbol{G}(\boldsymbol{x})$, needs to be computed and factorized every iteration. Figure 3 shows an overview of the TSE.

Because the Jacobian and Gain matrices need to be updated at each iteration of the state estimation process, the application of the TSE to typical distribution systems may require a great deal of computational effort. Furthermore, due to the nonlinear nature of the equations relating state variables to measurements, the elements of the Jacobian matrix are obtained from summations involving sinusoidal functions, state variables, and network parameters, increasing its implementation complexity, especially for three-phase modelings. Computationally efficient alternatives to the TSE are the estimators whose formulation results in constant Jacobian and Gain matrices [15, 25, 47].

2.1.2 Admittance Matrix Based State Estimator

The Admittance Matrix Based State Estimator (AMBSE) was proposed in [41] for three-phase distribution systems. In the AMBSE, the state variables are the bus voltage phasors in rectangular coordinates (i.e., $\boldsymbol{x} = [\Re\{\bar{\boldsymbol{v}}\},\ \Im\{\bar{\boldsymbol{v}}\}]$). Voltage and power measurements are converted into equivalent voltages and currents in rectangular coordinates, using the measured values and the state obtained at each iteration of the state estimation solution process. The linear relationship between the state variables

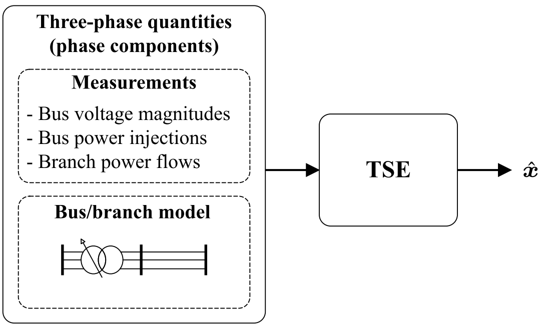

Fig. 3 Overview of the TSE. $\hat{\boldsymbol{x}}$ denotes the estimated state

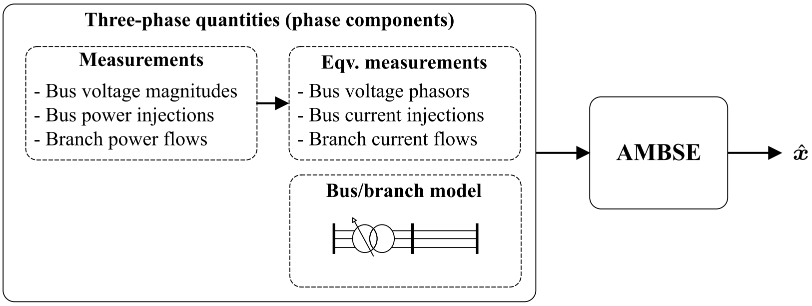

Fig. 4 Overview of the AMBSE

and equivalent measurements allows a constant Jacobian matrix, $\boldsymbol{H}$, composed of system admittances, zeros, and unitary elements.

The Gain matrix of the AMBSE, $\boldsymbol{G}$, can be made constant if the variances of the equivalent measurements in the weighting matrix are computed using a previously estimated state. This previous state can be obtained from a power flow calculation or a previous state estimation run [15]. Although linearly formulated, the AMBSE requires an iterative solution process so that the equivalent measurements are updated to match the measured values. Figure 4 shows an overview of the AMBSE. Even though measurements (actual, virtual, and pseudo) are converted into equivalents, the network topology and parameters adopted are the same as those adopted in the TSE.

The AMBSE presents great improvements over the TSE in terms of execution time and implementation complexity. The sparsity of its coefficient matrices is very similar to that observed in the TSE, while the convergence features may differ depending on the network and available measurements. The modeling of voltage magnitude measurements requires some attention [15].

2.1.3 Branch Current Based State Estimator

The Branch Current Based State Estimator (BCBSE) was proposed in [7] to exploit the radial topology of distribution systems. The state variables of the BCBSE are the branch currents phasors and the reference bus voltage phasor in rectangular coordinates (i.e., $\boldsymbol{x} = [\Re\{\bar{\boldsymbol{v}}_{ref}\},\ \Im\{\bar{\boldsymbol{v}}_{ref}\},\ \Re\{\bar{\boldsymbol{i}}_{km}\},\ \Im\{\bar{\boldsymbol{i}}_{km}\}]$). Similar to the AMBSE, voltage and power measurements are converted into equivalent voltages and currents in rectangular coordinates, using the measured values and the state obtained at each iteration of the state estimation solution process [47]. The state variables and the equivalent measurements are linearly related, enabling a constant Jacobian matrix, $\boldsymbol{H}$, whose entries consist of system impedances, zeros, and unitary elements. Similarly to the AMBSE, the Gain matrix, $\boldsymbol{G}$, can be made constant if the variances of the equivalent measurements in the weighting matrix are computed using a previously estimated state [15].

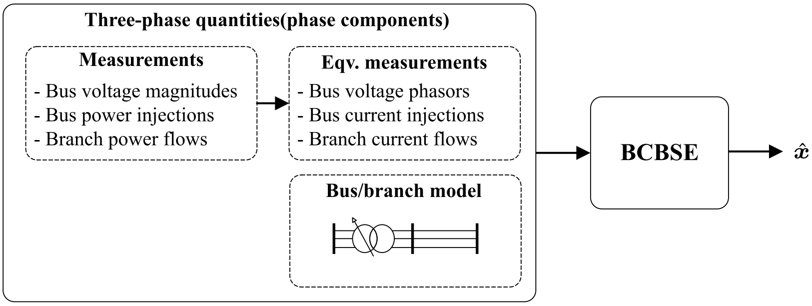

Fig. 5 Overview of the BCBSE

Figure 5 shows an overview of the BCBSE. The network topology and parameters are the same as those adopted in the TSE and AMBSE. BCBSE's inputs are the same as AMBSE's, while in the TSE, the inputs are the measurements (actual, virtual, and pseudo) and their corresponding variances. Similarly to the AMBSE, an iterative solution process is required in the BCBSE so that the equivalent measurements are updated to match the measured values. Note that, as BCBSE's output is given in terms of the branch currents, a procedure, such as a forward sweep [34, Ch. 10], is necessary to compute the bus voltages required to update the equivalent measurements during the state estimation process.

As the AMBSE, the BCBSE presents significant improvements over the TSE in execution time and implementation complexity. Its convergence features are similar to those observed in the AMBSE. The sparsities of BCBSE's Jacobian and Gain matrices are very high; however, they decrease as the number of voltage measurements increases [53]. The modeling of voltage magnitude measurements also requires some attention [15].

2.1.4 Symmetrical Components Based State Estimator

The theory of symmetrical components was first applied to state estimation in [28]. The proposed approach was developed for three-phase transmission systems considering only synchronized phasor measurements provided by PMUs, resulting in a linear (non-iterative) model. As transmission lines are typically transposed, the mutual couplings between the phases of the lines are similar, and the symmetrical components transformation decouples the three-phase system into three single-phase sequence networks. On the other hand, as distribution lines are usually untransposed, the symmetrical components transformation does not decouple the three-phase system. This is the primary reason why distribution system analysis generally uses the phase rather than the sequence domain [34].

Nevertheless, by introducing the concept of compensation currents into a three-phase untransposed distribution system modeled in the sequence domain, it is possible to decompose it into three single-phase sequence networks, considering the

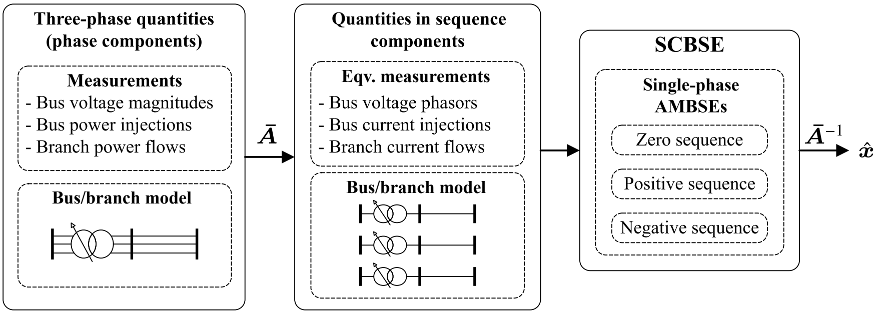

Fig. 6 Overview of the SCBSE. $\bar{\boldsymbol{A}}$ denotes the phase to sequence transformation matrix and $\bar{\boldsymbol{A}}^{-1}$ denotes the sequence to phase transformation matrix

line asymmetry effects [24, 25]. Based on this concept, reference [25] proposes a Symmetrical Components Based State Estimator (SCBSE) for three-phase distribution systems. The decomposition achieved significantly expedites the DSSE process, simplifies implementation complexity, and allows parallel running implementations.

Figure 6 shows an overview of the SCBSE. Essentially, SCBSE's algorithm consists of three main steps: (i) converting measurements into equivalent measurements (similarly to the AMB and BCB state estimators) and transforming them into their counterparts in sequence components, (ii) modeling the distribution system as three decoupled sequence networks using the concept of compensation currents, and (iii) employing single-phase AMBSEs to solve the sequence networks sequentially or simultaneously and obtain the estimated state in the phase domain.

As AMBSEs are employed to solve the sequence networks in the SCBSE, the state variables of the problem are the sequence bus voltage phasors in rectangular coordinates (i.e., $\boldsymbol{x} = [\Re\{\bar{\boldsymbol{v}}\},\ \Im\{\bar{\boldsymbol{v}}\}]$) and the sequence Jacobian matrices are constant. Furthermore, the sequence Gain matrices can be made constant if the variances of the equivalent measurements are computed using a previously estimated state [15]. The WLS solution requires an iterative process so that the equivalent measurements are updated to match the measured values. Note that the same single-phase AMBSE is applied to the three sequence networks, greatly simplifying the implementation complexity.

Table 2 presents some important features of the distribution system state estimators described in this section. Based on these features, it is possible to choose the DSSE more suitable for a given application and scenario.

2.2 *Modeling*

Power system state estimation is defined as the process of obtaining the most likely state of the system from measurements, system topology and parameters. The system

Table 2 Main features of the presented DSSEs

Estimator	Advantages	Disadvantages
TSE	• Widely-known • Does not require measurement conversion • Suitable for meshed networks	• State variables and measurements are nonlinearly related • Requires updating of Jacobian and Gain matrices • High computational burden
AMBSE	• State variables and equivalent measurements are linearly related • Constant Jacobian and Gain matrices • High computational performance • Suitable for meshed networks	• Requires measurement and variances conversion • Requires attention with voltage magnitude measurements
SCBSE	• State variables and equivalent measurements are linearly related • Constant Jacobian and Gain matrices • High computational performance • Suitable for meshed networks	• Requires modeling in the sequence domain • Requires measurements and variances conversion • Requires attention with voltage magnitude measurements
BCBSE	• State variables and equivalent measurements are linearly related • Constant Jacobian and Gain matrices • High computational performance	• Requires measurements and variances conversion • Requires attention with voltage magnitude measurements • Unsuitable for meshed networks • Loses efficiency when many voltage measurements are present

state is a set of variables that fully describe the power system. In distribution networks, the system state is usually expressed in terms of the bus voltage phasors, branch current phasors, or a combination of these.

The WLS solution for the TSE is derived from the nonlinear measurement model defined by (1), where vector $\boldsymbol{z}$ contains the measurements (actual, virtual, and pseudo types), vector $\boldsymbol{x}$ contains the state variables, vector $\boldsymbol{h}(\boldsymbol{x})$ comprises the nonlinear functions relating measurements to state variables, and vector $\boldsymbol{e}$ contains the errors inherent to the measurements [44].

$$\boldsymbol{z} = \boldsymbol{h}(\boldsymbol{x}) + \boldsymbol{e} \tag{1}$$

The WLS solution for the remaining state estimators presented in Sect. 2.1 is derived from a linear measurement model similar to (1), where vector $\boldsymbol{z}$ contains the equivalent measurements (obtained from the measurements and the state obtained at each iteration of the state estimation solution process), and vector $\boldsymbol{h}(\boldsymbol{x})$ comprises the linear functions relating measurements to state variables [15].

Table 3 Formulation for different state estimation solutions [18]

Solution	Objective function	Advantages	Disadvantages
WLS	$\boldsymbol{r}^T \boldsymbol{W} \boldsymbol{r}$	• Simple • Widely-used	• Sensitive to bad data
LAV	$\sum_{i=1}^{m} \lvert r_i \rvert$	• Robust against bad data • Small sensitivity to line impedance uncertainty	• High computational cost • Sensitivity to leverage points and measurement uncertainty
MN	$\lvert\lvert \boldsymbol{x} \rvert\rvert_2$	• Able to cope with underdetermined systems of equations	• Sensitive to bad data and measurement uncertainty
LMS	$\text{med}\{r_1^2, \ldots, r_m^2\}$	• Robust against bad data and leverage points	• High computational cost • High measurement redundancy requirements

Power system state estimation problems are desired to be overdetermined. Therefore, they are formulated as optimization problems whose objective functions depend on the adopted state estimation solution. The WLS is by far the most used solution; thus, in this text, the focus will be given to it. Alternatives to the WLS state estimation solution are the Least Absolute Value (LAV) [27], the Minimum-Norm (MN) [16], and the Least Median of Squares (LMS) [43].

The WLS solution is obtained by minimizing the objective function (2), where $\boldsymbol{W}$ is the weighting matrix and the difference $z - \boldsymbol{h}(\boldsymbol{x})$ denotes the measurement residuals, r. Usually, the weighting matrix $\boldsymbol{W}$ is chosen as the inverse of the measurement error covariance matrix, $\boldsymbol{R}$ [44]. Table 3 presents alternative state estimation solutions, as well as their main advantages and disadvantages [18].

$$J(\boldsymbol{x}) = \frac{1}{2}[z - \boldsymbol{h}(\boldsymbol{x})]^T \boldsymbol{W}[z - \boldsymbol{h}(\boldsymbol{x})] \tag{2}$$

2.3 Conventional Numerical Solutions

Power system state estimation problems are usually solved by iterative methods, such as the Gauss-Newton or the Newton-Raphson. The WLS solution for the TSE is obtained by the Newton-Raphson method by applying the optimally conditions in (2). By Taylor expansion, the estimated state, $\hat{\boldsymbol{x}}$, is obtained by the iterative procedure in (3)–(4), where $\boldsymbol{\Delta} z(\boldsymbol{x}^{\nu}) = [z - \boldsymbol{h}(\boldsymbol{x}^{\nu})]$, and ν is the iteration counter.

$$\boldsymbol{G}(\boldsymbol{x}^{\nu})\boldsymbol{\Delta x}^{\nu} = \boldsymbol{H}(\boldsymbol{x}^{\nu})^T \boldsymbol{W} \boldsymbol{\Delta} z(\boldsymbol{x}^{\nu}) \tag{3}$$

$$\boldsymbol{x}^{\nu+1} = \boldsymbol{x}^{\nu} + \boldsymbol{\Delta x}^{\nu} \tag{4}$$

Matrices $\boldsymbol{H}(\boldsymbol{x})$ and $\boldsymbol{G}(\boldsymbol{x})$ are the Jacobian matrix and the Gain matrix, respectively. For the Newton-Raphson method, the Gain matrix is given by (5).

$$\boldsymbol{G}(\boldsymbol{x}) = \boldsymbol{H}(\boldsymbol{x})^T \boldsymbol{W} \boldsymbol{H}(\boldsymbol{x}) - \sum_{i=1}^{m} \Delta z_i \frac{\partial^2 h_i(\boldsymbol{x})}{\partial \boldsymbol{x}^2} \tag{5}$$

The Gauss-Newton method for the TSE is obtained by ignoring the term that depends on the second derivatives in (5), such that $\boldsymbol{G}(\boldsymbol{x})$ reduces to (6). This solution is referred to as the normal equation.

$$\boldsymbol{G}(\boldsymbol{x}) = \boldsymbol{H}(\boldsymbol{x})^T \boldsymbol{W} \boldsymbol{H}(\boldsymbol{x}) \tag{6}$$

In most situations, the impact of ignoring the second derivatives on state estimation is negligible [44]. Furthermore, it grants computational simplicity for the state estimation process. As such, the Gauss-Newton method is generally used to find the WLS solution to the state estimation problem in (2).

The normal equation for the remaining state estimators presented in Sect. 2.1 can be derived from equations (3) and (4). As these approaches are based on a linear measurement model, matrices $\boldsymbol{H}$ and $\boldsymbol{W}$ can be kept constant and $\boldsymbol{z}(\boldsymbol{x}) = \boldsymbol{H}\boldsymbol{x}$. By substituting these conditions into (3), it is given that

$$\boldsymbol{\Delta x}^{\nu} = \boldsymbol{G}^{-1} \boldsymbol{H}^T \boldsymbol{W} [z(\boldsymbol{x}^{\nu}) - \boldsymbol{H}\boldsymbol{x}^{\nu}] \tag{7}$$

$$\boldsymbol{\Delta x}^{\nu} = \boldsymbol{G}^{-1} \boldsymbol{H}^T \boldsymbol{W} z(\boldsymbol{x}^{\nu}) - \boldsymbol{G}^{-1} \boldsymbol{H}^T \boldsymbol{W} \boldsymbol{H} \boldsymbol{x}^{\nu} \tag{8}$$

$$\boldsymbol{\Delta x}^{\nu} = \boldsymbol{G}^{-1} \boldsymbol{H}^T \boldsymbol{W} z(\boldsymbol{x}^{\nu}) - \boldsymbol{x}^{\nu} \tag{9}$$

Finally, substituting (9) into (4) yields

$$\boldsymbol{x}^{\nu+1} = \boldsymbol{G}^{-1} \boldsymbol{H}^T \boldsymbol{W} z(\boldsymbol{x}^{\nu}) \tag{10}$$

Note in (10) that the state for $\boldsymbol{x}^{\nu+1}$ is directly obtained. Recall that, as BCBSE's output is given in terms of the branch currents, is it necessary to compute the bus voltages before updating the equivalent measurements during the state estimation process. An efficient procedure to calculate the bus voltages from the branch currents is to use a forward sweep [34, Ch. 10]. Alternatively, it is possible to obtain the current injections from the node to branch incidence matrix and finally calculate the bus voltages from these currents and the bus admittance matrix [14, Ch. 11, Ch. 12].

2.4 Numerical Robust Solution

The WLS solution to the state estimation problem can almost always be successfully obtained via the normal equation. However, under special circumstances that are likely to occur in actual power systems, the normal equation can experience numerical instabilities. Such situations may prevent the estimator from reaching an acceptable solution or even cause divergence [2].

The numerical performance of the WLS state estimator via the normal equation can be negatively affected by [2, 44]:

- The use of very distinct measurement weighting factors.
- The presence of very low impedances.
- The presence of a large number of power injection measurements.

These problems arise because the normal equation uses the Gain matrix, which is the square of the Jacobian matrix (refer to Eq. (6)), making the condition number of the former matrix worse. In fact, if the condition number of $\boldsymbol{H}$ is κ, then, the condition number of $\boldsymbol{G}$ is κ^2.

In distribution systems, the condition number of the normal equation is mainly deteriorated by the large weights used to enforce virtual measurements associated with zero injection buses. These measurements are usually assigned large weights because they are perfect (i.e., free of error) injection measurements. To prevent this conditioning issues, virtual measurements can be treated in the WLS state estimator as equality constraints, giving rise to the Sparse Tableau [2].

2.4.1 WLS State Estimation via Sparse Tableau

To obtain the Sparse Tableau for the nonlinear measurement model in (1), virtual, actual, and pseudo measurements are treated as equality constraints according to (11), where vector $\boldsymbol{c}(\boldsymbol{x})$ contains the functions related to the virtual measurements (zero injections), $\boldsymbol{h}(\boldsymbol{x})$ comprises the functions related to the actual and pseudo measurements, and vector $\boldsymbol{r} = \boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x})$ denotes the measurement residuals.

$$\begin{aligned} \text{Minimize} \quad & J(\boldsymbol{x}) = \frac{1}{2}\boldsymbol{r}^T\boldsymbol{W}\boldsymbol{r} \\ \text{subject to} \quad & \boldsymbol{c}(\boldsymbol{x}) = \boldsymbol{0} \\ & \boldsymbol{r} - \boldsymbol{z} + \boldsymbol{h}(\boldsymbol{x}) = \boldsymbol{0} \end{aligned} \tag{11}$$

By applying the method of Lagrange multipliers in (11) to obtain the optimality conditions, the WLS solution is obtained and can be solved via the Gauss-Newton method by the iterative procedure in (12)-(13).

$$\begin{bmatrix} \alpha^{-1}\boldsymbol{R} & \boldsymbol{H}(\boldsymbol{x}^{\nu}) & \boldsymbol{0} \\ \boldsymbol{H}(\boldsymbol{x}^{\nu})^T & \boldsymbol{0} & \boldsymbol{C}(\boldsymbol{x}^{\nu})^T \\ \boldsymbol{0} & \boldsymbol{C}(\boldsymbol{x}^{\nu}) & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} \alpha\boldsymbol{\mu} \\ \boldsymbol{\Delta x}^{\nu} \\ \alpha\boldsymbol{\lambda} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\Delta}z(\boldsymbol{x}^{\nu}) \\ \boldsymbol{0} \\ -\boldsymbol{c}(\boldsymbol{x}^{\nu}) \end{bmatrix} \tag{12}$$

$$\boldsymbol{x}^{\nu+1} = \boldsymbol{x}^{\nu} + \boldsymbol{\Delta x}^{\nu} \tag{13}$$

In (12), $\boldsymbol{H}(\boldsymbol{x}) = \partial\boldsymbol{h}(\boldsymbol{x})/\partial\boldsymbol{x}$ is the Jacobian of $\boldsymbol{h}(\boldsymbol{x})$, $\boldsymbol{C}(\boldsymbol{x}) = \partial\boldsymbol{c}(\boldsymbol{x})/\partial\boldsymbol{x}$ is the Jacobian of $\boldsymbol{c}(\boldsymbol{x})$, $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$ are vectors of Lagrange multipliers, α is a scaling factor introduced to improve the condition number of the coefficient matrix. Equations (14) and (15) are alternatives to obtain the scaling factor [2].

$$\alpha = \frac{1}{\max(\boldsymbol{W})} \tag{14}$$

$$\alpha = \frac{m}{\mathrm{tr}(\boldsymbol{W})} \tag{15}$$

The coefficient matrix in (12) presents low condition numbers, once the the Gain matrix, $\boldsymbol{G}(\boldsymbol{x})$, is not included. The enlarged system of equations is not very much expensive concerning arithmetic operations than the solution via the normal equation, since the tableau is very sparse.

The Sparse Tableau for the AMB, BCB, and SCB state estimators can be obtained by a very similar procedure. For the sake of simplicity, considering a unitary scaling factor α, the corresponding WLS solution is obtained by solving the iterative procedure in (16). Note that the Jacobian matrices $\boldsymbol{H}$ and $\boldsymbol{C}$ are constant and, therefore, the tableau is constant [15]. Finally, observe that the state for the current iteration, $\boldsymbol{x}^{\nu+1}$, is directly obtained from (16).

$$\begin{bmatrix} \boldsymbol{R} & \boldsymbol{H} & \boldsymbol{0} \\ \boldsymbol{H}^T & \boldsymbol{0} & \boldsymbol{C}^T \\ \boldsymbol{0} & \boldsymbol{C} & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{\mu} \\ \boldsymbol{x}^{\nu+1} \\ \boldsymbol{\lambda} \end{bmatrix} = \begin{bmatrix} z(\boldsymbol{x}^{\nu}) \\ \boldsymbol{0} \\ -\boldsymbol{c}(\boldsymbol{x}^{\nu}) \end{bmatrix} \tag{16}$$

Figure 7 presents a summary of the DSSE approaches and solution methods discussed in this section. The TSE can provide a WLS solution via Newton-Raphson as well as Gauss-Newton methods. For the AMB, BCB, and SCB state estimators, the solutions via Newton-Raphson and Gauss-Newton are equal, once the second derivatives of $h(\boldsymbol{x})$ with respect to the state variables in $\boldsymbol{x}$ are null. The approaches presented can be solved via the normal equation or the Sparse Tableau. Alternatively, references [44] and [2] present other robust solutions that can be successfully applied to the estimators presented.

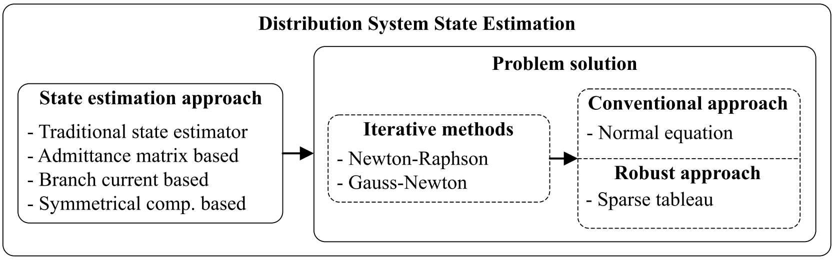

Fig. 7 Summary of the DSSE approaches and solution methods presented

3 DSSE Implementation Challenges

State estimation is widely used in transmission systems; however, it is not common in distribution systems. This is mainly because distribution systems are usually seen and managed as passive networks, where the “fit and forget” fashion is frequently adopted [49]. Nevertheless, with the advent of the ADN concept, the main challenges for DSSEs are being gradually overcome, especially concerning the monitoring and communication infrastructures. This section summarizes the main challenges that will have to be circumvented to enable state estimation and facilitate the automation capabilities required by ADNs.

3.1 Observability

A power system is observable if it is possible to obtain its state from the available measurements, system topology, and parameters [44]. Essentially, for a state estimation problem to be solvable, the number of available measurements must be at least equal to the number of state variables, which, considering that distribution systems require three-phase models, is six times the number of system buses. Nevertheless, such a monitoring level is rarely found in traditional distribution systems, making observability a challenge for DSSE [2, 26]. To make a distribution system observable, the so-called pseudo-measurements, which are normally inaccurate and may deteriorate the estimates, must be used [3]. Therefore, monitoring is probably the greatest challenge faced by state estimation in ADNs.

Observability analysis approaches can be numerical, topological, or hybrid [44]. Observability analysis is carried out before state estimation to check the suitability of the available measurement set. If the system is unobservable, additional measurements or pseudo-measurements need to be set at appropriate feeder locations to make the system observable. This process is known as observability restoration. Momentary loss of measurements, caused by communication or meter failures, and topology changes may make the system unobservable. Observability analysis detects

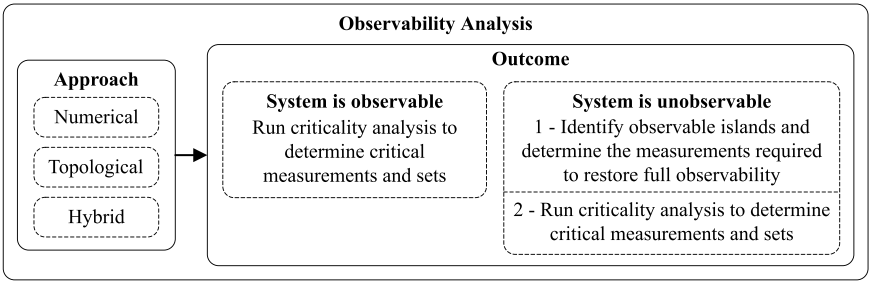

Fig. 8 Overview of observability analysis

such cases, identifies the network portions whose state can be estimated (observable islands), and determines where measurements must be placed to restore full observability.

Based on the same concepts of observability analysis, criticality analysis determines the redundancy relationships among measurements, classified as critical, belonging to a critical set, or redundant. Criticality analysis is essential for determining the bad data detection capabilities of the state estimation process [5]. Moreover, it can help to better understand the estimates. Figure 8 presents an overview of observability analysis.

3.2 Network Complexity

Regarding network complexity, the main characteristics of distribution systems that represent a challenge to state estimation are [18, 26]:

- **Unbalanced and asymmetrical operation.** Distribution systems are usually unbalanced and asymmetrical due to the presence of single-, two- and three-phase loads and branches. This issue is further aggravated by the increasing penetration of DERs. Consequently, three-phase models are required to represent these characteristics accurately.
- **Radial or weakly meshed topology.** The radial or weakly meshed topologies are the most common in distribution systems. While these configurations are cheaper and guarantee computational advantages for state estimation, they may deteriorate measurement redundancy, as the Voltage Kirchhoff Law cannot be applied to increase the number of equations when there are no meshes [2].
- **High R/X ratio of the lines.** The higher R/X ratio of distribution lines precludes the adoption of simplifications commonly used in transmission systems, such as neglecting line resistances because of the dominant reactances, and also hinders the use of decoupled state estimators.

- **High dimensionality.** Distribution networks are typically large, with a high number of nodes and branches. This aspect, along with the need for three-phase models, greatly increases the number of state variables and, consequently, the computational burden of the DSSEs. This hinders the use of well-established transmission system state estimators, such as the TSE.

Therefore, solving state estimation problems on distribution systems may require significantly higher computational efforts than on transmission systems. Alternatives to minimizing these efforts are using estimators that result in constant Jacobian and Gain matrices [15, 46, 47], and symmetrical components [25]. Additionally, utilities and operators may opt for topology simplification, multi-area (parallel) state estimation [1, 48], or focus only on particular areas and voltage levels of the distribution system under analysis [45].

3.3 *Sources of Uncertainty*

Distribution systems are usually designed to supply power under the assumption of unidirectional power flows from substations to customers. This paradigm simplifies the required monitoring and communication infrastructures [45]. Consequently, distribution systems typically present antiquated monitoring and automation, limiting the amount and reliability of the information available for state estimation, and adding uncertainties into the estimation process. This section discusses some sources of uncertainty that can negatively affect DSSE.

3.3.1 Network Parameters and Topology

The network data provided to the control center of a distribution utility usually comes from asset management and georeferenced databases [1]. Some parameters might change when maintenance crews repair lines, or when expansions and upgrades take place to host new customers; nonetheless, these updates are sometimes not inserted into the distribution network databases. Thus, it is a challenge to maintain an accurate network model, which significantly contributes to errors in state estimation.

Another difficult task is to ensure that the topology used for state estimation is the actual system's topology. This is because many equipment settings as switches, transformer tap ratios, protection equipment, and reactive elements, are typically unmonitored [45]. Furthermore, a distribution system can have frequent topology changes. Sometimes these changes are unknown or unreported to network operators and thus not inserted into the network databases. Topological errors on DSSE could result in severe deterioration of the estimates.

The uncertainties related to network parameters and topology can be minimized with upgrades in the monitoring and communication infrastructures of distribution systems, given that reasonable measurement redundancy levels enable parameter and topology estimations.

3.3.2 Pseudo-Measurements

Due to the typical low investments on the monitoring infrastructure of distribution systems, DSSE usually relies on pseudo-measurements. Moreover, even when a distribution system is designed to be completely observable, failures inherent to meters and communication medium can make the system momentarily unobservable. In these situations, pseudo-measurements represent backup information that can be used to replace real-time data.

However, as pseudo-measurements are usually based on statistical data, they are a great source of uncertainty in DSSE. Therefore, it is necessary to develop techniques to maximize pseudo-measurements accuracy. One way to do it is by deploying Advanced Metering Infrastructure (AMI) and using its data to generate accurate pseudo-measurements. Models based on machine learning have shown an improved accuracy of pseudo-measurements compared to the traditional statistical and probabilistic analysis models, taking advantage of both AMI data records and real-time samples [19].

3.4 Diversity of Measurement Types

Distribution systems comprise different voltage levels, from sub-transmission voltage to feeder voltage and down to delivery voltage on secondary systems [45]. Accordingly, measurement devices also vary between the voltage levels. Some networks may have phasor and SCADA measurements arrive at the control center periodically, while others may rely on AMI data or some combination of the three. Measurements provided by protection devices like reclosers can also be used. Thus, a challenge to DSSE remains in accommodating heterogeneous measurement types with various temporal resolutions and accuracies into a unified state estimator.

3.5 Tuning Measurement Weights

The objective of tuning measurement weights is to make that higher accuracy measurements are more influential on the estimates than those with lower accuracy. Although it seems simple, it is a difficult task in practical state estimation implementations [4].

Usually in state estimation, the inverse of the measurement variances (σ^2) is used as weight [44]. There are different forms to tune measurement weight [17]. A way is to assume that σ^2 is equal to a constant known value. Another way is to consider that

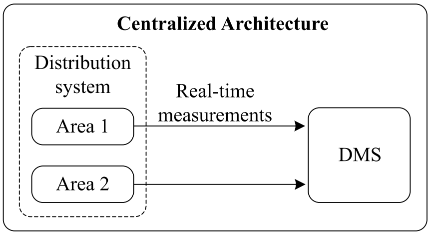

Fig. 9 Overview of the centralized architecture

σ^2 depends on the measured value. Different forms of tuning measurement weights will lead to different estimates. Therefore, comprehensive simulations considering the statistical analysis of the estimates should be performed to adjust measurement weights properly [23].

3.6 System Architecture

System architecture is a crucial aspect for DSSE. Depending on the architecture, the state estimation problem can be tackled with different requirements and performances. Therefore, the challenge is defining how the state estimators will have to be adapted to handle an extensive geographical area, and the massive amount of information provided by the heterogeneous measurement devices present in the envisioned ADNs.

The system architecture can be established according to a centralized or decentralized scheme [26, 29]. In the centralized scheme, all system areas send information to a central DMS, responsible for data collection, network data storage, running state estimators, integration of state estimation results of different areas, and ADN management and control. This scheme allows a more straightforward management of state estimation and DMS application functions, but requires considerable investments in communication infrastructure and computing power [29]. Figure 9 illustrates an overview of the centralized architecture.

In the decentralized scheme, all system areas have a Local Control Station (LCS) that collects local measurements, stores local network data, runs local state estimators, exchanges information with neighboring areas to integrate and improve the state estimation results, and, eventually, carries out control functions. Additionally, each area sends its estimates to the DMS, which concentrates only on coordination of local units, and ADN monitoring and supervisory tasks. Compared to the centralized scheme, the decentralized scheme requires less communication and computing power investments, at the expense of having a LCS in each area, and possibly inconsistent state estimation solution accuracies among different regions in some cases [48]. Figure 10 shows an overview of the decentralized architecture.

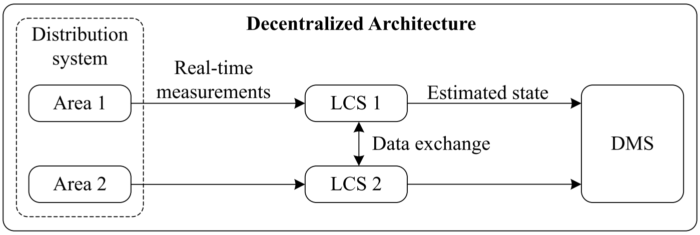

Fig. 10 Overview of the decentralized architecture

4 DSSE Applications for ADNs

By definition, ADNs must remotely and automatically manage their assets in an integrated and efficient way [13]. For that, generation dispatch, on-load tap changers, voltage regulators, reactive elements, and topology must be effectively managed to minimize the impacts of DERs and reduce the requirements for reinforcements while enhancing the distribution systems performance [49].

Advanced monitoring and communication infrastructures are required to make ADNs feasible. However, even in networks with properly planned monitoring and communication capabilities, incorrect measurements and communication failures are likely to occur. Therefore, the adoption of state estimation in ADNs is recommended to support system visibility and deal with the limitations inherent to monitoring and communication. DSSE can determine the most likely operating condition of an ADN, despite the errors in the measured quantities, communication failures or delays. Thus, it is prone to be the core of a DMS.

In this section, application functions of a DMS that can benefit from DSSE are briefly described. The focus is on how state estimators can be used to aid these functions. Indeed, all functions of ADNs that require the estimated state, both in normal or fault conditions, can benefit from state estimation.

In the following, the adoption of the DSSEs in Topology Estimation and Reconfiguration, Volt-VAr Control, Fault Location, Technical and Non-technical Losses Identification and Cyber Security are briefly discussed. Note that DSSEs can be used in these functions in several ways beyond it is discussed here.

4.1 Topology Estimation and Reconfiguration

State estimation applications are usually based on the assumption that the distribution system topology and parameters are perfectly known [44]. However, in practice, it is very common that the status of switching devices and transformer taps are unknown or, for some reason, the system parameters are under suspicion. In the presence of these errors, the state estimators will fail or provide bad estimates.

Several approaches to deal with errors in topology and parameters are based on state estimation concepts [2, 44]. At this point, the so-called Generalized State Estimator (GSE) deserves attention [35, 44]. In this approach, the status of switches is included as state variables. Given the basic topology, which means the way power system elements can be connected via switches, a set of switches whose status is under suspicion, and the measurements, the GSE can provide the bus voltages and the switches statuses. In addition to the status of the switches, the set of state variables can consist of voltages, currents, and powers in polar or rectangular coordinates. These approaches usually require significant changes in the state estimator [36]. Furthermore, their success depends on the number, location, and accuracy of the available measurements.

Alternatively, a simple trial and error search process can be adopted to check topology. In this case, the status of the suspect switches is changed in a driven way, and a state estimator is run. Then, the estimated residuals are compared to a threshold. Based on this threshold, the most likely status of switches can be defined [8]. In this case, changes in the state estimation equations are not required. However, this approach is very limited, and it is not adequate if there are many suspect switches. Additionally, the network topology can be determined by state estimation and optimization techniques [22, 57].

In general, the inclusion of parameters and status of switches as state variables in the generalized approaches increases the size of the involved matrices and the computational times required to run the state estimators. Therefore, modeling parameters and the status of switches as state variables must be carried out with parsimony.

4.2 Volt-VAr Control

The main objective of the Volt/VAr control is maintaining the power system's voltage profile within practical limits. To this end, given adequate monitoring and communication infrastructures, controllable Volt and VAr devices must be appropriately managed [30]. To manage these devices, in addition to an optimization tool comprising well-defined control rules, the knowledge of the operating condition of the distribution system is essential. Quantities as node voltages, load and generation forecasts, and the output from distributed generators are usually required.

Given the measurements, system topology, and parameters, the state estimator provides the estimates that describe the operating condition of the distribution system, as required by the Volt-VAr control. From these estimates and the control rules, the controllable Volt and VAr devices are set, and the system state is reestimated. In this case, the state estimators are used in their conventional modeling, as presented in Sect. 2.

The literature presents several Volt-VAr control approaches based on state estimation. For example, in [51], the Volt-VAr control runs in a closed loop every few minutes fitting the voltage profile within practical limits. In [9], a machine learning approach is applied to generate accurate pseudo-measurements to improve the DSSE results, used as inputs to a Volt and VAr control function based on well-established control rules.

4.3 Fault Location

Interruptions in energy supply are commonly associated with electrical faults. These faults are mainly due to severe weather conditions, contact with animals, equipment malfunction, human accidents, falling trees, etc. Thus, faults in distribution systems are among the main causes of power quality deterioration. In this context, the need for fast and accurate fault location approaches is crucial to utilities once they impact the quality of the services.

The main idea behind the fault location approaches based on state estimation is to check the fitting between measurements and the faulted distribution system. Depending on the fault type, the faulted distribution system will contain one or more resistances connecting the fault location to the ground. Since the fault location is unknown a priory, the fault location is a search process. The faulted distribution system is formed assuming the fault occurs at a given bus or branch. This faulted topology, the system parameters, and the available measurements are the input for the state estimator. From the estimates, indices such as $J(\boldsymbol{x})$ or the normalized residuals can be used to quantify the fitting between measurements and the faulted distribution system [12, 33]. This procedure is repeated for all suspect buses and branches. Search techniques can be applied to minimize the number of state estimation runs and, thus, the computational times.

Depending on the available measurements, the DSSE can be linear or nonlinear. For instance, if the monitoring system is composed exclusively of Phasor Measurements Units (PMUs), a linear (non-iterative) state estimator is enabled. Otherwise, a nonlinear DSSE can be successfully applied. Different from the remaining applications, in this case, the DSSE is used to a faulted system. In this scenario, it is possible to find very low voltages and high currents, hindering the state estimation convergence. Nevertheless, the literature indicates that with proper implementation, the DSSEs can provide adequate performance.

4.4 Technical and Non-technical Loss Identification

In power distribution systems, losses are the difference between the energy purchased by the utility and that sold to customers. Losses can be classified as technical or non-technical. Technical losses are inherent to the network elements. They can be reduced, for instance, by using more efficient equipment, changing the network topology, or adopting demand response techniques.

Non-technical losses are mainly due to theft and fraud, but also to default, reading, measurement, and billing errors. The energy that is intentionally diverted by theft or fraud is vital. The term detection refers to the act of becoming aware of non-technical losses. The term identification is used to pinpoint the customer where the issue occurs.

Literature shows approaches based on DSSEs to detect and identify non-technical losses [32, 42, 50, 56, 58]. The most used idea behind these approaches is to treat non-technical losses as gross errors in measurements. Consequently, these approaches are highly dependent on the number, location, and type of measurements. To be successfully applied, the gross error detection and identification techniques require redundant measurement sets without critical measurements and critical sets [44]. In general, the state estimators are used as presented in Sect. 2, and changes in the basic formulations are not required.

Literature also presents hybrid techniques, based on state estimation and machine learning approaches. For example, in [58], a state estimator is used to filter errors in measurements. Then, estimated error-free quantities are used as inputs to classification methods that identify non-technical losses.

4.5 Cyber Security

ANDs require advanced monitoring and communication infrastructures to remotely and automatically manage distribution systems' assets. Due to vulnerabilities inherent to these technologies, ADNs are exposed to cyber-attacks [20]. These attacks can alter and manipulate measurements, parameters, and topologies, threatening the security and proper functioning of the DSSE and the stable operation of the distribution system.

Cyber-attacks can be witnessed when inconsistencies among measured values, parameters, topology, and estimates are detected and identified. Different types of cyber-attack reported in the literature are: false data injection, topology attack, and eavesdropping [18]. In the false data injection scenario, an attacker with knowledge of a distribution system's information manipulates the measured values of certain metering devices [20, 38, 40, 59]. In a topology attack, the attackers tend to maliciously modify the system topology changing the branch switch on/off status [10, 39]. Eavesdropping defines a situation where an unauthorized party seeks to collect data from the system by accessing the communication infrastructure, compromising data privacy, and user confidentiality [37].

Depending on the nature of the cyber-attacks, DSSEs can be used to check topology, parameters, or gross errors in measurements. For instance, sudden changes maliciously caused in the network topology can be identified using topology estimation via generalized state estimation. Techniques for gross error detection and identification can also help to identify malicious manipulations on the measured values. It is important to note that the success of using DSSEs against cyber-attacks is related to the redundancy and quality of the measured quantities.

5 Conclusion

By definition, Active Distribution Networks (ADNs) should remotely and automatically manage the network assets in an integrated and efficient way. Therefore, advanced monitoring and communication infrastructures are fundamental to make ADNs feasible. However, even with adequate monitoring and communication infrastructures, incorrect measurements and communication failures are prone to occur. Thus, the adoption of a state estimator in the Distribution Management System (DMS) of an ADN is strongly recommended. Distribution System State Estimation (DSSE) can cope with errors in the measured quantities and communication failures and delays, providing the most likely state of an ADN.

This chapter presents four DSSE approaches well-consolidated in the literature. The main differences among the approaches reside in the choice of the state variables and on how the measurements are accommodated. Additionally, the following aspects should be highlighted:

1. In the Traditional State Estimator (TSE), the Jacobian and Gain matrices need to be updated at each iteration of the state estimation process. This procedure may require a great deal of computational effort in practical DSSE applications. The nonlinear nature of the equations relating state variables and measurements in TSE's model increases its implementation complexity.
2. Both the Admittance Matrix Based (AMBSE) and Branch Current Based (BCBSE) state estimators present significant improvements over the TSE in terms of execution time and implementation complexity. Their Jacobian and Gain matrices are constant and simpler to build in comparison to the TSE. Furthermore, their convergence features are very similar.
3. In the Symmetrical Components Based State Estimator (SCBSE), a three-phase untransposed distribution system is decoupled into three single-phase sequence networks. The sequence networks are solved using single-phase AMBSEs. This procedure significantly expedites the DSSE process, simplifies implementation complexity, and allows parallel running implementations.

Despite the features highlighted above, the choice for the better state estimation approach in ADNs requires further studies and considerations of the particular characteristics of the scenario where the DSSE will be applied. Moreover, literature presents less widespread approaches that may be more appropriate for specific ADN applications.

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DC Microgrids for Ancillary Services Provision

Filipe Perez, Gilney Damm, and Paulo Ribeiro

Abstract This chapter is dedicated to DC Microgrid's application to provide ancillary services to weak AC grids. In particular, control algorithms are designed to provide inertial, frequency and voltage support for weak grids, such as AC Microgrids composed mainly by sources interfaced by power converters, with a small portion of diesel generators. A number of synthetic inertia approaches are introduced to improve the stability properties of an AC grid face to strong variations on loads and productions, brought by electric vehicles and possibly other renewable energy sources. The power electronic issues related to control interactions and poor inertial response are described, where suitable solution is addressed. The power converter is driven as a Virtual Synchronous Machine (VSM), where the control strategy follows classical swing equation, such that the converter emulates a synchronous generator, including inertial support. This strategy can be exploited in low inertia systems with high penetration of renewables. An application example illustrates the performance of the Microgrid in the context of virtual inertia control.

Keywords DC Microgrids · Virtual inertia · Power system stability · Low inertia systems · Inertial support · Frequency regulation · Energy storage systems

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1 Introduction

Direct Current (DC) Microgrids are attracting interest thanks to their ability to easily integrate modern loads, renewable sources, Energy Storage Systems (ESS) and Distributed Energy Resources (DER) in general [1, 2]. They also acknowledge the fact that most renewable energy sources and storage systems use DC energy (as Photovoltaic Panels (PV), wind power, batteries and even electric vehicles for example), and allow the reduction of the number of power converters in the grid with simpler topology. By doing this, they increase energy efficiency, and allow faster control of the grid [3–5].

DC Microgrids are generally fully composed of DC/DC or AC/DC converters to adapt to the system's voltage level. Commonly, a DC bus operates as the main interconnection link, where power flow control is performed to balance the energy of the system. The devices of the Microgrid are integrated in the DC link to share power, where distributed generators inject the produced power, the load demand is supplied and the storage elements can absorb the power mismatch. The main target here is to control the DC bus voltage to ensure proper operation of the system, since fluctuations, ripples and deviation in the voltage amplitude may cause a collapse, harming the overall operation of the system. Also, DC/DC converters are used to interconnect buses with different voltage levels, so the devices are inserted according to their voltage level. Therefore, sensitive loads can be properly supplied through a specific bus with multiple DC links configuration [6, 7].

On the other hand, the connection of a large number of power converters may lead to stability problems, since the converters can act as a Constant Power Load (CPL), which introduces negative impedance into the system. The effect of the negative impedance reduces significantly the stability margins and the operating region of the entire system. Therefore, standard control techniques, as droop controllers and linear Proportional Integral (PI) controllers, are very limited to attain stability in this case, and different solutions must be achieved to improve the operation of this type of system. The nonlinear control can be introduced as a powerful tool to develop improved controllers, that are robust enough to keep safe operation in a wide operating region. Nonlinear control technique can easily suppress the negative impedance term and insert a stabilizing dynamic through feedback process, when the variables of the system are known [8, 9].

In this context, [10, 11] present a survey on the most relevant features of DC Microgrids, and it is summarized as follows:

1. The reduced number of converters between sources and loads improve efficiency and decrease losses.
2. A number of system variables are eliminated, such as frequency, reactive power, power factor and synchronization.
3. The system is more robust against voltage sags and blackouts, since they have fault ride trough capability from voltage control of the power converter and the energy stored in the DC bus capacitor.

4. DC distribution is not the standard shape and need to be built in parallel to the conventional AC distribution system.
5. The system protection is harmed, since zero cross detection is non-existent.
6. The power electronic loads and DC motors are easily integrated in DC systems, but there are a number of loads that must be adapted for DC power supply.
7. The absence of transformers reduces losses and inrush currents.
8. Voltage stability is directly affected by power flow control.

In the following, some examples of Microgrid studies are mentioned to highlight the possible solutions and improvements in Microgrid topic.

A complete nonlinear model of a DC distribution system driven by PI cascaded droop-based controllers including a damping factor is developed in [12], where a nonlinear stability analysis is conducted using Lyapunov techniques. Also, small signal stability studies are introduced as in [13], where different DC loads and a supercapacitor compose the DC network of aircrafts. Then, a large-signal-stabilizing study is proposed to ensure global stability by generating proper stabilizing power references for the whole system. In [14], a simplified model of a small DC Microgrid under droop control is addressed to reduce the complexity of the nonlinear stability analysis, which is based on bifurcation theory, and a relation among grid parameters is provided. Several strategies for stability analysis and stabilization techniques for DC Microgrids are presented in [4] and in [15].

In [16], a nonlinear distributed local control is proposed to interconnect a number of elements in a DC Microgrid. The Microgrid is composed of different time-scale's storage elements, like batteries and supercapacitors that are used to improve the system operation. A stability analysis of the proposed control strategy is conducted considering the system as a whole and its physical limitations. The proposed scheme can easily be scalable to a much larger number of elements and a comparison with standard linear controllers is also carried out. In this way, the control performance of the system is presented towards interconnected disturbances from loads and PV variations. The robustness of the proposed control is highlighted when compared with linear control. Subsequently, a power management controller to ensure power balance and grid stability of the DC Microgrid is designed in [17]. The secondary control scheme, based on Model Predictive Control (MPC), is developed to optimize the operation of the DC Microgrid in long term, considering weather forecasts and load demand profile. In this case, the power balance and the DC bus voltage regulation are considered as constraints.

Therefore, in [18], the connection with the main AC grid is carried out considering the stability of the Microgrid DC bus, still applying nonlinear control techniques. Afterwards, in [19], a more favorable power converter configuration is proposed to improve the electrical scheme of the DC Microgrid. A dynamical feedback controller is designed to reduce the complexity of the stability analysis and simplify previous controller design keeping the stability properties. And finally, a nonlinear control scheme to integrate regenerative braking from a train line is proposed in [20]. In this case, the DC bus stability is also taken into account, where the power surges from braking periods are considered as disturbances. The proposed controller must be able to properly operate regarding various disturbances in the network.

Ancillary services using DC Microgrid is carried out in [21, 22], where the available power on the DC side of the Microgrid is used to supply the AC side of the grid appropriately, ensuring voltage limits within grid requirements. Therefore, the power quality of the main grid is improved.

Relating the different applications of power electronics in power systems, High Voltage Direct Current (HVDC) transmission, Multi-Terminal Direct Current (MTDC) and Modular Multilevel Converter (MMC) [23–25] results can be adapted for DC Microgrids application, because of the following reasons: they have similar power converter configuration, differentiated only by their size and power value; the electrical model and dynamics of the system are similar; the perturbations' properties can be easily compared to each other; the control schemes are compatible, besides the gain tuning.

The main challenge in the operation of Microgrids is to maintain a safe operation of the system, balancing generation and demand, where the optimal management of the system can be done through heuristic algorithms or intelligent control. The Microgrid operation address different energy scenarios, where generation excess/deficit is minimized through optimization methods composed of cost functions. However, the open-loop feature of optimization systems does not allow to compensate uncertainties and disturbances. Therefore, MPC closed-loop feature allows corrective actions using measurements to update the optimization problem, which ensures the optimal operation of the system [26, 27].

The hierarchical control structure of Microgrids performs the separation of the variables according to time-scales, therefore variables with close time responses are controlled in the same control level. Hierarchical control are typically composed of three different levels: primary, secondary and tertiary level. Primary control deals with the stability of currents and voltages at the transient level, on a time-scale from milliseconds to seconds. The secondary control performs the control of power and energy of the system through optimization techniques in minutes to hours. The tertiary control deals with strategic dispatches, according to an energy market or human factors, in the range of hours or days [28, 29]. A general scheme of a Microgrid is presented in Fig. 1, where the Microgrid central control contains the hierarchical structure to optimal operation of the entire system.

1.1 Droop Control Strategy

Droop control strategy traditionally applied in AC Microgrids is also widely applied in DC Microgrids for power sharing purposes. This simple strategy is based on the linearized behavior of the system power flow around a operation point. The output power/current can be used as the droop feedback. In the Power-based droop, the DC bus voltage reference is given by the power variation in the grid according to the droop coefficient [14, 30, 31].

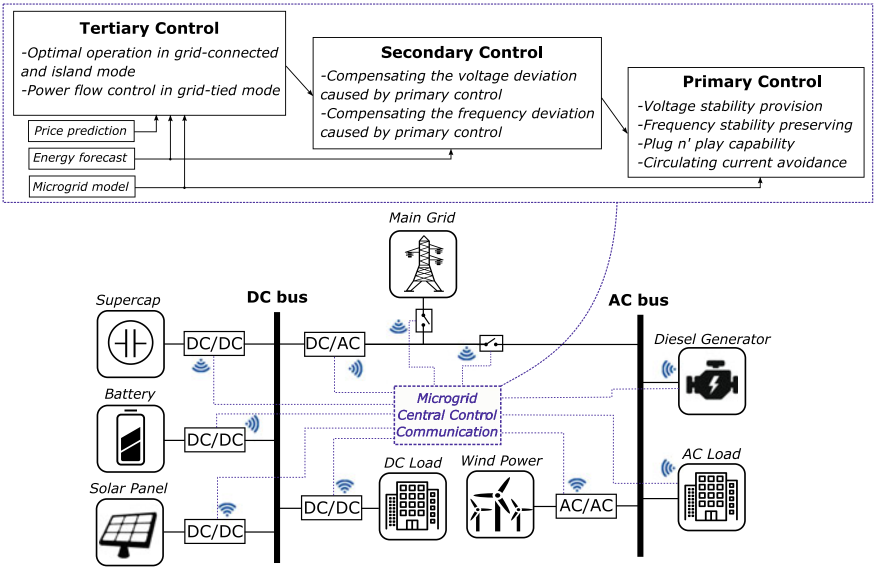

Fig. 1 A Microgrid composed of central control with hierarchical structure

$$V_{DC,ref} = V_{DC}^{*} - m_p P_{out} \tag{1}$$

where $V_{DC,ref}$ is the voltage reference value for the given operation condition, V_{DC}^{*} is the rated DC voltage value. m_p is the droop coefficient and P_{out} is the power output.

In the Current-based droop, the DC bus voltage is the control output, given by the droop coefficient and the current in the converter.

$$V_{DC,ref} = V_{DC}^{*} - m_i I_{out} \tag{2}$$

here, $V_{DC,ref}$ is given by the droop relation according to the current output I_{out}. m_i is the droop coefficient, which can be interpreted as a virtual internal resistance. A general control scheme of the conventional droop control is introduced in Fig. 2 according with [3].

The droop strategy is associated as an adaptive voltage positioning and the droop coefficients have a direct effect over system stability and power sharing accuracy. Higher droop coefficients may bring better sharing accuracy and damped response, but a commitment must be made not to cause major voltage deviations. Besides that, the droop coefficient can change the power sharing of the generation units.

An extension of conventional droop control is to introduce adaptive feature for droop control, where the droop coefficients become time varying ($m_p(t)$ and $m_i(t)$), and can change according to a specific strategy. The adaptive calculation of droop control can consider the State-of-Charge (SOC) of the ESS or other strong perturbations related to power injection and load demand. With the dynamic adjustment

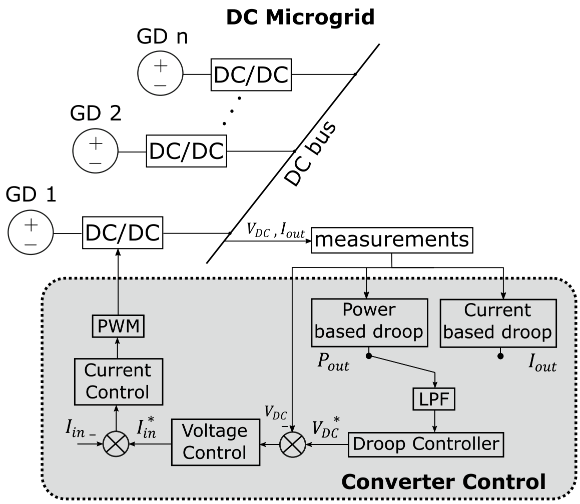

Fig. 2 Conventional droop control scheme for multiple generations units in a DC Microgrid

of the coefficients, the operation of the system and power sharing is improved. This approach also reduces the effects of the line impedance and also reduce line losses, but the control parameterization is too complex [31].

1.2 Power System Problems

Historically, power systems were based on synchronous machines rotating in synchronism, sharing power to supply the load, and providing natural inertia (frequency response) following disturbances or simply changes on operating conditions. This classical scheme is less and less true, because of the large penetration of power electronic devices like power converters and modern loads.

Power converters are inherent to the interconnection of renewable energy sources and storage units as mentioned before, but also by the HVDC lines that are being built to reinforce current transmission systems. For this reason, inertia is reducing fast, and in some situations, there are grids mostly composed of power converters where the frequency reference is completely lost [32–34]. This situation is a change of paradigm from the classic electric grid, and power systems practitioners are struggling to keep the grid running. A recent example of such situation is the 9 august 2019 black-out in the United Kingdon [35], where arguably the main cause was the reduction of inertia, and its effect in several power converters interconnecting distributed generation.

Distributed generation are mostly formed by renewable energy sources, which have power electronics interface. And so, the power converters do not have an inertial response due to the absence of a rotating mass, as conventional synchronous generators do. Power converters are unable to naturally respond to load change. Consequently, the frequency response worsens, causing oscillations and operating margins problems. Thus, the integration of renewables has a direct relationship with the reduction of inertia in power systems.

The inherent features for systems mainly composed of power converters are:

1. Fast response;
2. Lack of inertia;
3. Harmonic issues;
4. Interaction between controls;
5. Weak overload capacity.

The converter dominated grid is emerging from a traditional generator dominated grid, therefore the lack of inertia is becoming a main issue of concern. The grid modernization through power electronics advancements is a trend research topic in power systems related to Smart Grids. In this way, energy storage is required to balance generation and consumption in this kind of system, specially for strong variations on load or generation, when compared to the case of rotating mass reserve (inertia) and damping winding in traditional synchronous machines that buffer the strong oscillations maintaining the system's stability.

2 Ancillary Services in Brazil

The main responsibility of a Transmission System Operator (TSO) is to provide electric power from generators to the consumers through transmission lines meeting the standardized network requirements (*grid codes* - obligations of control areas and transmitting utilities) to maintain the proper and reliable operation of the system interconnection. In this context, the specific services and functions provided to maintain and support the power supply in the grid are called ancillary services. Ancillary services support the grid to maintain continuous and reliable operation of the system, properly supplying the loads while keeping stability and security. Traditionally, ancillary services are provided by generators controlled by the TSO, however the integration of power electronic based equipment in the network expanded the possibility of ancillary services provision. Therefore, power electronic devices and generators non-controlled by the TSO are now able to participate on the support to the grid in several operation modes, which has created a new opportunity in the energy market [36–38].

The ancillary services provision in Brazil is still very limited because of regulation aspects and restricted to the generation units controlled by the TSO (composed of hydroelectric and thermoelectric plants). There are some generation units able to operate as synchronous compensators, which provide reactive power compensation through a formal contract with the national TSO. These are centralized thermoelectric plants used as operational power reserves. Therefore, power plants non-controlled by the TSO cannot perform ancillary services, which greatly restrict these services in Brazil [39–41].

According to [40], the ancillary services' provision in Brazil includes the following supports: (a) Primary frequency control, performed by all generating units integrating the national electrical grid; (b) Secondary frequency control, where only the plants that are part of the Automatic Generation Control, requested by the TSO participate; (c) Reactive power support, performed by generation units integrating the network and by plants that operate as synchronous compensators, under prior authorization from the National Electrical Energy Agency (ANEEL); (d) Black-start, performed by all generation units integrating the network and by plants in compliance with ANEEL, and on demand from the TSO; (e) Complementary power reserve dispatch, performed by centrally dispatched thermoelectric plants.

In this context, the report in [41] proposes a normative review for ancillary services provision based on the reduction of the regularization of the reservoirs of hydroelectric power plants and the high penetration of intermittent renewable sources. It is also proposed to encourage the expansion of existing services (mentioned above) and the insertion of new services such as:

1. Development of new services for reactive power compensation using photovoltaic plants, reactive power support for wind power plants and even in the distribution system;
2. Inertia as an ancillary service through power electronics equipment, aiming at reducing the connection of thermal plants;
3. Load modulation by distribution agents, performed through the dispatching of power plants not operated by the national operator, but by the local distributor;
4. Paying for ancillary service provision: payment through ancillary services' charges by bilateral negotiation between consumer and the provider, raising the need for the development of an ancillary services market.

Thus, in the Brazilian scenario, there are still many barriers to the diversification of ancillary services provision, being restricted to large generation units controlled by the TSO. Also, technological adaptation costs and equipment deterioration costs combined with massive insertion of power electronics' devices and communication equipment make the valuation of ancillary service provision quite complex.

3 Power Converter Issues

As explained above, recent grid evolution has brought the integration of renewable energy sources, ESS and loads based on power electronics. But these power converters have different behavior than synchronous machines. Synchronous machines have an inherent energy storage from their rotational mass,[1] being able to naturally respond to a load disturbance contributing to system stability, while power converters are directly affected by their controllers with fast response and very low natural

[1] Synchronous generators store kinetic energy proportional to moment of inertia J and the square of their angular speed, with time response of few seconds.

energy stored.[2] Therefore, power converters do not have the natural ability to contribute to frequency stability in the active power sense [42, 43].

In Microgrids context, power converters use the measured voltage of the network to estimate the phase angle of the grid, being able to synchronize with the main grid to generate the voltage output, i.e., grid-following converters. The main issue related to power converters in Microgrids is the difficulty to implement isolated operation called as grid-forming converters. Grid-forming converters are a great concern in academia and industry, where numerous studies have been carried out to develop useful strategies to proper operate electrical grids only composed of power electronics technologies. In this context, droop control has been widely applied, since it allows power share among power converters with a distributed control approach.

A crucial issue in power electronics technology is the lack of inertia and interactions between control as stated by the United Kingdom Transmission System in [44]. In fact, the high penetration of power electronics based technologies decrease the inertia of the system, bringing frequency stability problems and reduction of transient stability margins.

The AC/DC power converters like Voltage Source Converters (VSC) are mostly controlled by Pulse-Width Modulation (PWM) and traditional control schemes in grid-following operation make these converters behave as current sources.[3] The Phased-Locked Loop (PLL) is used to synchronize the converter with the grid by estimating the phase angle of the network, where the calculation of the voltage reference depends on the grid impedance. Therefore, the control performance is affected by grid impedance, which makes these control schemes sensitive to grid condition. So, it is necessary to design a good interaction between the PLL, voltage and current control loops, PWM switching frequency and the output filter. The match of controllers' bandwidth can be a very complex task. Usually, current control loop bandwidth is tuned twenty times smaller than the PWM frequency and filter frequency is designed accordingly [45, 46].

Other important issues can be related to power electronics in power systems, where countries in Europe are dealing as priorities [47]:

1. Decrease of inertia, related to frequency stability;
2. Wrong participation of power converters devices in frequency regulation (control errors);
3. Reduction of transient stability margins due to decreased short-circuit capacity of power converters
4. Resonance and oscillations caused by power electronics;
5. Power electronics controller interaction among the devices (active and passive) in the grid.

In this scenario, new ancillary services and grid support are needed to fulfill the stability requirements for power system operation and reliability. A suitable solution

[2] The capacitors of power converters can store electrostatic energy in order of units to hundreds of milliseconds.

[3] Usually, VSC have outer voltage control loop and an inner control loop, which is the current control loop.

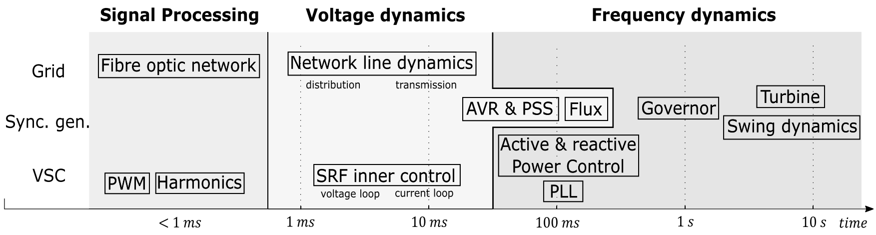

Fig. 3 Time-scale separation of power system dynamics considering conventional synchronous generators and power converters integration

is to develop new control strategies for power converters changing the original feature of power converters to provide ancillary services to the network and reduce the power electronics impacts [48].

Traditional power systems composed of synchronous generators have a well established time-scale separation considering the dynamics of the system. Usually, the time constant for frequency and voltage regulation are related to slow dynamics of turbines (about 10 s) and governors (about 1 s), compared with faster dynamics of the exciter (about 50ms), which can deal with the network line dynamics (time constants about 1–30 ms). Besides that, the time constant of the swing equation and flux linkages will be given by the flux and swing dynamics. So, in conventional systems, the controllers are typically designed considering its operational margins and can assure the stability of the whole system. However, in low inertia systems, the fast dynamics of power converter-based generation bring interactions among different controllers, affecting the time-scale separation and increasing complexity [49].

The time-scale separation of power systems including power converter-based generation and the dynamics feature of low inertia are introduced in Fig. 3, adapted from [49]. It is presented the physical and control dynamics, considering three different time-scales: signal processing, voltage dynamics and frequency dynamics. The voltage and frequency dynamics are related to the controllers designed for these purposes. The signal processing is associated to the fastest interactions (<1 ms), which may include PWM signals and harmonics from converters, and fiber optics network communication. Then, the voltage dynamics are associated with larger range timescale interactions (>1 ms to <100 ms), which includes the network line dynamics, Automatic Voltage Regulator (AVR), Power System Stabilizer (PSS), linkage flux dynamics of synchronous machines, and the Synchronous Reference Frame (SRF) inner control loops of converters. The frequency dynamics are associated with the slowest interactions (>10 ms to 10 s), including the Active and Reactive Power Control, PLL of power converters, Governors, Turbine and swing dynamics of synchronous machines [49–51].

In this sense, the controllers and Low-Pass Filter (LPF) of power converters have faster dynamics than synchronous generator controllers, resulting in control interactions and causing stability issues, since they have different time constants as shown in Fig. 3. So, power converters can potentially impact in the frequency regulation in low inertia systems, affecting frequency dynamics and the associated fast transients. The result is the deterioration of protection schemes that consider the limitation of frequency Nadir[4] and Rate of Change of Frequency (RoCoF) due to incompatible control strategies interacting with the main grid under high penetration of power electronic-based generators. The transmission line dynamics also interact with the dynamics of power converters' controllers, where the fast behavior of these dynamics can amplify the interactions. Therefore, when the X/R impedance ratio is high enough, the time constant of the line is able to suppress the gap between faster dynamics of power converters and slow dynamics of synchronous generators, acting as a buffer, improving the system stability. However, in distribution lines, the lower X/R relation restricts the operation and control of voltage and frequency, hindering system's stability. In this case, virtual impedance application may be a feasible solution for these stability issues.

3.1 Inertial Response and Low Inertia Issues

Since power converters' based generation is not able to provide natural frequency support (sub-second and primary controls), the reliability of renewable generators and Microgrids can be dramatically reduced. Consequently, the frequency response of the system as a whole can be affected, which is an European concern [45].

A reduced inertia may cause higher frequency excursions during and after a contingency and also increase the RoCoF. RoCoF is used to indicate load disconnections (Load Shed) and in protection schemes to detect the disconnection of generation units. Therefore, faster frequency ancillary services, inertial response emulation and increase of grid code requirements for RoCoF were proposed by [52, 53].

The active power response for a system with inertia (natural or virtual) depends on its inertial constant (H) and the derivative of frequency as:

$$\Delta P_{p.u.} = -\frac{2H}{f_0}\frac{df}{dt} \tag{3}$$

where f is the measured frequency and f_0 is the nominal grid frequency.

The inertial power variation ($\Delta P_{p.u.}$) is proportional to the RoCoF, then its maximum is just after a frequency disturbance and it goes to zero when a new equilibrium point is reached. Let us consider a disturbance like a load increase (or generation loss) in a power system with primary reserve used to hold the frequency drop. The behavior of frequency deviation and the inertial power variation are depicted in Fig. 4 from [47]. In this case, the frequency Nadir is reduced when the inertial support takes place, which means that inertial power helps to improve frequency variations.

This is a natural response of synchronous machines, but power electronics devices may mimic this phenomenon as a virtual inertia approach. The synthetic inertial

[4] Frequency Nadir is defined as the minimum value of frequency reached during the transient period.

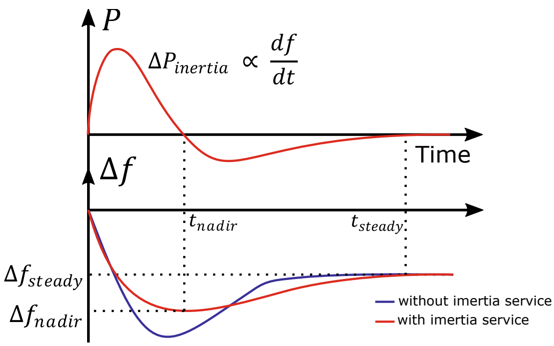

Fig. 4 Inertial response scheme with a primary control

response after a contingency can be a very good solution to systems presenting lack of inertia due to power electronics interfaced connections, since it results in an equivalent behavior of synchronous machines. The main difficulty in this process is to measure the frequency, when it is not possible to use the angular velocity of a synchronous machine (Power converters based grids). Therefore, the PLL can be used for frequency measurement in this case.

3.2 Frequency Problems in Weak Power Systems

Frequency stability issues caused by power converters have stronger impacts in weak grids and Microgrids, since they already have small inertia constants. Anyhow, reduction of system's inertia affects frequency deviations even in strong grids, since the arrival of renewables. The Electricity Reliability Council of Texas (ERCOT) has reported a continuous decline in the inertial response of its system and recommends additional inertial response [54]. Also, the European Network of Transmission System Operators for Electricity (ENTSO-E) has reported frequency violations growth related to large renewable integration in the grid [55]. So, frequency problems have a straight relation to renewables penetration and power converters based grids.

Frequency limits are imposed by TSOs, and these limits are well defined in grid codes. For example, the IEEE recommends a tight frequency operating standard of ±0.036 Hz for grid-connected systems, but for off-grid operation in Microgrids and isolated systems, the limits are redefined to fit limitations of this kind of operation. In the North American Reliability Corporation (NERC) the recommendation is to start load shedding when the frequency drops bellow 59.3 Hz to re-balance the system.[5] For variations lower than 57 Hz or higher than 61.8 Hz, the NERC recommendation is to disconnect generators units. To highlight the regulatory differences between grid-connected and isolated modes, Table 1 is introduced from [56]. Generally speaking, the limits for island mode are relaxed compared with grid-connected mode, allowing

[5] Nominal frequency in this case is 60 Hz.

Table 1 Microgrid operation standard for frequency levels

Grid-connected	Island mode
Frequency: main grid task	Freq. primary controller by VSC
Small number of critical deviation	Low inertia with critical deviations
IEEE	**ISO 8528-5**
Recommended range: ±0.036 Hz	Nominal range: ±1.5 Hz
NERC	Critical range: ± 9 Hz
Freq. <59.3 load shedding	Recovery time: 10 s
Freq. <57 or >61.8 disconnect generator	Maximum RoCoF: 0.6 Hz/s
EN50160	
49.5–50.5 Hz for 95% of a week	
47–52 Hz for 100% of a week	

variations of ± 1.5Hz in frequency, and up to ±9 Hz for critical periods according to ISO 8528-5 standard, which provides a guideline for frequency in off-grid context.

4 Virtual Inertia and Inertial Support

Virtual or synthetic inertia consists in emulate in power electronic devices the energy stored in rotational mass (inertia) of synchronous generators, such that the power converter is able to have natural frequency response. The definition of Synthetic Inertia from [55] is:

"A facility provided by a Power Park Module or HVDC System to replace the effect of Inertia of a Synchronous Power Generating Module to a prescribed level of performance."

The concept of virtual inertia implementation through power converters has first appeared in [57]. The synchronverter concept was then developed [58], subsequently called as Virtual Synchronous Machine (VSM)[6] in [59]. These are composed by power converters that mimic or behave like synchronous machines. In this way, it is much easier to integrate such systems to the power network, providing a framework that practitioners are well acquainted with [56, 60, 61]. These VSMs have raised much interest in recent years and have been widely applied to improve frequency stability and to provide inertial support in weak grids and Microgrids [62–64].

Virtual inertia uses a combination of control strategies, Distributed Energy Resources (DER), as renewables and storage systems, and power converters to emulate the inertia of conventional synchronous machines. The control algorithm for

[6] Note that VSM is said as the VSC operating as a synchronous machine.

virtual inertia approach can be implemented in a power converter, where the mathematical equations describing the inertial response are used to synthesise the control signal sent to the converter. Therefore, power converters become capital devices able to emulate inertia based on a control scheme. PV's and ESS with VSC converters (inverters), wind turbines with back-to-back converters and even HVDC links with multilevel converters can apply the virtual inertia approach to contribute with inertial response for the grid. The key element to emulate inertia in this case is the available energy from DER to proper inject power following inertial feature [43, 56, 65].

VSM reproduces the dynamic properties of a real synchronous generator in a power electronic unit, in order to achieve the inherent advantages of a synchronous machine for stability improvement. It can be applied in either strong grids on power converters based integration or in Microgrids.

The inertial response of a typical power system is given in less than ten seconds duration, where the synthetic inertia approach provides its contribution to improve system stability. The frequency Nadir can be greatly reduced along with high RoCoF thanks to inertial behavior created by this approach. Virtual inertia features can also improve the governor response, highlighting its contribution to primary control in general. Therefore, virtual inertia must operate in a short time range in autonomous way like inertial response from synchronous generators. The advantage here is that the inertial time response (H) can be adjusted as needed,[7] and even can become a state variable to behave, such that, frequency stability is improved.

4.1 Virtual Inertia Topologies

The basic concepts of virtual inertia in the literature are quite similar, even because as shown above, its definition is related to its effect and not to the means to obtain it. Hence, there are various topologies distinguished by their model and implementation strategy. A topology may mimic the exact behavior of a synchronous machine, by applying the mathematical model of such machine, while other approaches applies directly the swing equation of synchronous machines to simplify the implementation on power converters, and yet others incorporate a responsive DER to respond to frequency changes. Next, the main topologies described in literature are discussed.

4.1.1 Synchronverter

Synchronverters developed in [58] are based on the dynamical equations of synchronous machines from the network point-of-view. Such control strategy allows a traditional operation of the power system without major changes in the operational infrastructure. The electrical torque (T_e), terminal voltage (e) and reactive power (Q) result from the equations written in the converter such that, a synchronous generator

[7] The comparison can also be done with moment of inertia J.

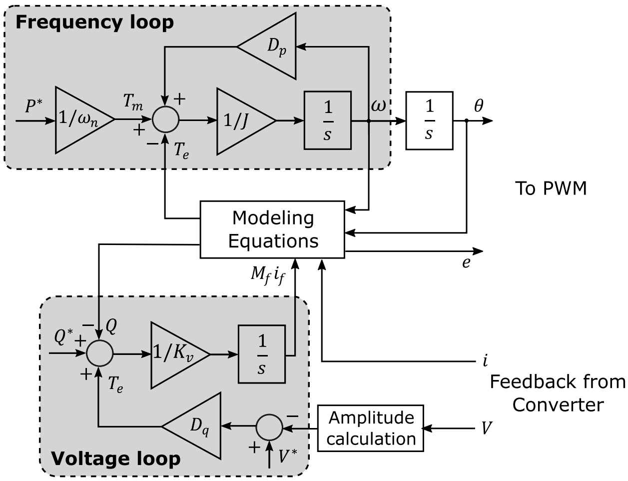

Fig. 5 Control diagram of a synchronverter

behavior is captured. A frequency droop strategy is applied to regulate the output power from the converter. The equations to model the synchronverter are:

$$T_e = M_f i_f i_g \sin\theta \tag{4}$$

$$e = \dot{\theta} M_f i_f \sin\theta \tag{5}$$

$$Q = -\dot{\theta} M_f i_f i_g \cos\theta \tag{6}$$

where M_f is the magnitude of the mutual inductance between the field coil and the stator coil, i_f is the field excitation current, θ is the angle between the rotor axis and one of the phases of the stator winding, and i_g is the stator current.

Figure 5 presents the block diagram of the proposed control scheme of a synchronverter presented in [58], where i and v are the current and voltage feedback used to solve the equation within the controller. J is the moment of inertia and D_p is the damping factor, which are arbitrary control parameters used to impose desired dynamic behaviour. The design of these parameters is intrinsically related to the stability properties of the system and will dictate the RoCoF, frequency Nadir and power injection limits to keep the grid requirements.

The frequency and the voltage loops are used to generate the control inputs: mechanical torque T_m, given by the active power reference P^* from the swing equation and excitation variable $M_f i_f$, given by the desired voltage amplitude in the terminal v^* and the reactive power reference Q^* from the droop strategy. The voltage loop have a droop constant D_q, where the measured reactive power is compared to its reference (Q^*). The resulted signal is then integrated with a gain K_v to eliminate steady-state error, resulting in $M_f i_f$. With $M_f i_f$, it is possible to generate e, which is the first control output for the converter related to the modulation index (voltage amplitude regulation). A virtual angular frequency is generated (ω) from the swing equation loop, hence its integral θ can be calculated to be the reference for PWM, which is the second control output of the converter related to power injection.

In the synchronverter topology, PLL is only used for initial synchronization and frequency measurement purposes, since the frequency loop from swing equation generates a natural ability to attain synchronism with the terminal voltage. A self-synchronized version of this approach is introduced in [66], greatly improving the stability performance, because PLL application may lead to instabilities in weak grids. In the synchronverter topology, the frequency derivative is not necessary for the control implementation, which is a great advantage since frequency derivative computation may bring noise and poor control performance. Another great advantage is the fact that voltage source implementation allows grid-forming operation for isolated systems. Synchronous motors can also be obtained when this topology is applied to the power electronic based loads (rectifiers), helping with inertial response in the load side [67]. Concluding, synchronverters is seen as a great solution for power converters based application in power systems to improve system's stability.

4.1.2 ISE Topology

The ISE lab topology is based on the swing equation of a synchronous machine, where the power-frequency relation is used to emulate the inertial response of the system [59]. In this strategy, the voltage v and current i on the output converter is measured to compute the grid frequency ω_g (which can be done by the PLL) and the active power output P_{out}. The swing equation of this approach is written as follows, where the phase angle θ can be computed to generate the signal for PWM:

$$P_{in} - P_{out} = J\omega_m \frac{d\omega_m}{dt} + D_p(\omega_m - \omega_g) \tag{7}$$

where $\theta = \int \omega_m dt$, P_{in} is the active power input given by the prime mover and ω_m is the virtual rotor speed.

A governor model is used in this case to control the grid frequency (ω_g) to its reference ω^*. The prime mover power input reference P_{in} is computed by a first order system with gain K and time constant T_d, where P_0 is the active power reference received from a higher level controller.

$$P_{in}(s) = P_0(s) + \frac{K}{1 + T_d s}[\omega^*(s) - \omega_g(s)] \tag{8}$$

The voltage reference (e), can be implemented via $Q - V$ droop control to generate the amplitude reference for the PWM. Similarly, $P - f$ droop control may be applied to generate the power reference P_{in} instead of a prime mover approach. The general scheme of ISE topology is illustrated in Fig. 6 from [56].

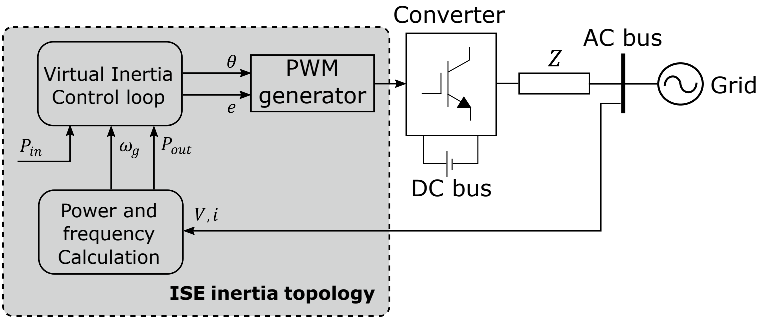

Fig. 6 General control scheme of ISE lab topology for virtual inertia

As in the synchronverter approach, frequency derivative is not required in the present case, what improves the control performance, avoids signal pollution and can be applied for grid forming units. Nevertheless, a poor design of swing equation parameters (J and D_p) may result in oscillatory behavior and instability problems.

4.1.3 Virtual Synchronous Generators

Virtual Synchronous Generators (VSG) is a Frequency-Power response based topology that emulates the inertial response feature of synchronous generators focused on frequency deviation improvement. It is a simple way to insert inertial characteristics in power converter units,[8] since it is not necessary to incorporate the detailed equation of synchronous generators. VSG can be easily compared with standard droop controllers, but they can also provide dynamic frequency control, unlike droop controllers that only have steady-state performance. The dynamic frequency control is implemented by frequency derivative measurement, where the system reacts to a power imbalance [68, 69]. So, VSG provides a power output (P_{vsg}) according to frequency deviation, which equation is written as follows:

$$P_{vsg} = K_D \Delta\omega + K_I \frac{d\Delta\omega}{dt} \tag{9}$$

where $\Delta\omega = \omega - \omega^*$ is the frequency deviation and $d\Delta\omega/dt$ is the RoCoF. The gains K_D and K_I represents the damping factor and the inertial constant respectively, based on a synchronous generator model.

The inertial constant (K_I) impact the RoCoF improving the dynamic frequency response, which is a suitable solution for isolated systems where the RoCoF may have high values, harming system stability. Therefore, this approach can be applied to enhance RoCoF values, and the damping constant (K_D) have the same effects of a

[8] Power converter units can be understand as a generalization for DER integrated via power converters.

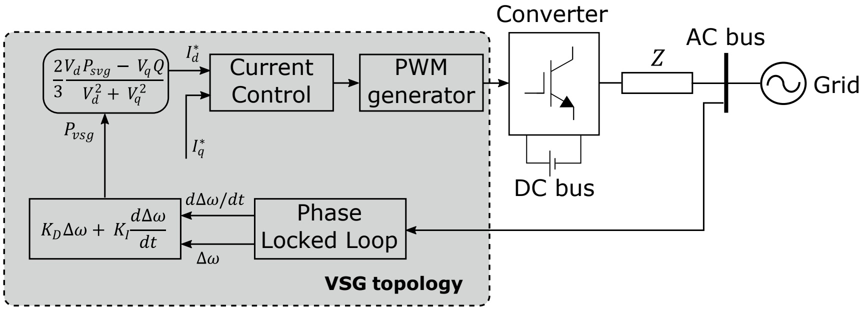

Fig. 7 General control scheme of VSG topology for virtual inertia

$P - f$ droop controller. In this topology, a PLL must be used to measure frequency deviation and RoCoF, which can be challenging, since the harmonic distortions and voltage variations may lead to poor control performance, while, in the other topologies, PLL is not really necessary. The VSG scheme is depicted in Fig. 7 adapted from [56].

VSG can be seen as a dispatchable current source, where P_{vsg} is used to calculate the current reference for power converter control loop. Equation (10) presents the current reference I_d^* related to active power injection:

$$I_d^* = \frac{2}{3} \frac{V_d P_{vsg} - V_q Q}{V_d^2 + V_q^2} \tag{10}$$

where V_d and V_q are the voltages in dq reference frame from Park transformation, Q is the measured reactive power.

The reactive power can also be controlled by calculating current reference I_q^* related to reactive power injection:

$$I_q^* = \frac{2}{3} \frac{V_d Q^* - V_q P}{V_d^2 + V_q^2} \tag{11}$$

where Q^* is the reactive power reference, which may be obtained by a droop control strategy, and P is the measured active power in the grid.

VSG topology is used by the European VSYNC group, because of the simplicity and effectiveness features of this approach. When applied as current sources as described in equations (10) and (11), VSG approach is not able to operate as grid-forming unit. Also, the inertia is not emulated during power input variations, but only in frequency variations. And the main problem of this approach is the complexity to compute and measure frequency deviations and RoCoF, since the derivative operation involves noise pollution and stability issues.[9] Stability problems can also be noticed, when cascaded control loops are used, such as PI controllers with an inner-current loop and an outer-voltage loop for converters. This happens because the gains of these controllers may be complex to tune, which results in inaccurate control performance [71].

4.1.4 Droop Based Topology

The droop control is a well known approach used for power sharing both in strong grids and Microgrids without the need of communication among distributed generation units, which contributes for an easy application. The designed control loop is composed by $P - f$ and $Q - V$ droops considering an electrical grid with inductive impedance ($X >> R$) and large amount of inertia, which is the case of conventional power system with high voltage transmission lines. In the classical case, equations (12) and (13) model the droop relation. But, when dealing with Microgrids composed of medium and low voltage lines, in many cases the impedance is not inductive ($X \approx R$) and the active and reactive power decoupling is not true. Then, the traditional droop relation ($P - f$ and $Q - V$) is not applicable. In fact, in resistive lines, the reactive power will depend on the phase angle (or frequency) and the voltage is related to the real power exchange. Therefore, an opposite droop may be addressed by $P - V$ and $Q - f$ droops to provide proper power sharing [72].

The steady-state equation that relates frequency and active power is given as:

$$\omega_g = \omega^* - m_p(P_m - P^*) \tag{12}$$

where ω_g is the grid frequency, P_m is the power in the generator, P^* is the active power set point and ω^* is the grid frequency reference [30].

The steady-state equation for voltage droop equation is written as:

$$V = V^* - m_q(Q_m - Q^*) \tag{13}$$

where V is the grid voltage amplitude, V^* is the nominal voltage reference, Q_m is the filtered reactive power, Q^* is the reactive power set point [73].

Droop strategy has only steady-state properties, with no dynamical contribution to frequency or voltage regulation. This is because the droop equations only includes frequency and voltage deviation. Therefore, the result is a slow transient response with improper active power sharing. In addition, droop control is not able to bring the system back to the original (or desired) equilibrium point. The inclusion of a frequency derivative term can bring a inertial response for droop strategy, approach-

[9] PLL performance problems can also be cited here, since may bring steady-state errors and instability mainly in weak grids application. So, this approach requires robust PLL implementation [70].

ing the VSG control scheme and can be compared with the following virtual inertia strategy [30, 74].

Another approach to provide virtual inertia is to insert a time delay in the active power response, to emulate the inertial behavior of a synchronous machine [75]. In droop control applications, the measured output power is filtered to avoid noise and high frequency components from power converter switching. Usually, a low-pass filter with a suitable time constant is applied, so the filter will induce a slower behavior in active and reactive power that can be compared with the inertial behavior of a synchronous machine [76]. Consequently, the droop control with a well designed filter may be used for virtual inertia purposes. A standard low-pass filter for active power can be described as follows:

$$P_{out}^{*}(s) = \frac{1}{1 + sT_f} P_m(s) \tag{14}$$

where P_{out}^{*} is the filtered output active power measured in the system, T_f is the filter time constant and P_m is the measured active power.

According to [77], applying the filter dynamics (14) in the frequency droop equation (12), we may result in the following expression that presents a virtual inertial component, which is the frequency derivative term:

$$P_{out}^{*} - P_m = \frac{1}{m_p}(\omega^{*} - \omega_g) + \frac{T_f}{m_p}\frac{d\omega_g}{dt} \tag{15}$$

where the derivative term is equivalent to the inertial response, which results in a low-pass filter with analogous function of a virtual inertia approach. It is necessary to correctly tune the parameters of the droop regulator to obtain a small-signal behavior of a synchronous machine [77].

4.2 Virtual Inertia Control Application

The VSM can act to provide transient power sharing and primary frequency support independently, using only local measurements. VSM can also be implemented with no need of PLL, being used just for sensing the grid frequency or during initial machine starting.[10] As result, VSM are conceptually simple thanks to intuitive interpretation as synchronous machines responses [56, 78]. The VSM is implemented to provide frequency reference output, with the power flow been related to inertia emulation and the angle from the swing equation, while voltage amplitude and reactive power control is made separately by the modulation index in the converter. The VSM scheme is introduced in Fig. 8, where the direct application of VSM concept is

[10] The swing equation of VSM allows interactions with the grid frequency, influencing its behavior.

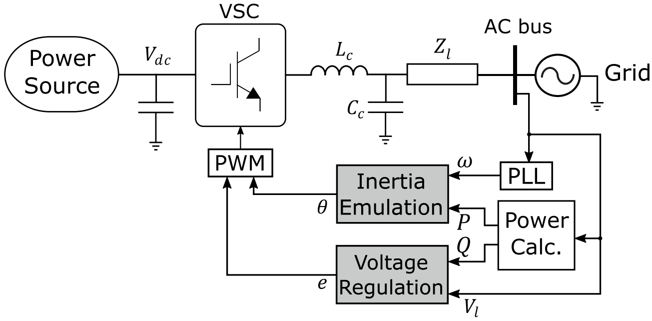

Fig. 8 VSM general control scheme for a Microgrid integration

built, which means that the voltage amplitude and the phase angle are directly used to generate the PWM signal in the converter [77].

To develop a VSM, it is necessary to implement the swing equation of a Synchronous Machine in the VSC control structure as detailed in [58]. In the following, it is presented the general swing equation of a synchronous machine applied for VSM implementation, where the inertia acceleration is represented by the power balance and a damping factor:

$$\dot{\tilde{\omega}} = \frac{1}{H}[P_{ref} - P - D_p(\omega_{vsm} - \omega_g)] \tag{16}$$

where $\tilde{\omega} = \omega_{vsm} - \omega_g$ is the frequency deviation, ω_{vsm} is the VSM's frequency, H the virtual inertia coefficient and D_p the damping factor. P_{ref} is the active power droop reference and P is the measured power into the AC grid.

The inertia coefficient is defined in [51]:

$$H = \frac{J\omega_o^2}{2S_{nom}} \tag{17}$$

where S_{nom} is the nominal apparent power of the VSC converter, ω_o is nominal grid value and J is the emulated moment of inertia. In (17) it is evident the inverse ratio between moment of inertia and its time constant, H given in seconds.

The electrical model applied here was developed in two parts: the Microgrid with an output LC filter, and the VSM model. The VSM with proper virtual inertia parameters is applied to improve frequency stability and reduce power oscillations in the grid. The synthetic inertia scheme is incorporated in a VSC converter connected to an AC Microgrid composed by a diesel generator and loads. The DC side of the grid is formed by a DC Microgrid able to provide energy (ancillary services) to the AC side of the grid. The DC side of the grid is summarized here as voltage V_{dc}. The electrical model of the system is depicted in Fig. 9.

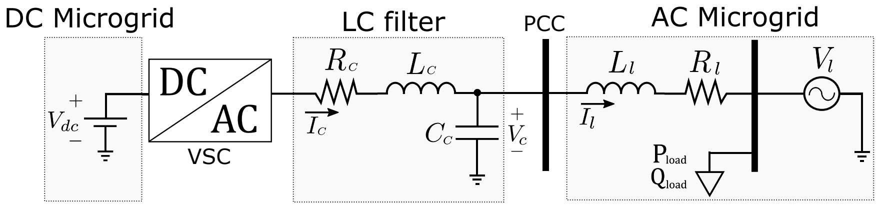

Fig. 9 Virtual Synchronous Machine (VSM) connected to an AC Microgrid based on diesel generation

The VSC converter has a LC filter, represented by L_c and C_c, connected to the Point of Common Coupling (PCC) with the AC Microgrid. The line impedance is represented by L_l and the active losses are given by R_l. The state space model of the system can be written as:

$$\dot{I}_{c,d} = -\frac{R_c}{L_c} I_{c,d} + \omega_g I_{c,q} + \frac{1}{2L_c} V_{dc} m_d - \frac{V_{c,d}}{L_c} \tag{18}$$

$$\dot{I}_{c,q} = -\frac{R_c}{L_c} I_{c,q} - \omega_g I_{c,d} + \frac{1}{2L_c} V_{dc} m_q - \frac{V_{c,q}}{L_c} \tag{19}$$

$$\dot{V}_{c,d} = \frac{I_{c,d}}{C_c} - \frac{I_{l,d}}{C_c} + \omega_g V_{c,q} \tag{20}$$

$$\dot{V}_{c,q} = \frac{I_{c,q}}{C_c} - \frac{I_{l,q}}{C_c} - \omega_g V_{c,d} \tag{21}$$

$$\dot{I}_{l,d} = -\frac{R_l}{L_l} I_{l,d} + \omega_g I_{l,q} + \frac{V_{c,d}}{L_l} - \frac{V_{l,d}}{L_l} \tag{22}$$

$$\dot{I}_{l,q} = -\frac{R_l}{L_l} I_{l,q} - \omega_g I_{l,d} + \frac{V_{c,q}}{L_l} - \frac{V_{l,q}}{L_l} \tag{23}$$

$V_{c,dq}$ is the voltage on the LC filter capacitor C_c and $I_{c,dq}$ is the current on inductor L_c. $I_{l,dq}$ is the SRF line current and the modulation indexes are m_d and m_q. V_l is the voltage on the diesel generator and P_{load} and Q_{load} are the active and reactive power demand of the load in the AC Microgrid respectively. The angular speed is given by ω_g, where $\omega_g = 2\pi f_g$.

The scheme of the proposed control strategy is composed by the active and reactive power control, given by the droop controllers. The active power control provides the power reference for the swing equation of the virtual inertia to generate the power angle of the converter. Here, the control system is used to directly generate the voltage references for PWM signals driving the power electronic conversion. Modulation indexes (m_d and m_q) provide the signal reference to obtain the desired sinusoidal waveform for voltage and current output (V_c and I_c) on the VSC converter in synchronism the diesel generator, such that, the ancillary services purposes are accomplished.

According to the control target, frequency (ω_{vsm}) and voltage ($V_{c,d}$) are chosen as the control outputs. Modulation indexes (m_d and m_q) provide the reference to generate the PWM signals, where m_d and m_q are transformed into phasor signal with amplitude m and phase θ, chosen as the control inputs. The angle is given by θ_{vsm} from the swing equation in (16) and voltage reference $V_{c,d_{ref}}$ is given by the droop strategy in (13):

$$\frac{V_{dc}}{2} m\angle\theta = V_{c,d_{ref}}\angle\theta_{vsm} \tag{24}$$

The signal obtained in (24) is the reference signal for the PWM modulation, making possible to emulate inertia in the VSC.

4.2.1 Stability Analysis

The stability analysis of the virtual inertia can be compared with the conventional stability analysis of synchronous machines. The swing equation can be rewritten considering the total inertia of the system and defining $\tilde{\omega} = \omega_{vsm} - \omega_g$:

$$M\dot{\tilde{\omega}} = P_m - P_{max}\sin(\delta) - D\tilde{\omega} \tag{25}$$

where δ is the power angle, $P_{max} = |V_{vsm}||V_g|/X_{eq}$ is the maximum power for the remaining of the grid and the VSC converter. D is the equivalent damping factor and M is the equivalent inertia coefficient given by [79]:

$$M = \frac{H_{vsm}H_{grid}}{H_{vsm} + H_{grid}} \tag{26}$$

H_{vsm} and H_{grid} are the inertia coefficient of the VSM and the remaining grid respectively.

The equivalent input power is given by:

$$P_m = \frac{H_{grid}P_{vsm} - H_{vsm}P_g}{H_{vsm} + H_{grid}} \tag{27}$$

If the damping term is neglected and the swing equation in (25) is multiplied by $\tilde{\omega}$, the following equation is arranged [80]:

$$M\tilde{\omega}\dot{\tilde{\omega}} - (P_m - P_{max}\sin\delta)\tilde{\omega} = 0 \tag{28}$$

To find a positive function, equation (28) is integrated from its equilibrium point ($\delta^e = \bar{\delta}, \tilde{\omega}^e = 0$):

$$W_{vi} = \int_0^{\tilde{\omega}} M\tilde{\omega}d\tilde{\omega} - \int_{\bar{\delta}}^{\delta} (P_m - P_{max}\sin\delta)d\delta = C \tag{29}$$

where C is a positive constant.

The Lyapunov candidate is given by the energy function of the system [80]:

$$W_{vi} = \tfrac{1}{2}M\tilde{\omega}^2 - [P_m(\delta - \bar{\delta}) + P_{\max}(\cos\delta - \cos\bar{\delta})] = E_k + E_p \tag{30}$$

where the kinetic energy is given by $E_k = \frac{1}{2}M\tilde{\omega}^2$ and potential energy given by $E_p = -[P_m(\delta - \bar{\delta}) + P_{max}(\cos\delta - \cos\bar{\delta})]$, with respect to the equilibrium points ($\delta^e = \bar{\delta}$, $\tilde{\omega}^e = 0$). The energy function is positive definite around the considered equilibrium point.

The time-derivative of the Lyapunov function can be calculated as follows:

$$\dot{W}_{vi} = \frac{\partial E_k}{\partial\tilde{\omega}}\frac{d\tilde{\omega}}{dt} + \frac{\partial E_p}{\partial\delta}\frac{d\delta}{dt} \tag{31}$$

Therefore,

$$\dot{W}_{vi} = \tilde{\omega}M\dot{\tilde{\omega}} - (P_m - P_{\max}\sin\delta)\tilde{\omega} - D\tilde{\omega}^2 \tag{32}$$

The result is a negative semi-definite function of the time derivative of the Lyapunov function [81].

$$\dot{W}_{vi} = -D\tilde{\omega}^2 < 0 \tag{33}$$

where one can see that the energy of the system is dissipated proportionally to the damping factor and the frequency deviation. Therefore, the given equilibrium point can be shown (using Barbalat's Lemma) to be asymptotically stable [51, 80].

4.3 Application Example

The proposed model was built on *Matlab/Simulink* using *SimScape Electrical* toolbox. The VSC converter interfaces the DC Microgrid to The AC one, which is composed of a diesel generator and loads, as depicted in Fig. 9. The diesel generator in the AC Microgrid has a Governor (speed control) to control the frequency and active power. The control parameters of the governor are presented as follows: Regulator gain $K = 150$ and time constant $T_{reg} = 0.1s$, actuator time constant $T_{act} = 0.25s$ and engine time delay $T_d = 0.024s$. The AVR is implemented to control the excitation of the machine, terminal voltage and reactive power regulation [82]. The AVR parameters are presented as follows: Voltage regulator gain $K_{va} = 400$, time constant $T_{va} = 0.02s$ and low-pass filter time constant $T_r = 0.02s$.

Table 2 Microgrid parameters

VSC	$S_{nom} = 1MVA$	$f_s = 20$ kHz	$\hat{V}_{c,nom} = 400$ V
LC filter	$R_c = 20\,\text{m}\Omega$	$L_c = 0.25$ mH	$C_c = 150\,\mu\text{F}$
VSM	$K_w = 20$	$D_p = 50$	$H_o = 2$ s
AC grid	$R_l = 0.1\Omega$	$L_l = 0.01$ mH	$V_{l,nom} = 400$ V

Table 3 The AC load power demand

Time (s)	0	4	12	23	31
Active power (MW)	0.5	1	1.8	1.8	1.3
Reactive power (kW)	50	100	200	150	100

The VSM and the AC grid parameters are presented in Table 2. The nominal frequency of the grid is $f_n = 50Hz$ and the nominal power of the diesel generator is $S_{diesel} = 2MVA$ with $V_l = 400V$ rms nominal voltage, 2 pairs of poles and inertia coefficient of $H_{diesel} = 3s$. The Q-V droop coefficient is $K_q = 0.3$.

Here, the VSM has a nominal power of $S_{vsm} = 1$ MVA and same nominal rms voltage as the grid $V_{vsm} = 400$ V, where these values are the base for per unit transformation. The active and reactive power demand for the load in the Microgrid is introduced in Table 3.

Active power (P) and reactive power (Q) injected by the VSC converter are controlled in their references (P^* and Q^*), given by a higher control level, according to power dispatch schedule. The controlled active and reactive power are presented in Fig. 10. Active power is well controlled, following the reference with small overshoots during the load changes. The reactive power is controlled to maintain the voltage regulated in the desired value, and the reactive power reference is given by a secondary control. The steady-state errors in reactive power are due to the droop control feature.

The VSM have about the same power level of the main generation, given by the synchronous machine. Then, in this case, the operation of the generator is affected by the power converter and the dynamic of the system is completely changed, so the power variations in the machine in combination with the VSM assures the stability of the system. The diesel generator has a governor to control the frequency without steady-state error, acting as a primary frequency controller. Voltage and machine excitation are regulated by the AVR control, according with standard paramatrization of the controllers and also ensure the elimination of steady-state error in voltage. Therefore, it is clear that the power response of the synchronous machine is slower than the power variations in the VSM. And, the VSM participates in the operation of the network, contributing to the system stability together with the diesel generator.

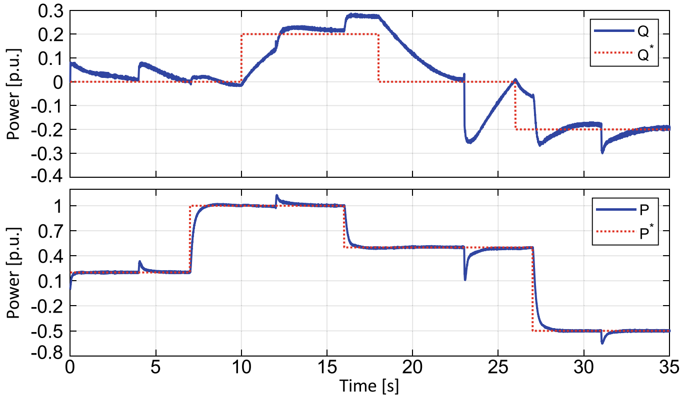

Fig. 10 The controlled active and reactive power in the VSC converter of the Microgrid

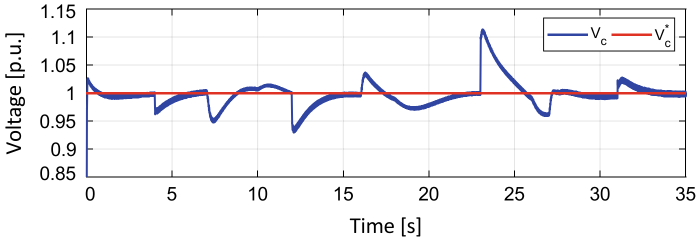

Fig. 11 The voltage amplitude profile on the PCC

The voltage on the PCC is controlled according the $P - V$ voltage droop. The voltage amplitude, given by $V_{c,d}$ is introduced in Fig. 11, where the overshoots are caused mainly during the load changes and the reactive power reference changes. But, even with deviations, the voltage operates within the established limits

The frequency of the grid and its reference are depicted in Fig. 12. The diesel generator has a governor to track the frequency in the desired value, therefore, there is no error in steady-state. The virtual inertia with the droop equation provide the power sharing with the VSM. As result, the frequency has some transient overshoots during load changes and when the active power injection dispatch changes in the VSM, but remains with good transitory behavior, and quick response to disturbances. The VSM provides a better frequency response to the system, decreasing frequency variations improves the speed of convergence during transients.

Next, the frequency deviation ($\Delta\omega$) and the frequency RoCoF is introduced in Fig. 13, where the operational margins of the grid can be analyzed, as the maximum frequency deviation and the rate of change of frequency. These operating margins are given according to the limits imposed by load and power variations, that can trigger load shedding and machine disconnection procedures.

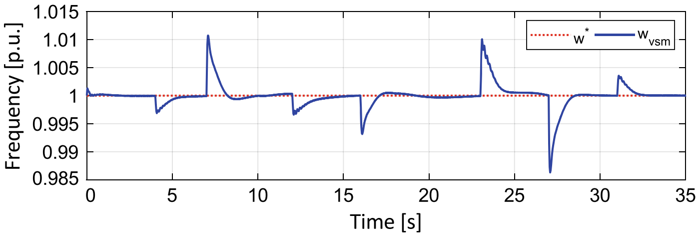

Fig. 12 The controlled frequency from the VSM approach

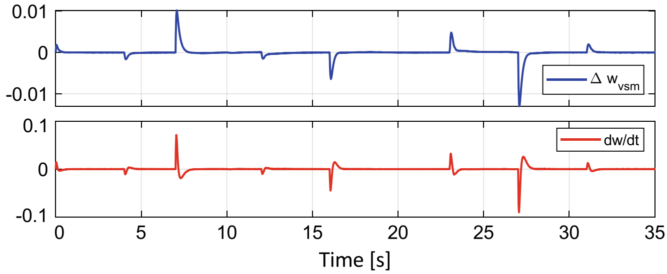

Fig. 13 The frequency deviation (Δw) and RoCoF

4.4 Isolated Operation

In the context of Microgrid operation, errors and failures may exist. In the event of a diesel generator failure, the Microgrid converter must be able to operate standalone, controlling the frequency and voltage in the network within the established grid requirements. In this case, it is possible to use the concept of virtual inertia and droop control to maintain the operation of the system. An example is provided here, where only the VSM is supplying the AC loads from the DC side of the Microgrid, i.e., no rotating machines are connected into the system.

Considering the VSM as the main generation, the P and Q dispatch is provided, such that the frequency and the voltage is controlled. Therefore, the reference values of the droop Eqs. (12) and (13) are set to zero ($P^* = 0$ and $Q^* = 0$). The swing equation of the VSM becomes:

$$\dot{\tilde{\omega}} = \frac{1}{H}[P_{ref} - P - D_p(\omega_{vsm} - \omega^*)] \tag{34}$$

where $\tilde{\omega} = \omega_{vsm} - \omega^*$. The swing equation in (34) can be applied for isolated operation of the Microgrid. The droop equations can be expressed as follows:

$$P_{ref} = -K_\omega[\omega_{vsm} - \omega^*] \tag{35}$$

$$V_{c,d_{ref}} = K_v[V_{c,d} - V_{c,d}^*] - K_q Q \tag{36}$$

Table 4 The AC load power demand in stand-alone operation

Time (s)	0	4	12	23	31
Active power (MW)	0.25	0.55	0.9	0.55	0.25
Reactive Power (kW)	50	100	200	100	50

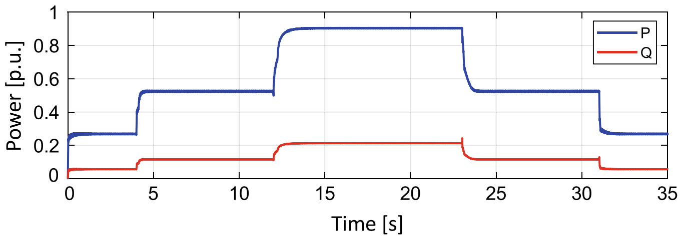

Fig. 14 The active and reactive power from the VSM in the stand-alone operation

where K_v is the voltage droop coefficient.

The simulation of the full converter operation is built considering the same Microgrid parameters of previous simulations. Table 4 presents the load variation during these simulations. The power generated in the VSM is to attend the load demanded power of the Microgrid, such that the frequency and the voltage are regulated. The active and reactive power injected by the VSM are introduced in Fig. 14. The power response of the VSM model is slower than the traditional control of power converters, to emulate the behavior of a synchronous machine.

The voltage on the PCC and the grid frequency are presented in Fig. 15. The voltage and the frequency present steady-state errors due to droop control behavior. Therefore, when the power demand of the load increases, the voltage and frequency values are stabilized below their references, which can be more clearly seen at 12 and 23 s of simulation. The transient overshoots are caused by the load change, with larger variations when compared to the system operating with the diesel generator, where the smallest value of frequency is 48.7 Hz during transients. In this case, the voltage and the frequency varies according to the operating condition of the system, with steady-state errors.

The frequency deviation and the RoCof are depicted in Fig. 16. In this case, the frequency deviation is much larger than in previous simulations with the diesel generator in operation, and also has a steady-state error. But the frequency RoCoF have smaller peaks when compared with the previous simulations.

An integral term from a secondary level control can be inserted in the droop control equations to eliminate the steady-state error of the frequency and the voltage of the system, improving the operating margins and power quality. Therefore, the droop equations are rewritten as follows:

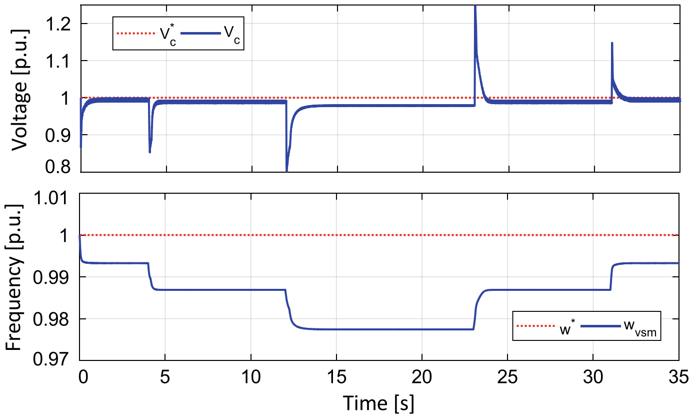

Fig. 15 The voltage profile and the grid frequency in the stand-alone operation

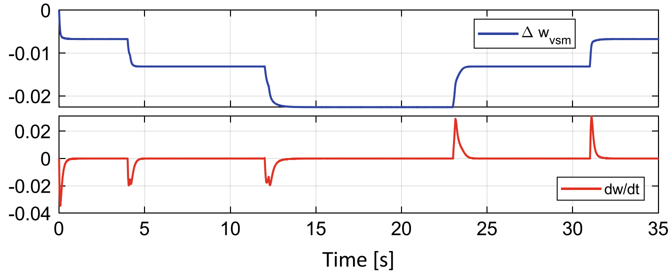

Fig. 16 Frequency deviation and RoCoF in stand-alone operation

$$P_{ref} = -K_{\omega}[\omega_{vsm} - \omega^*] - K_{\omega}^{\alpha}\alpha_{\omega} \quad (37)$$

$$V_{c,d_{ref}} = K_v[V_{c,d} - V_{c,d}^*] - K_q Q - K_v^{\alpha}\alpha_v \quad (38)$$

where the integral gains are K_{ω}^{α} and K_v^{α}, the integral terms are given as $\alpha_{\omega} = \int(\omega_{vsm} - \omega^*)dt$ and $\alpha_v = \int(V_{c,d} - V_{c,d}^*)dt$.

The following simulations show the behavior of the system when the integral terms representing the secondary controller are employed. The Microgrid parameters are kept the same and the load variations are presented according to Table 4.

The voltage profile on the PCC is introduced in Fig. 17, where the steady-state error is eliminated by the secondary control, improving the voltage profile. The same behavior can be seen in frequency, where the steady-state error is eliminated, remaining only the transient overshoots during load changes. The transient levels can be reduced according to the secondary control tuning. The frequency behavior with the integral term is introduced in Fig. 18.

The frequency deviation and the RoCoF are presented in Fig. 19, where frequency deviation is reduced without steady-state error.

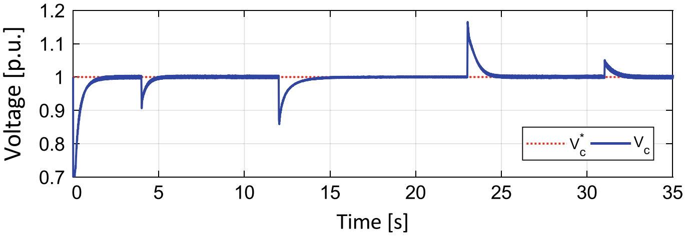

Fig. 17 Voltage profile on PCC applying the integral term

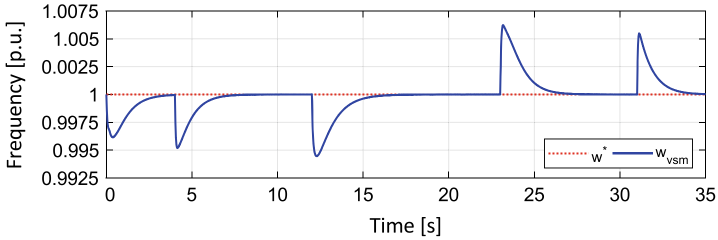

Fig. 18 Frequency response with the integral term (secondary control)

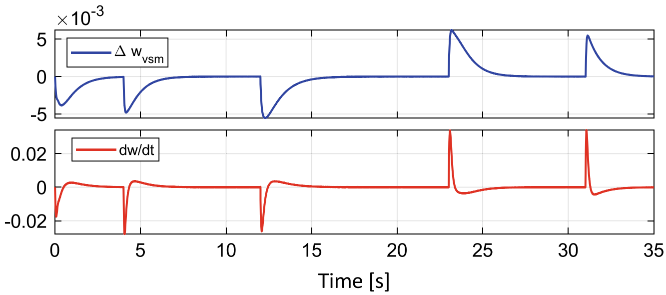

Fig. 19 Frequency deviation and RoCoF when the integral term is applied

5 Conclusions

In this chapter, an introduction for Microgrid issues is drawn introducing standard control techniques for frequency, inertial stability and power share. The ability of a DC Microgrid to provide ancillary services to an AC grid is highlighted where the virtual inertia approach rise up as a suitable solution for frequency regulation and inertial support. Also, voltage support is given by droop control strategies.

Energy storage and renewable sources technologies may be applied to improve grid support from the DC side of the system. In this way, power converters issues as support to low inertia grids bring great impacts to modern grids affecting the inertial response of the power systems based on power electronic devices. Power converter issues are discussed considering the dynamics of the system and their time-scale properties. The inertial response and the frequency problems are brought to the context of weak grids, where ancillary services can be applied to improve the system operation.

Different virtual inertia approaches are presented in the chapter, where the Virtual Synchronous Machine (VSM) is detailed. A stability analysis for the Synchronous Machine approach is conducted and an application example is provided highlighting the operation combined with traditional synchronous generators and stand-alone operation. The frequency parameters as frequency Nadir and RoCoF are discussed, and inertial support is improved when compared with typical control strategy for power electronic based grids.

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Sustainability and Transformative Energy Systems

Ian H. Rowlands

Abstract Inventions and improvements of advanced energy technologies—technologies that power active networks, that catalyze greater use of renewable resources, that improve energy efficiency, and that are developed synergistically with broad sustainability goals—are necessary to improve local, national, and global well-being. Indeed, all dimensions of 'energy sustainability'—including the historically-overlooked issue of social acceptance—are critical. Events during 2020 highlighted further many elements of the contemporary sustainability agenda. Because energy is central to human existence and well-being, and because the sustainable provision of critical energy services will continue to be a key priority for communities in the future, those working in the energy sector must ensure that sustainability considerations are integrated into their work. This article offers perspectives and insights to guide this integration.

1 Introduction and Purpose

The purpose of this chapter is to investigate sustainability within the context of transformative energy systems. While inventions and improvements of advanced energy technologies—technologies that power active networks, that catalyze greater use of renewable resources, and that improve energy efficiency—are necessary to improve local, national, and global well-being, they are not, by themselves, sufficient. Instead, it must be ensured that such technological development takes place in ways that are synergistic with other parts of the broader social, economic, and environmental context. This chapter provides those focusing upon specific technological innovations with details of that broader context so that their actions can be designed to have greater impact; likewise, this chapter also equips those working within this broader context with an increased appreciation for how such connections can effectively be made.

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The chapter is divided into seven main sections. Following this brief introduction, the following two sections introduce the concept of sustainability—initially in its broadest form, and then with a particular focus upon energy sustainability, providing some historical context and also outlining the current global agenda. The fourth section then looks at social acceptance issues associated with transformative energy systems, arguing that they were, until recently, a relatively oft-overlooked set of topics.

The fifth section briefly reviews the monumental events of 2020, focusing upon the global pandemic and the Black Lives Matter movement, highlighting their impacts upon particular areas of concern for energy professionals and society more broadly. Material from this section—and indeed from all parts of the chapter—is then used, in the following section, to sketch out the contemporary sustainability agenda for those whose work serves to invent and/or to improve advanced energy technologies. A brief final section summarizes and concludes the chapter.

2 Sustainability

The term 'sustainable development' was widely popularized in the late 1980s, in the wake of the 1987 publication of the Report of the World Commission on Environment and Development (commonly known as the Brundtland Report). Defined as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs', attention to the term increased the awareness of both spatial and temporal impacts of activities that served to advance economic growth [40].

During the 1990s, 2000s, and 2010s, sustainable development issues were addressed at various levels. At the international level, activities around a number of global mega-conferences served to advance the issue—namely, the 1992 United Nations Conference on Environment and Development (Rio de Janeiro, Brazil), the 2002 World Summit on Sustainable Development (Johannesburg, South Africa), and the 2012 United Nations Conference on Sustainable Development (Rio de Janeiro, Brazil). They focused global attention upon a range of challenges and opportunities that transcended environmental, social, and economic boundaries (let alone geographic boundaries), and they also served to be a location whereby individuals and institutions from around the world could work together to build systems of monitoring, evaluating, and potentially transforming. While many analysts give such summits mixed reviews, it is nevertheless the case that they provided unique universal opportunities for reflection and discussion [27, 43].

Also noteworthy at the global level during this period was the world's activity to develop a set of universally-agreed ambitions for sustainable development. In 2000, 147 heads of state met at the United Nations Millennium Summit (New York City, United States) and agreed on the Millennium Development Goals (MDGs). The MDGs consisted of specific targets for the year 2015 across eight areas (see Table 1). While some criticized the MDGs for being too narrowly focused and not

Table 1 Millennium development goals [48]

1. Eradicate extreme poverty and hunger
2. Achieve universal primary education
3. Promote gender equality and empower women
4. Reduce child mortality
5. Improve maternal health
6. Combat HIV/AIDS, malaria, and other diseases
7. Ensure environmental sustainability
8. Global partnership for development

sufficiently comprehensive, they nevertheless catalyzed many conversations around global targets, encouraged goal setting in global governance, and set the stage for the 2015 agreement of the Sustainable Development Goals, to which I return below [6, 41, 57].

Further to this global level activity on sustainable development during the 1990s, 2000s, and 2010s, much activity also occurred at national and local levels. And much of this was catalyzed by a particular emphasis upon implementation of global aspirations and commitments: this was initially prompted by the 1992 publication of Agenda 21 (at the United Nations Conference on Environment and Development, noted above), subsequently further stressed in the 2002 and 2012 conferences mentioned above. Nationally, several countries produced (and continue to produce) sustainable development strategies, which would not only be used domestically but would also often be fed into United Nations processes [1, 31]. And locally, 'Local Agenda 21' was a prominent vehicle for such discussions during the latter part of the twentieth century and the initial part of the twenty-first century; more recently, a variety of terms have been used to advance the same priorities, including sustainable cities, sustainable communities, and sustainable urbanization [5, 26].

While activity at all of these levels yielded some success—though not met entirely, the MDGs did much to address, in particular, global poverty [49]—it was clear that, by the middle of the 2010s, efforts to advance sustainability needed not only to continue but indeed needed to be accelerated. Annual reporting on the 'emissions gap' by the United Nations Environment Programme (UNEP), for one, contributed to this sentiment. This emissions gap was calculated by finding the difference between two values: (i) the 2030 greenhouse gas emission levels needed to keep anticipated average global temperature increases by 2100 below 2 °C; and (ii) the 2030 greenhouse gas emission levels anticipated, given then-current national projections and plans. In 2015, for instance, the gap was calculated to be the difference between 42 $GtCO_2e$ (where emission levels needed to be in 2030 in order to ensure global climate stability) and 54 $GtCO_2e$ (a 'best case scenario', given then-current trajectories and plans; the baseline was closer to 65 $GtCO_2e$). This gap of 12 $GtCO_2e$ was expected to have monumental socio-ecological impacts [47]. And UNEP was by no means alone in its assessment. The Stockholm Environment Institute's work on planetary

Table 2 Sustainable development goals [50]

1. No poverty
2. Zero hunger
3. Good health and well-being
4. Quality education
5. Gender equality
6. Clean water and sanitation
7. Affordable and clean energy
8. Decent work and economic growth
9. Industry, innovation, and infrastructure
10. reduced inequality
11. Sustainable cities and communities
12. Responsible consumption and production
13. Climate action
14. Life below water
15. Life on land
16. Peace and justice strong institutions
17. Partnerships to achieve the goal

boundaries across nine critical processes, for instance, also served to reinforce the conclusion that the world's efforts to advance sustainability were falling short [42].

Thus, on 5 September 2015, at the United Nations headquarters in New York City, United States, 193 countries agreed to the 2030 Agenda for Sustainable Development, and—as part of that—17 Sustainable Development Goals (SDGs). Succeeding the Millennium Development Goals, the SDGs were accompanied by 169 targets, whith countries committed to implementing by 2030. In the half-decade since their introduction, the SDGs have come to be part of many discourses, being focal points for a range of governmental, business, and other organizations' activities, plans, and aspirations. Their impact, moreover, appears set to continue to grow. The SDGs are listed in Table 2.

Finally, let me offer a note about terminology. I have used two terms throughout this section—namely, 'sustainable development' and 'sustainability'. There have been several investigations into which term is most appropriate given any particular purpose that has been identified—([32], 6), for instance, draws upon earlier work, arguing that 'while "sustainability" refers to a state, [sustainable development] refers to the process for achieving this state'. While such discussions are indeed worthwhile, they are beyond the scope of this chapter. Indeed, in this chapter, I follow much of the more recent literature (e.g., [19]) by primarily using the term 'sustainability'.

3 Energy Sustainability

Unlike the earlier Millennium Development Goals—which did not have energy as a focus for any of its eight goals (see Table 1)—energy is prominent in one of the Sustainable Development Goals (see Table 2). More specifically, SDG7 is concerned with 'committing to ensure access to affordable, reliable, sustainable and modern energy for all'. Full details of it and its associated targets and indicators are provided in Table 3.

In addition to the focus upon energy in SDG7, energy issues were also 'part of' many of the other 16 SDGs. Indeed, the attention drawn to such cross-connections was not least of all an effort to address one of the perceived failings of the MDGs—namely, their narrow focus; their 'siloing'. Thus, while each of the SDGs has a particular focus (see Table 2), that does not mean that how that particular goal contributes to, or obstructs, progress on the other goals should be ignored. Instead, many argued, such connections—some of which could well be unanticipated and/or unintended—should be thoroughly investigated. For energy project proponents—and energy transition advocates—that means considering the impact of energy initiatives upon the other 16

Table 3 Sustainable Development Goal 7 and associated targets and indicators [51]

Sustainable Development Goal 7—Ensure access to affordable, reliable, sustainable and modern energy for all
Target 7.1—By 2030, ensure universal access to affordable, reliable and modern energy services
Indicator 7.1.1—Proportion of population with access to electricity
Indicator 7.1.2—Proportion of population with primary reliance on clean fuels and technology
Target 7.2—By 2030, increase substantially the share of renewable energy in the global energy mix
Indicator 7.2.1—Renewable energy share in the total final energy consumption
Target 7.3—By 2030, double the global rate of improvement in energy efficiency
Indicator 7.3.1—Energy intensity measured in terms of primary energy and GDP
Target 7.a—By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology and promote investment in energy infrastructure and clean energy technology
Indicator 7.a.1—International financial flows to developing countries in support of clean energy research and development and renewable energy production, including in hybrid systems
Target 7.b—By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programs of support
Indicator 7.b.1—Investments in energy efficiency as a percentage of GDP and the amount of foreign direct investment in financial transfer for infrastructure and technology to sustainable development services

SDGs (and also being cognizant as to how initiatives advanced under other banners—'oceans', 'equality', etc.—affect progress towards SDG7). These connections have been theorized and operationalized in a variety of ways (e.g., [29, 35]).

While not explicitly connected with the Sustainable Development Goals (for that term only entered the debate explicitly in 2015), how analysts have been connecting energy issues and sustainability issues date back decades. Indeed, Lovins's call—in the wake of the first so-called energy crises of the 1970s—for a move to a 'soft energy path' (emphasizing energy efficiency), away from a 'hard energy path' (activities and policies that privileged fossil-based, centralized, supply-prioritized energy systems) is a prime early example [28]. Foci through the 1980s, 1990s, and 2000s included sustainability issues with an economic emphasis (for instance, re-regulation for efficiency in energy markets) and sustainability issues with an environmental emphasis (for instance, reduction of polluting air emissions to ameliorate both local smog and global climate change). Reviews of this period can be found in, for example, [16], [53], and [54].

Today, discussions around the movement towards energy sustainability continue. Indeed, major energy-focused organizations have their proposals—or scenarios—associated with this transition. The International Energy Agency presents a number of scenarios in its flagship *World Energy Outlook* report, including different sustainable development scenarios [23]. The World Energy Council, for its part, emphasizes energy security, energy equity, and environmental sustainability of energy systems [58]. Other intergovernmental institutions that have a broader remit also have energy high on their respective agendas—for instance, the United Nations Development Program [45, 46] and the World Bank [64]. Business-based international organizations—like the World Economic Forum—have also advanced their particular perspectives on energy sustainability [59].

If the above can be called 'mainstream' global perspectives, alternative perspectives—often calling for a faster transition that is less reliant upon conventional market forces—are also being advanced. For instance, plans for more rapid decarbonization, explicitly accompanied by economic justice goals, have been put forward by [13]. By contrast, prioritization of renewable resources characterizes the work of the aptly-named International Renewable Energy Agency [25].

Finally, in addition to these international-level perspectives, there have also been debates at the national and sub-national levels—for example, Germany's discussions around its energy transition (*Energiewende*) [38] and the work of the C40 [10], respectively.

To summarize this section of the chapter, note that there is an agenda focused upon energy sustainability. Having evolved over the past five decades, it—like sustainability more broadly—was originally fractured into its constituent economic, environmental, and social components. Encouraged not least of all by the emergence of the SDGs in 2015, however, recent investigations have been much more comprehensive and interconnected (and, as the next section will argue, have brought social considerations into greater focus). [11] document this by presenting a detailed literature review of sustainability evaluation for energy systems (2007–2017), as well as an associated database that can be used by energy professionals. And, to cite a specific example of such investigations, [12] advance the Sustainable Development Goals Impact Assessment Framework for Energy Projects (SDGs-IAE) and apply it to power generation projects in Ethiopia and the United Kingdom. Indeed, energy sustainability is the focus of an active, important, and rich set of discussions today.

4 Integrating Social Dimensions

As noted above, of the different constituent dimensions of sustainability, it is the economic and environmental elements that received the majority of the early attention; indeed, ([9], 1) reported that 'the social pillar [of sustainable development] has earned a reputation for elusiveness, and even chaos in part because social priorities are diverse and context specific'. In this section, I consider the concept of 'social acceptance' of transformative energy systems.

Experience with the siting of energy projects, particularly nuclear power stations and wind-farms, has revealed that citizen acceptance of a project is critical to the success of the same project. More recent experience with the 'user-end of energy systems'—in particular, programs like time-of-use tariffs and demand response incentives—has further demonstrated that acceptance can involve not only technology that is 'much closer to home' (e.g., solar panels on one's rooftop), but also energy control procedures that though 'technically invisible' (e.g., an external signal that raises an air conditioning system's set point by two degrees Celsius) may be viewed as intrusive by some. Without acceptance of such technologies and programs, transformative energy initiatives can 'come off the rails', even at advanced stages of development. In response, investigations as to how citizen acceptance can develop and be sustained have been undertaken.

Ground-breaking literature examining social acceptance of energy technologies and energy programs distinguished among multiple dimensions of social acceptance, most commonly: communities, markets, and socio-political dimensions [65]. More recently, increasing attention to the role of multiple actors has supplemented this traditional framework with the following foci: public acceptance, key stakeholder acceptance, and political acceptance [52]. Together, approaches like these have catalyzed many empirical studies that have served not only to refine these conceptual ideas but also to extend the range of energy technologies and energy programs investigated from an acceptance perspective.

Key recent investigations include the following: [15] propose a research agenda regarding the social acceptance of energy storage technologies, [17] examine elite-level attitudes towards energy storage in Ontario, Canada, [4], while examining renewable energy, argues for a conceptual reframing of the literature to consider 'community of relevance', [8] reviews public perceptions of energy technologies research, considering both large scale and customer-facing energy technologies, and [56] do a systematic review of the literature associated with the social acceptance of neighborhood scale distributed energy systems. These, and other, studies point to the importance of a multidimensional social acceptance research agenda to continue studying the deployment of advanced energy technologies and energy programs (in isolation and in systems) and to evaluate how the social acceptance of these technologies and programs evolve through interaction among multiple actors using multiple channels at multiple levels.

Indeed, coming out of this literature—and it is continuing to grow (and indeed accelerated by events of 2020, but more about that below)—are three key messages.

First, energy issues are multi-sector and multi-stakeholder, and different people will bring different understandings, different experiences, different priorities, and different lens to issues and projects. Thus recognize that people will see 'the same things' differently, and plan accordingly. Consider, for instance, a study by [22], who conducted a questionnaire study among 217 citizens living near the first publicly accessible hydrogen fuel station in the Netherlands. She found a range of emotions arising from the same project—varying levels of anger, fear, joy, and pride all arising from a hydrogen fuel station that was placed in the city of Arnhem in 2010. Of course, people are different, and their calculations will be informed by a variety of perceptions, understandings, and values (among other factors). It is nevertheless a useful reminder that multiple responses will almost certainly emerge within a population.

Second, effective engagement—between, for instance, proponents and residents for new energy projects—is critical. Engagement must be early, sustained, and meaningful. There must be multiple opportunities for information provision and two-way exchange, and commitments made must be fulfilled promptly and transparently. A number of those actively involved in siting transformative energy projects have published their own 'how-to' manuals regarding what they perceive to be effective community engagement. As but one example, consider the work of Australia's Clean Energy Council. Being the industry association for that country's renewable energy industry, the Council has collated resources that help project proponents build effective relationships with their host communities, arguing that trust and respect must be at the foundation [14].

And third, communication must be fulsome, truthful, and accessible. All involved must be committed to open dialogue and to working to agree on statements of fact and to clarify misunderstandings as quickly as possible. Indeed, such suggestions can be broadened to offer 'best practices' on communications more generally. [2], for instance, highlight the importance of what they call sociotechnical approaches to effective communications on a range of energy and environmental issues. A key message of theirs is that a broad understanding must be developed: breadth in the kinds of approaches that can be useful (technological, structural, and cognitive 'fixes'), breadth in the kinds of actors sending and receiving communications (individuals, organizations, technologies), and breadth in the understanding of peoples' engagement (motivations, attitudes, behaviors). This can be extremely useful to those taking forward particular transformative energy initiatives.

Research and analysis in this field have shown the importance of social acceptance to ensure that the right energy initiatives are adopted in timely, cost-effective, and sustainable ways. Recognizing differences among stakeholders and their perspectives, implementing effective engagement strategies, and communicating clearly will go a long way towards ensuring energy activity success.

As mentioned above, consideration of integrating social aspects of energy sustainability more fully—including those above—was accelerating in any case during the 2010s, but events during 2020 served to augment it even further. In the next section, I briefly review key events in 2020 and the broader societal changes they encouraged. Then, in the following section, I examine how those impacts—combined with all that has been presented in this chapter to this point—have effectively combined to construct an agenda for energy professionals going forward.

5 Events of 2020

The year 2020 was remarkable for a variety of reasons. The two reasons that I will focus upon here are the coronavirus crisis and the Black Lives Matter movement.

First, the World Health Organisation declared a global pandemic as a result of COVID-19 on 11 March 2020. As of November 2020 (the time of writing of this chapter), the global impact had been devastating. Most importantly, more than 1.3 million people had lost their lives, and 54.7 million people had been infected by the virus (figures from Johns Hopkins University, 16 November 2020). Economically, the world's economy had contracted by 4.4% during 2020 (figure from the International Monetary Fund, 16 November 2020). Hundreds of millions of people had lost their livelihoods, and virtually no one had escaped impact: it was estimated that the physical and mental toll upon many would last for months, if not years, while the consequences for groups (be they communities, or countries, or regions) were both immediate and longer-term. Geopolitical reordering was looked to be another potential long-term consequence of the virus [63].

Second, on 25 May 2020, George Floyd—a black man—was killed in Minneapolis, United States by Derek Chauvin—a white police officer—while being arrested for allegedly using a counterfeit bill. Floyd's death triggered worldwide protests against police brutality and systemic racism more generally. Collectively, the responses reignited the Black Lives Matter movement and directed greater attention to issues of equity, diversity, and inclusion. Indeed, the disproportionate impact of the global pandemic upon vulnerable communities was shocking to many; the fact that the United States was in the midst of a national election campaign provided additional platforms for discussions about equality and related issues [7].

Many had reflections upon how events like these in 2020 were changing global social and economic life in significant ways. Some investigations highlighted, for instance, the potential long-term impact upon the economy (e.g., [24]), upon the nature of work (e.g., [3]), and upon the role of technology (e.g., [30]). Building upon all of this reflection in wake of a remarkable 2020, I will highlight three areas that I believe are particularly important for those working to advance energy sustainability.

They serve to help set the stage for the next section of this chapter, which advances a current set of priorities for energy professionals.

First, evidence-based decision-making is more important now than perhaps ever. Experience through the events of 2020 has demonstrated the value of rigorous and independent investigations that place a premium upon standards like validity and reliability. This sentiment was often voiced by different scientific and other associations during the year. For example, many US-based scientists wrote about the value of science, and the importance of an engaged and well-informed public [62].

Second, collaboration is vital. Again, experience during 2020 revealed that society often needs multiple perspectives—across disciplines, jurisdictions, ecosystems, and cultures—to solve problems and to embrace opportunities. It was shown that bright minds with different experiences, knowledge-bases, sets of resources, and ways of thinking coming together on challenges and opportunities are needed. Like many themes that climbed global agendas during 2020, this had previously been oft-noted—[37] had eloquently laid out the value of interdisciplinary approaches through diverse teams, and [18] was similarly impactful regarding the importance of international research.

And third, we must ensure that we leave no one behind. We need to ensure that those who are most vulnerable—individuals, households, communities, countries—are fully included as we move towards solutions and sustainable livelihoods; we must eliminate racism and discrimination of all kinds. Indeed, the concept of 'co-creation'—of involving those impacted by issues, supported by evidence and expertise, in problem-solving—serves to integrate all three areas.

Much of the discussion around these, and associated, areas, came together in calls to 'build back better', 'build forward better', or undertake a 'great reset' (e.g., [36], [21], and [60]). Collectively, these were calls to acknowledge that, given the size of the impact upon economies and societies during 2020, communities around the world would—once they had the virus eradicated, or at least better controlled—have to 'emerge' and 'rebuild'. Given this, there was also a widespread feeling that this crisis should be viewed as an opportunity: these same communities should not slavishly rebuild whatever it is that got torn down during 2020. Instead, they had the chance to determine what future was'best'—particularly in light of all that had been learned from the pandemic and Black Lives Matter experiences—and to move towards that new goal. Such recommendations should indeed be kept in mind as more specific work on energy innovations are carried out. It is in the next section where I make those connections.

6 Current Priorities for Energy Professionals

Given all of our learnings—learnings that were happening pre-2020 in any case, along with learnings that were catalyzed and/or revealed and/or effectively created by the 2020 pandemic—I offer, in this final substantive section, three interconnected priorities for researchers, analysts, managers, regulators, and others who have been attracted to the subject material in this book. In other words, because I envision readers of this book as being those who are at the forefront of knowledge with respect to innovation in advanced energy technologies—that is, technologies that power active networks, that catalyze greater use of renewable resources, and that improve energy efficiency—I offer three priorities for them to keep in mind. These are not priorities for the specifics of their work, but instead are priorities for how they place the work they are developing within its wider context—so that their contributions can be as impactful as possible. Accompanying each of the priorities, I point to some themes that appear to be set to be important as activity to advance energy sustainability continues. Let me also note that these priorities are also important for those who already work within this broader context to consider—the importance of context, and all of its constituents, should not be lost on anyone.

First, in the spirit of the aforementioned discussions to build forward better, a priority should be to ask, 'what is the goal?' As with much being discussed in this section, this issue was already moving toward the front of the proverbial energy consciousness—even before the events of 2020. Many were successfully challenging the traditional energy focus upon 'supply' by highlighting the importance of 'demand' as well. Indeed, a 'whole system' approach is now often—and rightly—taken in energy studies. This is to be encouraged further, and analysts would be wise to think about the 'energy service' that is ultimately desired; work can then proceed to determine what kind of system would best serve to meet this energy service requirement. (For elaboration and inspiration, see, for instance, the 'system diagrams' in [20].)

Moving forward, those working on energy projects will be increasingly asked, 'Why is it being done this way?' Assumptions, inertia, and comments like 'That is how we've always done it' will no longer pass muster (if they ever did). Demands for social and economic accountability will require respondents to speak to the energy services to which they are contributing, and the reasons why.

Second, in addition to recognizing how the issue upon which one is working sits within the broader energy system, recognize, as well, the importance of how the issue is connected to other issues—particularly (in this case), in terms of spatial connections and sectoral connections.

Regarding spatial connections, recognize that most energy issues have local, regional, national, international, and global dimensions involving a whole range of players. Put more academically, the term 'multilevel governance' is one with which those working on energy projects should be familiar. To clarify, it is usually the case that any particular energy system of interest will have linkages that reach across borders, so multiple jurisdictions (and their associated players—be they governments, businesses, civil society organizations, or others) have their particular stakes in the outcomes. Opportunities and challenges—catalysts and constraints—will be presented by these different governance players working at these different levels. As a case in point, energy politics in North America can often have local flashpoints (e.g., the siting of a power plant), intra-regional elements (e.g., plans to integrate electricity markets), trans-border dimensions (e.g., varying definitions of 'renewables' in different jurisdictions' policies), and continent-wide elements (e.g., discussions about a large-scale power grid), each of which can be connected to the other [33].

Sectorally, let me reemphasize that while energy service provision is a goal in itself—indeed, a priority Sustainable Development Goal, as reviewed above—it is nevertheless also connected with multiple other goals that society is trying to advance. All would be wise to evaluate explicitly how energy ambitions impact these other priorities; the Sustainable Development Goals may well be a useful means to frame that investigation. While the discussion above already highlights works that show connections between SDG7 (energy) and other SDGs, Table 4 points to a few, in particular, that may be particularly relevant for readers of this book. Going forward, it will be critical to engage with others in an interdisciplinary manner to discover pathways to win-wins for sustainability.

And third, resilience is critical. Going forward in virtually every part of our lives—energy activities included—we will have to expect the unexpected. Consequently, we will have to build our energy research, our energy projects, our energy policies, and our energy institutions to be as nimble, flexible, and adaptable as possible. The year 2020 has shown us that low probability and high-risk events do indeed occur. And even before 2020, a number of observers had identified a range of such events that could happen—pandemics included. Indeed, in the World Economic Forum's

Table 4 Sample connections between advanced energy transformation initiatives and other SDGs

SDG	Advanced energy technology	Potential impacts	Indicative reference
No poverty (SDG1)	Implementation of time-of-use electricity rates	Movement from traditional to dynamic tariffs can have dramatically different cost impacts upon different customer segments	[39]
Gender equality (SDG5)	Increased development of smart energy and internet-of-things technologies for in-home use	Without gender analyses, technologies can embody particular images and privilege particular groups	[44]
Reduced inequalities (SDG10)	Increased deployment of 'energy projects' (e.g., wind farms, energy storage facilities)	There can be notable distributional impacts of projects—e.g., siting locations can burden particular communities with negative local impacts	[34]
Climate action (SDG13)	Increased use of hydrogen as an energy carrier	There can be substantial climate impacts, depending upon how hydrogen is made	[55]

annual analysis of global risks, 'infectious diseases' was—at the beginning of 2020—in a quadrant characterized by 'higher impact'/'lower likelihood' risks; 'weapons of mass destruction', 'information infrastructure breakdown', and 'food crises' were the other global risks in that same quadrant [61]. Indeed, all 31 risks presented on the landscape warrant attention.

So, in summary, a message to energy professionals is to work with purpose, to identify and to respond to connections, and to embed resilience in their work going forward.

7 Summary and Conclusions

The purpose of this chapter has been to investigate sustainability within the context of transformative energy systems. To do this, the scene was set by investigating sustainability, generally, and energy sustainability specifically (with a further focus upon social acceptance issues). More recent events—namely, the remarkable developments during 2020—were briefly described, and some of their key impacts were identified. This—and, indeed, all the material in the chapter—then led into a discussion of the current sustainability agenda for those working directly in the energy sector. The motivation for the inclusion of this discussion was to ensure that energy professionals' efforts—which often focused upon a relatively small part of the broader landscape—had a maximum impact going forward.

Energy is central to human existence and well-being. The sustainable provision of critical energy services will continue to be a key priority for communities in the future. Success in this regard will be important in helping to advance everyone's well-being and communities' collective livelihoods. Regardless of the extent to which one's work involves energy issues, all need to understand, generally, the systems at work, and—at a minimum—connect with those who have more detailed knowledge. Collectively and collaboratively, we can, together, move towards a sustainable future.

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The Role of Smart Grids in the Low Carbon Emission Problem

Claudia Rahmann and Ricardo Alvarez

Abstract One of the greatest challenges faced by humankind is to stop global warming. Although this challenge requires joint efforts from the entire society, the energy sector—being responsible for most of the global GHG emissions—is called to take a leading role. One of the pillars in this quest is the decarbonization of electricity systems, where conventional generating technologies are largely displaced by low-carbon ones based on renewable energies sources (RES). Moving towards low-carbon electricity systems is the only way to effectively slow down climate change, but it poses enormous technical challenges for the operation and control of electric power systems. A cost-efficient and secure transition to future low-carbon electricity systems requires a fundamental change in the way power systems are designed and operated. We need to evolve from today's electricity grids into next-generation ones, the so-called smart grids. Future smart grids use advanced sensing spread across all voltage levels, distributed energy sources, flexible transmission and distribution technologies along with two-way communication networks to enhance the use of existing network infrastructure. This in turn facilitates the large-scale integration of RES and ultimately allows for the reduction of CO_2 emissions. In this chapter, we review key aspects of the ongoing energy transition, present some of its challenges and possible solutions. Then, we introduce the concept of smart grids and present how they can help in reducing CO_2 emissions. Finally, we present some of the major challenges that need to be addressed for the successful implementation of smart grids.

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1 Introduction: Energy Sector as a Key Vector in the Transition Towards a Low-Carbon Emissions Society

The energy transition towards low carbon electricity systems is already underway.

The constant use of fossil fuels in the twentieth century provided society with countless opportunities to progress both socially and economically. However, opportunities taken up by one generation can cause challenges to subsequent ones [1]. In this regard, the burning of fuels in power generation plants has resulted in both pollution and production of carbon dioxide (CO_2), which is currently the main originator of global warming, among other greenhouse gases (GHG). Both pollution and CO_2 emissions do not only threaten human health but also jeopardize mid-and long-term sustainability of our planet. According to the International Energy Agency, the global CO_2 emissions in 2018 reached a historical high of 33.5 $GtCO_2$ [2], which is about 66% higher than emissions in 1990 [3]. From this amount, around 40% was originated by the electricity generation sector [2] through the combustion of fossil fuels, such as coal, oil, and natural gas to produce the heat needed to power steam-driven turbines. The power generation from coal was by far the most used strategy, reaching 38% of the electricity produced globally in 2018 [4]. Coal-fired power plants were therefore the single largest contributor to the emission rise observed in 2018, with an increase of 2.9% compared to 2017 levels [5]. Although the 2020 COVID-19 pandemic has led to an unprecedented reduction of global CO_2 emissions[1] [6], a similar rate of decrease would have to be sustained for decades in order to achieve the 1.5 °C warming limit [7].

Nowadays, there is a wide consensus that one of the greatest challenges of the twenty-first century is to stop the increase of global warming. In response to this challenge, several countries have set ambitious targets for reducing their GHG emissions in the context of the global Paris Agreement signed in 2015 [8]. For the year 2030, countries like Germany, Japan, and China have set targets for reducing their GHG emissions by 55% below their 1990 levels, 26% below their 2013 levels, and 60–65% below their 2005 levels, respectively [9]. The European Council has also decided to reduce its GHG emissions by 80–95% by 2050, as compared to their 1990 levels [10]. Further examples of national climate goals can be found elsewhere [9].

The climate goals have pushed countries into pursuing strong decarbonization pathways to achieve a relatively swift transition toward a low-carbon emission society. Although this is a widespread challenge requiring joint efforts from the entire society, the energy sector—being responsible for around two-thirds of global GHG emissions considering energy production and use—is called to take a leading role [11]. The *decarbonization of electricity systems* therefore emerges as one of the cornerstones to address global climate issues. Among the pillars for achieving

[1] The Covid-19 pandemic reduced the global CO_2 emissions in the first quarter of 2020 by more than 5% compared to the same period in 2019. Further, according to [6], global CO_2 emissions in 2020 are expected to decline by 8%, or almost 2.6 gigatons (Gt).

this ambitious objective are an accelerated deployment of renewable energy sources (RES), as well as energy efficiency measures [12, 13]. According to the Intergovernmental Panel on Climate Change (IPCC), renewable energy must supply 70–85% of the world's electricity in 2050 to limit global warming to 1.5 °C [13].

The transition towards low-carbon electricity systems with high shares of RES is already underway. A quarter of the total electricity produced worldwide in 2018 came from renewables, which became the second-largest contributor to global electricity production after coal [14]. Since 2009, the cumulative renewable energy capacity (including hydropower) rose from 1136 to 2537 GW by the end of 2019 [15]. Growth has been especially high for solar photovoltaic and wind power generation. Between 1990 and 2018, both technologies have grown at average annual rates of 36.5% and 23.0%, respectively [14]. 2019 represented a record-breaking year for RES with an additional installed capacity of more than 200 GW—the largest increase so far [16]. Solar photovoltaic power led the capacity expansion with an increase of 115 GW, followed by wind energy and hydropower, with 60 GW and 16 GW, respectively.

Electricity systems based on 100% RES are no longer a dream. While some countries already have solar and/or wind power capacity to cover more than their own electricity demand [17], others are targeting to reach 100% renewable energy-based electricity systems in the future [18]. While Iceland supplies 100% of its electricity needs using geothermal and hydropower, countries such Norway, Costa Rica, Brazil, and Canada have electricity systems with 97%, 93%, 76%, and 62% of hydropower, respectively.

Although moving towards low-carbon electricity systems is a unique opportunity to effectively slow down climate change, it also poses enormous technical challenges for the operation and control of electric power systems [19]. The main reasons are the inherent differences between converter-based RESs, such as wind and photovoltaic power plants, and conventional generation technologies [20]. On the one hand, RES power plants are powered by variable energy resources with changing availability levels over time (variability), which cannot be predicted with perfect accuracy (uncertainty). As the level of RES increases, the additional variability and uncertainty introduced in electricity systems may significantly challenge their frequency regulation. This is because most RES do not (yet) contribute to system frequency regulation [20–22]. On the other hand, the overall performance of RESs, as well as their interaction with the grid, is largely determined by the characteristics of their control systems and strategies used to control the interface power converter between the energy source and the electric grid [20]—in contrast to conventional synchronous generators, where the physical properties of the machine itself, such as the amount of inertia and electrical parameters, play the most important role in determining their transient behavior [23].

The transition from fossil-based to low-carbon electricity systems involves a total overhaul of the energy sector. It is not simple enough to switch from one fuel source to another. We need to conceive a brand-new way of producing, transporting, and consuming energy. While energy transition is already underway, urgent actions are needed in order to make this transition as safely as possible. We are now facing "the third industrial revolution" [24], and the scientific community should rise to this challenge.

2 Technical Challenges Related to the Energy Transition

The paradigm shift in energy supply towards electricity systems dominated by RES requires a gradual breakaway from the essential pillars on which existing power systems have been based. This is mainly due to the physical nature of RES, and the fact that they are connected through power converters to the system, meaning that RES power plants behave differently than conventional generation facilities. Significant, collaborative efforts and innovative changes are required not only at the technological and operational levels, but also at the regulatory, economic, political, and social ones.

Next, we present the main technical challenges of low-carbon electricity systems, and a summary of current solutions that may be considered and deployed for overcoming these challenges. Our discussion is contextualized from a system operation perspective with special emphasis on system stability and control. Other relevant challenges that future power systems will also have to face are not discussed.

2.1 The Flexibility Challenge

To ensure the security of the electricity supply, the frequency of electrical power systems must remain nearly constant around its nominal value. This is a compulsory requirement for avoiding the social and economic consequences that sustained frequency deviations can have on society [19]. Keeping the frequency within the allowed band requires that the total energy production be equal to the total consumption at each point in time. For this, synchronous generators used in conventional power plants keep a certain energy margin (or power reserves), which allows for controlling possible imbalances between consumption and generation.

From a control viewpoint, frequency in electrical power systems is regulated through a combination of fast-local and slow-centralized controllers [23]. In case of a mismatch between generation and consumption, fast closed-loop controllers act locally at each synchronous machine by increasing or decreasing its output power in order to restore the power balance in the system (primary frequency control). Once the primary frequency control has been completed, a slower, centralized controller, known as Automatic generator control (AGC), begins to act in order to return the frequency to its nominal value.

The aforementioned way of controlling the frequency of electrical power systems has shown to be a straightforward and effective strategy for successfully keeping frequency within permissible limits in conventional systems dominated by synchronous machines. However, different studies and practical experiences have shown that this strategy alone will not be sufficient to keep the balance between consumption and generation in the face of high levels of RES. On the one hand, the integration of RES in electrical power systems increases the variability and uncertainty that system operators and planners must deal with far beyond the levels they have been used to, thus making the frequency regulation even more complex. The generation of RES such as wind and photovoltaic generation is determined by local weather conditions, meaning that its power production is variable and difficult to predict [23]. Although the output power of photovoltaic generation plants is usually less variable and more predictable[2] than wind generation, the inherent challenges related to its day cycle and fast power ramps due to moving clouds still remain [25, 26]. Depending on system operating conditions, large and sudden changes in the power generated by RES can exhaust the ramping reserves available in conventional generation units and threaten power balance in the system [25]. On the other hand, since most RES power plants are usually operated to reach maximum power production (operation at their maximum power point, MPP), they cannot participate in system frequency control as conventional generators do. Under these circumstances, the replacement of conventional synchronous generators by RES leads to a decrease in the number of generators used for frequency regulation and, therefore, to a decline of the power system's ability to deal with frequency deviations during normal conditions. Note that even if RES are operated with a given energy margin for frequency control, their stochastic nature prevents guaranteeing this reserve [17], meaning that this problem would still persist.

The challenges that emerge with frequency regulation at high levels of RES will require to increase the power system's flexibility to counteract the variable and partly unpredictable generation of RES. This is a mandatory requirement for guaranteeing the security of the electricity supply and hence for moving toward low-carbon electricity systems.

2.2 Stability Challenges

Over the last years, several studies and practical experiences worldwide have shown that an increased use of RESs in electricity systems leads to new types of stability problems, such as converter-driven stability (including slow- and fast-interactions), and electric resonance stability [20]. These problems are caused by the inherent differences between the dynamic behavior of RES and synchronous generators. A Task Force of the IEEE Power System Dynamic Performance Committee has recently addressed the issue of stability definition and classification in bulk power systems including the new phenomena and concerns due to high levels of RESs [20]. According to the Task Force, key elements that need to be considered when assessing the impact of RESs on system dynamic behavior are (a) overall reduction in system inertia, (b) limited contribution of RES to short circuit currents during faults, and (c)

[2] At least in areas with good solar potential.

new control interactions that may arise between fast-response devices with the grid. The combination of these elements, together with the shift from synchronous generators to RESs, leads to an overall decrease in the robustness of electricity systems, thereby making them more prone to instabilities.

In electricity systems, the term system robustness is typically used to roughly characterize their performance under all possible operating conditions. It indicates how well a system can cope with different disturbances and still sustain a stable behavior. Two common indicators used for quantifying system robustness are the short circuit level (SCL) at a given network busbar, and system inertia.

The SCL at a given location is a common indicator of system robustness: the higher its value, the higher the network strength at the pertinent busbar [27–29]. SCL represents the voltage stiffness of a network busbar [27, 28]: high SCLs indicate a strong system with stiff voltages, meaning that their values will not deviate much when subjected to small disturbances. This is because the series impedances of *strong* electricity systems are relatively low and, consequently, the sensitivity of voltages to changes in power flows is also low [27]. Since synchronous machines are the major sources of short-circuit current contributions [28], high SCLs are usually found in areas close to generators, while low levels are usually found far from generation centers. SCL is also a good measure of the dynamic performance of electricity systems during contingencies [30]. Electricity systems with high SCLs are usually characterized by a large number of synchronous generators providing high fault currents that greatly contribute to the stability of the grid [27]. SCLs are then a measure of system response robustness to different faults.

Inertia is often considered one of the key system parameters upon which the synchronized operation of electricity systems is based [22]. It is an indicator of how well a system can cope with power imbalances and still maintain a stable frequency [23]. Accordingly, the level of inertia in an electricity system also represents a good indicator of system robustness. The inertial response is naturally provided by the rotating masses of power systems, such as synchronous machines and motors. It influences both the activation of under frequency load shedding schemes during contingencies and the performance of the frequency control in steady-state (small load/generation fluctuations) [31]. During the first seconds after a major power imbalance, the system frequency will decrease at a rate mainly determined by its total inertia: the lower the system inertia, the faster the drop of system frequency. Due to their electromechanical coupling, the rotating masses will inject or absorb kinetic energy into or from the grid for several seconds to counteract the frequency deviation according to their inertia [22, 23]. This natural counter-response from synchronous generators is produced whenever there is a mismatch between generation and consumption. This action renders the system frequency dynamic slower and thus easier to regulate. As such, in case of the sudden disconnection of a synchronous generator, the imbalance is initially compensated by the extraction of kinetic energy from the remaining rotating machines. This natural action is essential to arrest the frequency decline. Beyond this natural response, primary frequency controls of synchronous generators react by changing the generated power to recover power balance.

So far, the robustness in electricity systems has been largely ensured by having large amounts of synchronous generators distributed throughout the network. These rotating machines naturally provide high fault currents during contingencies, which strongly support the stability of the system, as well as its recovery after a fault clearance (over-excitation limiters in synchronous machines usually include a substantial delay, so that the machine can provide significant over-currents for short periods of time). In this regard, RES-based power plants behave quite differently from conventional generation facilities. On the one hand, the short circuit current contribution from RESs is usually limited to values between 1.0 and 1.5 times their rated current due to thermal limits of the power electronics equipment [20, 29]. Type-3 wind turbine generators (double fed induction generators) can contribute more short circuit current though, as their stator is directly coupled to the grid [20, 29]. Still, these values are significantly lower than the fault current that a synchronous machine can provide [20], which can be up to 6 times their nominal current [23]. On the other hand, RESs do not naturally provide an inertial response during power imbalances, as conventional generators do, unless a specific control is carefully designed for this purpose [17, 20, 22]. Photovoltaic power plants do not have rotating elements, and therefore, there is no stored energy available as in the case of synchronous generators [22]—except for the energy stored in its DC link, which is negligible [17]. In the case of wind turbines, the power converter fully or partly electrically decouples the generator from the grid, which implies that kinetic energy stored in their moving parts cannot be used for supporting frequency [22].

Operational and stability problems in weak electricity systems with low inertia and SCLs can emerge in several different ways. On the one hand, the reduction of SCLs leads to higher values of dV/dP and dV/dQ, meaning that small disturbances in power flows can significantly change network voltages [27], which makes controlling them extremely difficult. On the other hand, stability problems such as control instability, control interactions, small-signal instability, and voltage instability are more likely to arise in grids with low SCLs. During contingencies, these power systems may experience extremely depressed voltages over a wide network area, which may pose difficulties for voltage recovery after fault clearance. Accordingly, systems with low SCLs are more prone to face voltage instabilities or just collapse [27, 28]. Severe voltage drops may also considerably speed up the rotors of nearby machines, which in turn may provoke loss of synchronism [32]. From a frequency perspective, the replacement of synchronous machines by inertia-less RESs can lead to degradation in both primary frequency response and system inertial response [17, 22]. This can be especially critical in the case of islanded systems and small isolated systems, where inertia (without RESs) is already low [22]. Reduced system inertia increases the frequency nadir after a loss of generation and leads to a steeper rate of frequency change at the inception of a contingency. Hence, system frequency dynamics become faster [17, 33]. This may result in more frequent and larger frequency excursions following a loss of generation, which can in turn jeopardize the frequency stability of the electricity system [22].

2.3 Control Challenges

A key factor differentiating RESs from conventional generators is that the dynamic response of RES along with its interaction with the grid during contingencies, are dictated by the characteristics of the chosen control strategy and not by the converter's physical properties [20]. This is in contrast to synchronous generators, where the physical properties of the machine itself, such as inertia and electrical parameters, play a key role in determining their transient behavior [23]. This dependence on the control system poses significant challenges to the operation of electricity systems, because their dynamic performance may substantially vary, not only depending on system operating conditions, but also on the chosen control strategy, parameters, and equipment vendor. The challenge becomes even more complex when we consider that the shift of energy supply does not only occurs toward large-scale RES power plants at high voltage levels but also toward smaller RES producers connected to distribution networks (also known as distributed energy resources, DER) [34]. Additionally, the energy transition is also characterized by the integration of other power electronic converter interfaced technologies, such as storage systems, flexible ac transmission systems (FACTS), High Voltage Direct Current (HVDC) lines, and power electronic interfaced loads [20]. When hundreds of power electronic devices are added to the electricity systems at different voltage levels, two key elements affecting their control emerge: (i) the response of the system becomes progressively more dependent on (complex) fast-response power electronic devices, thus altering the power system dynamic behavior [35] and (ii), hundreds of new control points are created in the grid, thereby imposing challenges in their coordination and tuning.

Converters are modular and nearly fully actuated devices that admit a wide variety of flexible and fast control alternatives with actuation times on very fast time scales [17, 20]. While these characteristics offer a wide range of opportunities from a control perspective, they also add an additional layer of complexity. Among these control challenges are:

(1) Possible RES instabilities due to low SCLs (connection to a weak system) and/or due to current limitation of converters during faults,
(2) Unexpected fast dynamic interactions induced by the coupling between converters and the grid or between several converters nearby, and
(3) Actuation delays due to signal processing.

The vast majority of large-scale RES power plants use voltage-source converters [36, 37] that allow the converters to independently control the active and reactive power exchanged with the grid, as long as the total current remains within the rated capability of the power electronic switches [20]. Depending on the control mode used, a typical RES converter comprises control loops and algorithms with fast response times, such as the phase-lock-loop (PLL) controllers and inner current loop controllers. The experience has shown that these control loops are often key instability drivers in modern RES power plants [27–29]. Particularly in case of weak networks with low SCLs, RESs are more likely to experience control loop instabilities, such as in the inner current control loop [29, 38], the closed-loop voltage control [29, 39, 40], and the PLL [27, 29, 39–43]. This is because as the system is weakened, the voltage reference becomes less stable, meaning that its value is likely to be affected by the current injection of RES (higher sensitivity of voltage to changes in power flows). Accordingly, complex control interactions are more likely to arise, because each device controlling an electrical quantity has more impact on other devices [27].

During faults involving low voltages, inaccurate calculation of the voltage phase angle by the PLL may result in inaccurate control of active and reactive power, which can, in turn, lead to instabilities. Especially when RES are connected at busbars with low SCLs, the response of the inner current-control loop and PLL can become oscillatory, either because the PLL is not able to quickly synchronize with the network voltage or due to high gains in the inner-current control loop and PLL [20]. Although many control parameters can influence the dynamic performance of RES during faults, under weak grid conditions, the PLL parameters play the most significant role in driving instability [27–29, 40, 44]. SCL at the PCC, that is, the robustness of the system, also strongly influences the performance of RES-based power plants [39–41, 44]. Indeed, there is a high dependency between PLL controller gains and bandwidth, SCL at the PCC, and stability of the RES plant during low voltage conditions. After a fault clearing, the PLL should quickly regain synchronism to control reactive power to maintain system voltage. In a short period following a fault (1–2 cycles), this critical PLL function becomes even more challenging in electricity systems with low SCLs, as the phase angle may have shifted drastically, and the post fault voltages may be especially noisy [27].

Although the ability of RES to cope with low voltages can be extremely challenging [27, 29, 42, 45–47], tripping RES units during abnormal conditions is (usually) not allowed anymore by current grid codes, because it can worsen an emergency further. Indeed, in most countries, RES must remain connected to the grid during faults and also support voltage stability through the injection of reactive currents [46, 48]. Several studies have reported the importance that RES power plants stay connected to the grid and inject reactive currents during faults for sustaining system stability. In these cases, however, special attention must be paid to the tight current limitations of the converters, because overlooking them may also result in stability problems [20, 46]. In [46], it is shown that the support that RES can provide during a short circuit becomes even more relevant in terms of improvement of the voltage dip and recovery, as the network to which the RES is connected becomes weaker (i.e., as the SCL decreases). The exact fault current contribution of RES during a short circuit will vary depending on the fault, its duration, pre-fault operating condition, and the grid requirements. The control strategy implemented in the converter, including its structure and parameters, as well as the SCL of the network at the connection point, are also key aspects strongly affecting RES dynamic performance during low voltage conditions.

Traditionally, the dynamics of conventional power systems have been tackled by slow electromechanical phenomena of synchronous machines and their controls. Fast electromagnetic transients, such as those related to the network and stator transients of generators decay very quickly, thus being practically negligible [20, 35].

The dynamics of power electronic converters are, however, on a similar timescale as the network dynamics, and their controls are faster than the controls of synchronous machines. Accordingly, as the use of RES increases, the system dynamic response starts to be progressively faster and therefore, more difficult to control [35]. In this context, the timescale related to RES controls can result in cross-couplings with both the electromechanical dynamics of synchronous machines and the electromagnetic transients of the network, which may lead to unstable power system oscillations over a wide frequency range. Instability phenomena with low frequencies (less than 10 Hz) are classified as Slow-Interaction Converter-driven Stability, while phenomena showing higher frequencies (tens to hundreds of Hz, and possibly into kHz) are classified as Fast-Interaction Converter-driven Stability [20]. Fast interactions induced by the coupling between converters and the grid have been reported in [17]. High and very high-frequency oscillations ranging from 500 Hz to 2 kHz have been observed in large-scale wind power plants connected to VSC-HVDC [49, 50].

The last control aspect that must be carefully considered in systems with RES are the actuation delays due to signal processing. Each part of the control system of RES power plants is a complex signal processing unit that is unavoidably subjected to time delays [17]. The delays due to signal processing in RES can significantly limit their dynamic performance during normal operation and contingencies, and also lead to unstable behaviors.

2.4 Current Solutions

Nowadays, a wide range of solutions have been proposed to overcome the control and stability challenges that may arise in power systems due to low inertia and SCLs. Even though many of them have been only explored in theory, others have been tested in practice. The solutions are system-specific and depend on the characteristics of the electricity system itself.

To partially solve problems caused by low SCLs, one of the simplest solutions is to incorporate additional equipment in weak network areas in order to locally improve system robustness. FACTS devices, such as SVCs and STATCOMs can help control system voltages through fast dynamic reactive support [51, 52] by limiting voltage fluctuations and also improving the fault ride-through capability of nearby RES power plants [53, 54]. However, FACTS devices have also fast control loops that may interact with RES control, which can lead to instabilities in the case of weak networks [27]. Accordingly, special care must be taken when designing and implementing their controls. Synchronous condensers may be another alternative for increasing SCL, as well as system inertia. Denmark has installed several of these devices to provide both fault currents and inertia to the system [23]. Changes in the control system of RES power plants can also be undertaken to reduce the risks of instabilities caused by the PLL, inner current control loop, or the closed-loop voltage control during low voltage conditions. These changes can include adjusting some control parameters like time constants or reducing gains [27]. However, it is important to recall that the underlying stability issues of weak power systems will not be solved just by changing the parameters of RES converters.

The lack of inertial response in RES can be counteracted by integrating fast-acting energy storage systems (such as batteries, flywheels, or super-capacitors) [23, 55] or through the implementation of additional control loops specially designed for responding to frequency variations [22, 31]. Although power converters of RESs are normally not operated to respond to frequency variations in the grid, the incorporation of an additional control loop allows RESs to provide fast frequency response (also known as virtual inertial response) to support the system during major power imbalances. Some investigations have shown that the fast response times of power converters can provide important benefits to system frequency in comparison to the frequency support provided by conventional generators. However, fast frequency response capability in RES without energy storage may require operating RES in the so-called de-load mode [22, 23, 31]. That is, instead of injecting all the available power, RES supplies only a percentage of it, meaning that they operate at a sub-optimal operating point [25, 26]. In this way, there is some energy buffer available to contribute to the inertial response and thus counteracting the effects of a power unbalance. For wind power plants, it is also possible to provide fast frequency response without operating in de-load mode. This can be achieved by using kinetic energy stored in the blades to compensate for power unbalances [22, 23]. However, in this case, special attention must be paid to the post fault frequency recovery. References [56, 57] present a comprehensive review of different control techniques proposed for providing fast frequency response with solar and wind power plants. In general, most of these strategies are conceived considering a post fault frequency representative for electricity systems dominated by synchronous machines (considering their physical dynamics and traditional controls approaches) and using the measured frequency as the main control signal for keeping the power balance in the system. However, it should not be expected that electricity systems dominated by RESs exhibit the same frequency behavior as those dominated by conventional machines. As previously discussed, electricity systems dominated by RESs are characterized by hundreds of fast-response converter-interfaced devices distributed throughout the grid, which results in a much faster and complex dynamic response. This can lead to situations in which traditional frequency control approaches become too slow for preventing large frequency deviations [33]. Moreover, several challenges related to current limits, time delays, and practical implementations must first be solved before adding an extra control loop in RES for frequency response as a solution to low inertia problems. Moreover, in the case of a system 100% based on RESs (zero-inertia), frequency is not a physical variable coupled to synchronized rotating machines anymore, and therefore, it has no significance to determine power imbalance [17].

2.5 Summary

Previous sections have shown that RES power plants can quickly lose stability when connected to weak networks with the risk of even leading to instabilities in bulk power systems. Unfortunately, many large-scale RES power plants are often located in weak areas of electricity systems with low SCL, because attractive wind and solar potentials are commonly located in remote areas, far from generation centers and with sparse transmission capacity. The displacement of synchronous generators by RESs, on the other hand, leads to a reduction of system robustness in the area where generators are replaced and to an overall reduction of system inertia. This decrease in system robustness can impair the dynamic performance of power systems during both normal operation and contingencies, making them more prone to instabilities. Electricity systems with high levels of RES are thus intrinsically less secure than conventional power systems dominated by synchronous machines. Considering that synchronous generators are the major sources of system robustness, the path toward decarbonization will probably lead to inherently weak electricity systems in which several control complexities and underlying—and new—stability problems will push future engineers far beyond the limits they have ever known. Although current RES control approaches for supporting the grid during faults and avoiding control instabilities may be a good starting point, once power converters start to dominate the grid, these control strategies will not be tenable anymore [58]. The coordination of hundreds of control points related to power electronic devices distributed throughout the grid, as well as faster and more complex system dynamics, will entail exploring new control methods that go far beyond currently used methods. Anything less may jeopardize the secure decarbonization of the electricity systems.

For conceiving how the control of future electricity systems might be, the fundamental differences between RESs and synchronous generators, as well as the challenges that these differences impose, must be taken into account. In this regard, it is important to recognize that in the case of synchronous machines both inertial response and the contribution of short-circuit currents are naturally provided during contingencies, while in the case of RESs, both actions must be implemented through a control loop, meaning that their effects will be fully determined by the chosen control strategy and parameters. Moreover, despite the wide variety of control alternatives that power converters allow, several inherent limitations add a layer of complexity that cannot be circumvented in any way. Among the issues hindering the control are (i) operation subjected to actuation delays, (ii) current saturation of the converters, (iii) unexpected fast dynamic interactions between the converters and the rest of the network, and (iv) possible wrong operations.

From a technical perspective, the secure transition from up-to-date power systems to low-carbon networks dominated by RES is essentially a complex control problem. We must conceive how the operation of thousands of fast-response power electronic converter interfaced technologies can operate in parallel and also in harmony with existing grid infrastructures. Although there are still many open questions to be addressed, the cornerstones to overcome *this challenge* are technology innovation, intelligent management and control, fast coordination and communication between network agents, real-time monitoring of system security, making the right decisions, among others. In other words, we need a "smart upgrade" of our electricity systems, or a smart or intelligent grid.

3 Definition of Smart Grid

Before defining what a smart grid is, it is useful to review the basic elements that compose an electrical grid. An electrical grid is an infrastructure that converts fuel and energy resources into electric power and transports it to the end-users. Major physical elements of an electrical grid are generation, transmission, distribution, and load [59]. Generation is composed of several power plants of different sizes, ranging from very small distributed units of a few kW to large central stations of hundreds of MWs. Transmission is composed of high-voltage lines above 100 kV that allow a cost-efficient energy transport from generation to load centers over long distances. Distribution consists of lower-voltage lines, where the voltage is gradually stepped-down as transmitted power approaches the end customer. Finally, the load completes the system and is composed of the electrical equipment of the network customers. Besides the aforementioned equipment, the grid is embedded with measurement devices, as well as with information and control systems that allow transmission and distribution network operators to manage and coordinate the assets of the grid to deliver the electricity required by end-users in a secure, reliable, and economic way. Today's electricity systems are largely characterized by power flows in one direction, from the main generation to load centers, limited power flow control throughout the network; an inelastic demand, where consumers are constrained from reacting to actual price signals [60] or hazardous operating conditions, and limited levels of visibility and coordination across the boundary between transmission and distribution network operators.

Even though today's grids are highly reliable and cost-efficient in supplying energy demand, the large-scale introduction of RES poses significant challenges, as previously discussed in Sect. 2. In this context, a smart grid appears as a key solution to facilitate large-scale integration of renewable energies and meet energy and climate goals. A smart grid can be defined as a next-generation electricity network that "*uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users. Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end-users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimizing costs and environmental impacts while maximizing system reliability, resilience and stability*"[61].[3] A smart grid can be built from an existing grid by deploying smart technologies. However, the transition

[3] There are numerous of other definitions of a smart grid such as the ones proposed by the European Commission (EC), the United States Office of Electricity Delivery & Energy Reliability (USA OE),

from a conventional electricity system to a smart one is a gradual process. Also, the deployment of smart grid technologies is not a goal in itself. Rather, a smart grid is an enabler to increase electricity end-use efficiency while optimizing network asset utilization and increasing grid resiliency [61].

A smart system is composed of technological deployments that need to be installed to obtain enhanced network capabilities, information and communication technologies and protocols needed for monitoring and controlling the power flow throughout the grid, and applications that process the information flowing through the grid and use it to optimize the performance of the system. Some authors also include data-processing tools for analyzing large volumes of information [62]. Altogether, a smart grid enables real-time, two-way communication between system operators, generators, consumers, and automated devices to promptly respond to changes in the system conditions, thus improving reliability, resiliency, flexibility, and economic efficiency of electrical power systems [63, 64].

From a technological viewpoint, many smart grid technologies span the entire grid, from generation through transmission and distribution [61]. While some of these technologies are commonly applied in current power systems (e.g., smart meters, SCADA, and FACTS), some others are still being developed or in early deployment stages (e.g., vehicle to grid or V2G). Some of the key technologies of a smart grid are:

- Advanced Metering Infrastructure (AMI): A system-wide implementation of AMI is the first major step in turning a conventional grid into a smart one. One of the visible components of AMI are Smart Meters [65]. Smart Meters support shorter metering intervals approaching 5 min or less, which is key for enabling the provision of ancillary services and distribution capacity management. Smart Meters also provide full two-way communication including a home-area network that allows using home appliances. In addition, their capability to instantaneously read voltage, current and power factor supports state estimation and optimized system volt-VAR control at a distribution level. Finally, Smart Meters also offer remote connect/disconnect functionality that can be used for reliability and customer service applications.
- Demand response (DR): DR consists of re-distributing consumption and engaging demand-side resources for supporting the grid. These schemes can provide a wide range of flexible services at different time frames, such as primary and secondary frequency response, short-term operating reserves, congestion management, and security of supply [66]. DR can be provided by multiple technologies, such as flexible industrial and commercial loads, flexible heat pumps, electric vehicles, smart domestic appliances, etc. [67].
- Distributed generation (DG): DG refers to power generation resources at consumer locations or stand-alone DG plants, which are connected to the utility distribution system [68]. DGs include small engine or turbine generator sets, wind turbines, and solar electric systems [69]. DG deployed at the consumption level may not

the International Electrotechnical Commission (IEC) and the Japan Smart Community Alliance (JSCA). However, all point out to the same concept.

only serve to supply local demand, but also the excess power can be made available to the grid. In addition, they can also provide ancillary services, for example, to support system stability and power balancing.

- Distributed storage (DS): DS refers to electricity storage devices connected to the grid that can store electric energy drawn from the grid and deliver the stored energy to the grid when necessary. Examples of DS technologies include batteries, flywheels, supercapacitors, and pumped hydro [68]. Hence, DS can provide ancillary services, such as primary frequency response, system balancing, and voltage support.
- Distribution automation (DA): DA consists of using the available information collected from Intelligent Electronic Devices (IEDs) connected to the feeders and use it to control those feeder devices. Examples of DAs are advanced protective relays with dynamic and zonal control capabilities, dynamic capacitor bank controllers (CBC), condition-based transformer-management systems, fault detectors, reclosers, switches, and voltage regulators (VR) [69, 70]. DAs can provide a wide range of grids supporting services, such as fault detection, voltage support, line balancing, network reconfiguration, among others.
- Wide-area monitoring systems (WAMS) and wide-area control systems (WACS): WAMS is a collective technology to monitor power system dynamics in real-time, to identify system stability related weakness, and to help design and implement countermeasures. WAMS consist of phasor measurement units (PMUs) that provide precise, time-stamped data, together with phasor data concentrators that aggregate the data and perform event recording [71]. WACS, on the other hand, is a modern grid wide-area control system. It uses data gathered by WAMS and carries out real-time stability and voltage control on the grid.
- Electric vehicles (EVs): when plugged into the grid, the EVs batteries can be charged from the power supplied by the grid, and, based on the agreement with the utility, batteries can also be discharged into the grid [68]. Hence, EVs can also be considered distributed storage systems. Within a smart grid, EV owners may charge the batteries when energy prices are low, whereas the unused energy of the battery can be discharged into the grid when energy prices are high. In this way, owners of EVs can profit from energy arbitrage and, at the same time, support the utility in managing peak demand and reducing power losses.
- Flexible transmission technologies: there are several flexible technologies in the transmission and distribution system that can control active and reactive power to enhance real-time system controllability and performance. Examples of these technologies are Phase Shifting Transformers (PST), Flexible Alternative Current Systems (FACTS), Special Protection Schemes (SPS), Soft Open Points (SOP), and High Voltage Direct Current (HVDC) networks.

Fully deploying smart grid strategies and visions requires the availability of proper communication infrastructure and technologies that allow for high-speed, two-way communication [72]. Some of the cutting-edge communication technologies of a smart grid are:

- Wide-area network (WAN): the WAN consists of communication technologies that support transmitting high data rates, ranging from 10 Mbps to 1 Gbps over long coverage distances. Among commonly used technologies in a WAN are optical communication—characterized by its high capacity and low latency—, Cellular and WiMAX—with wide coverage range and high data throughput. Satellite communication is also used for providing redundant communication and backup at critical transmission and distribution substations, as well as for remote locations [70].
- Field Area Network (FAN): in the distribution domain, FANs are responsible for collecting traffic from smart meters and WANs in the transmission domain [73]. FAN applications include smart metering, demand response and distribution automation and require communication technologies supporting data rates ranging from 100 kbps to 10 Mbps and coverage distances up to 10 km. These applications can be implemented over ZigBee mesh networks, WiFi mesh networks, PLC, as well as long-distance technologies such as WiMAX, Cellular, DSL and Coaxial Cable [70].
- Home Area Network (HAN): HAN is a communication network of appliances and devices within a home [72]. HAN enables users to monitor and control electricity usage of a wide range of devices as refrigerators, washing machines, heaters, lights, air conditioners, among other appliances. Communication technologies in a HAN need to provide data rates up to 100 kbps with short coverage distances (up to 100 m). HAN may include wireless communication technologies such as Zigbee, Z-wave, WiFi, 3G and 4G cellular, or wired ones such as Power Line Communication (PLC), Fiber Optical Comm and Ethernet [70].

Some authors differentiate the aforementioned customer premises and include area networks in Building Area Networks (BAN), Industrial Area Network (IAN), and Neighborhood Area Network (NAN), and Field Area Network (FAN) [74].

The functionalities and services that a smart grid can support, and thus its benefits, vary significantly across different countries. In this regard, various functions may be harvested or not depending on several factors, such as supply mix, system technology and infrastructure, data availability and access, regulatory and market regulations, policy incentives and consumer capability, and willingness to engage [75]. Main functions and services that a smart grid can support can be summarized as follows [75, 76]:

- Facilitating renewable integration and EVs;
- Enhancing customer services;
- Enabling active participation by consumers in demand response;
- Improving operational efficiency;
- Enhancing power quality, reliability, and self-healing; and
- Increasing observability and controllability of the power grid.

Each one of the aforementioned characteristics allows reducing CO_2 emissions, as will be shown next.

4 Benefits of Smart Grids: How Can Smart Grids Reduce CO_2 Emissions?

Smart grids offer great potential for reducing CO_2 emissions [77]. However, harvesting this potential is a gradual process and depends on the level of integration of smart technologies to the grid and the functions and services that are enabled. In what follows, we present some examples of how a smart grid can help reduce CO_2 emissions, depending on the smart grid functionalities presented in the previous section.

4.1 Facilitating Renewable Integration and EVs:

One of the main characteristics of a smart grid is the ability to increase the utilization of existing assets at transmission and distribution levels. This is achieved by the deployment of storages and flexible transmission and distribution technologies with either power flow control capabilities or capabilities to introduce topological changes based on system needs [66]. In addition, the use of smart meters together with enhanced communication capability allows for designing price or incentive signals to engage demand response, distributed storages and EVs [69], which further increase the system operational flexibility. At a transmission level, this means that a smart grid can integrate further sources of large-scale renewable energies with less transmission expansion and/or upgrade requirements. At a distribution level, a smart grid allows integrating greater quantities of distributed renewables, as well as facilitating the incorporation of EVs without jeopardizing system reliability and stability. In both cases, smart grids foster and speed-up the integration of renewable energies and EVs, which in turn allows the displacement of conventional generating resources and thus reduce CO_2 emissions.

4.2 Enhancing Customer Service

At a distribution level, smart grids would allow utilities to improve customer services by monitoring the performance of their customer's major equipment (e.g. chiller system, refrigerator equipment, etc.), identify sources of inefficiencies, and take proper actions [78]. For example, if a major equipment is not working according to nameplate efficiency specifications, they may adjust the operational settings, perform maintenance on the equipment, or even replace the sub-optimal equipment with a more energy-efficient one. As a result, the customer may benefit from an improved operation and reduced energy costs and, ultimately, reduce carbon emissions [78].

4.3 Enabling Active Participation by Consumers in Demand Response

The deployment of smart grids also allows a utility to offer demand response services to their customers, cutting some of their costs [78]. Examples of these services are peak demand reduction by load reduction or load shifting. In addition, utilities can offer enhanced options for pricing and tariff structures [79]. Dynamic pricing provides strong incentives for customers to adjust their consumption patterns according to the system needs [79], and therefore it benefits both customers and the gird [80]. The increase in frequency and duration for which customers respond to demand response events would lead to energy savings across the utility and therefore to reducing carbon emissions. Furthermore, some studies suggest that more informative billing inspires changes in customer energy use behavior, which yields leverage energy and demand savings [78], and also reduces greenhouse gas emissions.

4.4 Improving Operational Efficiency

Smart grids offer a wide range of improved operational efficiency both at the transmission and distribution levels. Examples of operational benefits that can be achieved are distribution management functions, outage management, power theft detection, improved asset management, greater ability to load profiling, grid stabilization, and a variety of advanced metering functions [78].

An example of the above is the ability to reduce line losses [78, 81]. For instance, a higher level of instrumentation in a smart grid and its subsequent increased system visualization facilitates a more effective reactive power compensation and voltage control, which in turn leads to a reduction of system losses. A more effective voltage control can be accomplished by monitoring and controlling smart technologies, such as synchronous generators, synchronous condensers, shunt capacitors, shunt reactors, static VAR compensators (SVC), and STATCOM. Furthermore, through the implementation of adaptive voltage control, line drop compensation on voltage regulators and load tap changers to levelize feeder voltages at a substation level, a utility may render further reduction in distribution line losses.

Another example of improved operational efficiency that can be achieved by a smart grid relates to network security. Currently, network security is provided mainly through asset redundancy and preventive control. This paradigm results in low utilization of network assets for fulfilling the N-1 security criterion, and thus to higher operating cost and potentially increased emissions [66]. The wide implementation of information and communication technologies across the network, as well as advanced control technologies within a smart grid, allows a shift toward a corrective control paradigm. By relying on post-fault corrective measures, for instance, through the implementation of special protection schemes, the system can be operated much closer to its limits without jeopardizing its security. This ability may lead to significant savings in network infrastructure investment, a reduction in generation operating costs, and to a subsequent reduction in carbon emissions.

At the distribution level, a more efficient meter reading process may also lead to a reduction in carbon emissions [78]. Indeed, in smart grids, the metering functions are greatly simplified, since meters can be automatically read from a central location. Hence, the reduction in transportation requirements means less fuel consumption and consequently lower carbon emissions.

4.5 Enhancing Power Quality, Reliability and Self-Healing

Smart grids have a great potential for improving power quality [82] and reliability. On the one hand, future grids will have a significantly larger number of production units connected to the grid through power electronic interfaces, such as wind, PV and batteries. These units have the capability of injecting reactive power and, with a proper control scheme, they can effectively be deployed to provide voltage control over the grid [83] and improving power quality. With the introduction of new methods for Voltage-Var Control, a positive impact on the supply voltage variations is to be expected: both undervoltage and overvoltages will diminish, and very fast methods may even improve voltage flicker and reduce the number of severe voltage dips and swells. On the other hand, improving system reliability can be achieved throughout many smart grid functions, one of them being the automatic feeder reconfiguration following a fault. With the aid of communication technologies and automated switches and reclosers, smart grids will be able to quickly identify, isolate and restore the faulty part or section of the network [83]. The ability of a smart grid to react instantly to abnormal situations and isolate the problem before it derives in a major blackout [84] can significantly improve reliability indices.

Enhanced power quality and reliability have a positive impact on the reduction of CO_2 emissions since they arrest the deterioration of major equipment and increase their efficiency. This in turn leads to reduced energy costs and, ultimately, to the reduction of carbon emissions.

4.6 Increasing Observability and Controllability of the Power Grid

One of the major characteristics of smart grids compared to conventional power systems is their increased observability and controllability. At a transmission level, this is achieved by the deployment of WAMS and WACS [85]. At a distribution level, key technologies are AMI, along with the deployment of control schemes in the end customer equipment. Increased observability and controllability of the grid have significant benefits, such as improved grids stability, reliability and security, optimized transmission capacity, minimized transmission congestions, among others. Altogether, these benefits allow more efficient use of resources, particularly low-carbon generation units, and a successive reduction of CO_2 emissions.

5 Major Challenges for the Implementation of Smart Grids

The concept of smart grids is still evolving and despite its potential, several challenges must be overcome before they can be widely implemented. These challenges involve meeting social and technical changes that are likely to affect and replace established practices such as energy production, distribution and consumption.

5.1 Security and Privacy Challenges—Gaining the Trust of Customers

Different from conventional grids, a smart grid is a complex cyber-physical system that not only manages the flow of electricity but also massive amounts of information [86]. In smart grids, both the number of devices transmitting sensitive information, and the volume of data interchanged, will increase by several orders of magnitude [87]. This makes smart grids more prone to suffer from cyber-intrusion and cyber-attacks from industrial espionage and terrorism, as well as the inadvertent compromises due to user errors and equipment failures, as conventional grids do [88]. Therefore, information security in smart grids is considered a crucial problem [89, 90] with potentially catastrophic implications [91]. Some authors even identify the provision of security and privacy as the main challenge in developing a smart grid, even before physical support. Major security requirements and vulnerabilities include trust components, third-party protection, non-repudiation, auditability, authorization, authentication, integrity, availability, and privacy [69]. Given their importance, security has become a major area of interest for the research community, especially in cybersecurity, which is particularly challenging. For example, the "profile-then-detect" method used for identifying denial-of-service (DoS) attacks increases the detection time, while long key sizes in public-key encryption worsen the delay performance in data transmission [92].

Closely related to security challenges, privacy issues are becoming increasingly important as the grid incorporates smart metering and load management [87]. For end-users, electricity use patterns could disclose when they are at home, at work, or traveling, which devices they use, and when. This information may be used for criminal activities targeting homes [90]. For companies, a change in power draw may suggest changes in business operations and strategy. This information could be used by business competitors to take advantage of certain circumstances to their benefit.

Privacy of information is still uncertain and is needed to assure that sensitive information is protected and its released is controlled [93]. The most important requirements for protecting smart grids are confidentiality of power usage, the integrity of data, commands and software and availability against DoS and distributed DoS (DDoS) attacks [94].

5.2 Data Communication, Collection and Interoperability Issues

The current communication infrastructure in conventional grids is designed for unidirectional information flow and has limited efficiency and information sharing [95]. Data is acquired from a limited number of sensors located in the main generation, transmission and distribution points, and it is sent to the corresponding system operation for supervision and control purposes. On the contrary, smart grids include a large number of devices and applications that provide bidirectional information flow and that rely on real-time information. Consequently, smart grids require a fast and reliable communication infrastructure between multiple users. This two-way communication is an integral part of future smart grids [96]. Considering the vast development of new smart grid applications and the increasing number of devices that rely on real-time information, current communications infrastructure is inadequate and must be improved [93] to meet all application requirements. Upgrading communication infrastructures to enable smart grid applications involves several challenges. Some of the key ones are related to interoperability standards, communication networks and latency requirements [70].

Measurement science and standards play a key role in many of the technical challenges related to smart grids [93]. In smart grids, utilities and customers should be able to buy pieces of equipment from any vendor and be sure that they will work properly with existing equipment at every level [97]. Hence, a key challenge is the implementation of global interoperability standards that are accepted by all companies involved in smart grid development [95]. Several authorized organizations are already working on smart grid standardization, such as the Institute of Electrical and Electronics Engineers (IEEE) [98], the European Committee for Standardization (CEN) [99], the American National Standards Institute (ANSI) [100], the International Telecommunication Union (ITU) [101] and the Electric Power Research Institute (EPRI) [101]. However, gaps in communication standards are still significant [93], and therefore further discussions of such standards are still needed [102].

Upgrading the communication network of current power grids, which is based on decade-old technologies is another major challenge [70]. In this regard, an integral part of a smart grid is to have a high-performance, reliable, secure and scalable communication network [103]. The selection of an appropriate communication technology depends on the required network coverage, the types of data traffic and the quality-of-service (QoS) requirements, among others [73].

Finally, data latency may become the most important issue in the data collection and transmission, especially for wide-area control and protection applications [70]. In these applications, the data gathered at the control center needs to be issued within a few milliseconds in order to take proper control actions aimed at preventing cascading outages in real-time. To meet such requirements, utilities may adopt private networks through fiber-optic communication that allows for delivering high data rates over long distances, perform data compression to reduce latency or implement congestion management for data classification and prioritization of communication channels for emergencies [70].

5.3 Power Quality Issues

Power quality issues have been pointed out as one of the most important concerns in smart grids [104]. In smart grids, several power quality issues may arise both at the distribution and transmission level. At the distribution level, power quality issues may arise due to the massive incorporation of renewable energies in the distribution grid, the increasing use of power electronic converters, and the large deployment of end-user equipment communicating with the grid. On the one hand, renewable energies connected to the low-voltage network (e.g. solar panels) may result in over-voltages that may affect power quality [83]. Additionally, fast variations of renewable energies (e.g., in PV generation due to passing clouds) may significantly affect power quality, which is undetectable with current methods for quantifying power quality: these variations are too fast to impact the 10-min rms value and too slow to impact the flicker severity [83]. On the other hand, power electronic converters from wind, PV, and EVs are a source of harmonic emission, making high-frequency signals flow into the grid. In addition, as smart-grid solutions are deployed to improve system stability or increase network utilization (e.g., by removing overload limits), new power quality issues may arise [83]. Finally, the massive integration with two-way communication end-user equipment may interact adversely with power line communication that may reduce power quality [105]. For example, communication signals may distort the voltage waveform resulting in incorrect operation of the end-user equipment. When microgrids are present within a smart grid, further quality issues may arise. Microgrids within a smart grid can be operated either in grid-connected mode, where DERs operate in current-controlled mode or islanded, where DERs are operated in a voltage-controlled mode [104]. In islanded mode, the faster and more complex dynamics introduced by the power electronic converters, as well as the wider interactions between loads and DERs will result in more pronounced, more frequent and longer voltage and frequency variations [104]. This situation will be further aggravated by the reduced short circuit levels and inertia of microgrids and harmonics introduced by traditional grid commutated topologies [104]. The transition to different modes may also cause voltage stability problems due to the delay in detection of non-intentional islanding [104].

At the transmission level, HVDC links, whose number is increasing fast, is a known source of harmonics [83]. Even though conventional HVDC links are usually equipped with harmonic filters, these filters could also create resonance at other frequencies. In addition, new VSC-based HVDC links will introduce new types of harmonics, for example, supraharmonics caused by the switching of the valves [83]. Besides HVDC links, the deployment of AC cables may also affect power quality by shifting resonances to lower frequencies that impact harmonic distortion levels [106].

The transition from conventional systems to smart grids will bring new issues regarding power quality, different from the ones experienced in the past. As such, a great deal of research is required [83]. This would include, among others, further research efforts focused on improving and maintain the reliability of the grid when implementing smart grid [104], the impact of large-scale introduction of power-electronic converters at end-user equipment [83] and fundamental research in new types of disturbances that may appear [83]. In addition, even though novel power quality indices have been introduced, for instance, based on wavelet packet transform [107], further developments of new power quality indices and standards are needed [82].

5.4 Control Issues

Control science and engineering is a key discipline for realizing the objectives of smart grids initiatives [108]. In smart grids, the wide availability of modern monitoring, communication, and equipment forecasts the implementation of novel and advanced optimization schemes, which is an active research area. For instance, with renewables, the control of generation to match electricity demand becomes significantly more challenging because of increased intermittency and uncertainty [108]. In addition, production units connected to the distribution system will be able to provide network and system ancillary services, including voltage control. However, under this new paradigm, part of the voltage control would have to be performed on-site by customers or customers' equipment, which raises a general concern by network operators, since the responsibility in keeping the voltage within acceptable levels is still theirs [83]. Consequently, the provision of grid services in smart grids requires regulatory changes in order to re-defining roles and responsibilities [102].

Another challenge related to control issues results from the shift from large conventional power units to small distributed ones. This shift would result in operating conditions with a shortage of reactive power at the transmission level, which would have to be supplied by customers or production units connected at the distribution level [83]. This large flow of reactive power from the distribution to the transmission grid would lead to uncontrolled reactive power flows at higher voltage levels. One option to counteract this effect is an increased involvement of distributed generation to support the transmission system, which in turn can make voltage control of distribution networks even more complex [109].

The wide availability of information and communication technologies and flexible technologies within a smart grid also allows moving operational decisions much closer to real-time thus enhancing the utilization of existing network infrastructure without compromising system security [66]. However, this requires fundamental changes in the way power systems are operated. In smart grids, the current paradigm for ensuring system security against disturbances—throughout asset redundancy and preventive control actions—has shifted to corrective control actions that rely on post-fault corrective measures. This capability can be realized by a coordinated use of power electronic devices such as Phase Shifting Transformers (PST), battery energy storage systems, Flexible AC Transmission Systems (FACTS), System Integrity Protection Schemes (SIPS), HVDC, as well as renewable energy sources at both transmission and distribution level. Here, the main challenge is to develop appropriate control schemes that allow fully utilizing this capability.

5.5 Modeling and Forecasting Issues

The trend toward the introduction of smart-grid technologies in transmission and distribution networks does not only involves challenges in monitoring and control tasks but also more accurate forecasting when solving problems of accumulation and redistribution of consumption between different resources [110]. These challenges do not only arise because of the increasing use of renewable energies at both transmission and distribution levels, but also because of the deployment of distributed storage capacity—whose operation depends on customer behavior, which is, at the same time, hard to predict, even if sufficient price signals are available. For example, the large-scale introduction of EVs will significantly change consumption patterns and therefore the load profile in distribution networks will also change. End customers will probably charge their EVs whenever they see fit, so forecasting proper user-behavior may be very challenging. Hence, proper modeling and analysis tools are required, especially to address variability and uncertainty [102] introduced by renewable energies and customer behavior. The overriding issue is the lack of experience and understanding of customer behavior, for example, in relation to the demand response at a system level, where demand from different sectors and applications is aggregated [111].

5.6 Regulatory Challenges

The deployment of smart grids does not only require significant technological advances, but also several regulatory changes to take place to fully utilize their potential [112]. Challenges to regulators include utility disincentives, monopoly power, information asymmetry, consumer inertia and breach of personal privacy [112]. In addition, increased investment in innovation is urgent to allow for sufficient time for developing new solutions needed for multiple sectors and processes—many of which have long investment cycles. Technology innovation efforts will need to be complemented by new market designs, new policies and by new financing and business models, as well as by technology transfer. These technological innovations do not only refer to hardware changes, but also to new software, for example, dynamic pricing systems to encourage consumer participation, data management systems able to manage massive flows of information [112]. All these changes require regulatory modifications to set up new market rules and protocols [113].

6 Conclusions

The electric grid ushered in by Tesla about 120 years ago hasn't changed much in decades. However, like all things in life, sooner or later changes always come and we must be prepared to face them. The electric power industry is now experiencing a critical moment in its evolution where changes have already begun. The changes to the energy landscape are mostly driven by the need to decarbonize electricity systems, in an unbridled attempt by our society to stop the harmful effects of global warming and save our planet.

The transition towards low-carbon electricity systems is, however, not an easy task. It is not simple enough to switch from one fuel source to another. The energy sector must conceive a brand-new way of producing, transporting, and consuming energy. Although this transformation imposes several challenges, several opportunities arise.

Smart grids are the cornerstones to meet most of these challenges. Through a "smart upgrade" of our electrical systems, we will be able to overcome existing barriers and achieve the needed decarbonization of our electricity systems. However, smart grids are not a single silver bullet but a collection of technologies that, together with an enhanced communication infrastructure, advanced control schemes, as well as appropriate standards and regulatory schemes, will allow the economic and secure transition towards low carbon electricity systems.

We are now facing the third industrial revolution in the energy sector, and the entire society should rise to this challenge.

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Smart Grids from a Holistic Perspective

Antonio Carlos Zambroni de Souza and P. Alencar

Abstract The chapter provides some discussion regarding the social aspects of active networks, with special attention to the emerging technologies that may shape active networks and the connection with smart cities. For this sake, the role of other professionals is also highlighted, helping the reader to cement the concepts addressed in this book.

1 Introduction

The world has been experiencing a wide range of global issues in areas such as health, energy, food, water, poverty, and immigration, as well as social issues related to equality, inclusion, social justice, and human rights. Addressing these issues has increasingly become the focus of several approaches to social aspects that have been proposed in the literature [1, 2]. These approaches are becoming critical and are expected to transform the way we tackle global challenges and have a significant impact on science and engineering research, practice, and education.

Engineering education for social well being aims at paying attention to these issues and their impact on emergent technologies. In this context, these technologies, which include smart cities, smart grids [3], and Internet of Things (IoT) [4, 5], must be supported by holistic approaches that enable professionals with the appropriate knowledge and skills to tackle the critical social issues that modern societies are facing. These approaches should address how the syllabus can be extended to reflect a holistic perspective so that students can be in a position to make relevant contributions to the social good of communities and the world. In this chapter, we provide a holistic approach to engineering education on smart grids.

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1.1 Some Real Cases

Mr. X was a Ph.D. student at a high-reputation university. Usually, he worked until late hours with determination, and was restless toward completing his degree. As a demand from his university, he needed to publish in good journals so that the academic community could judge his research contributions. He worked hard and published some refereed articles that made him capable of defending his work before a thesis committee. Further, he was also encouraged to participate in good conferences, having successfully submitted his work to several international conferences. Unfortunately, one of his articles contained substantial material extracted from another work, which created a problem. Mr. X argued that he did not know he was violating any rule. This problem is more common than expected. Indeed, on May 30th, 2019, a search in *ieeexplore.org* based on the terms "notice of violation" obtained 10347 responses. So, Mr. X was not alone and, most likely, he was honest by arguing that he did not (intentionally) break any law. In fact, the story of the hypothetical Mr. X could have taken place in many other universities and research centers around the world. The concern about this problem exists in a wide range of professional activities, from arts to engineering and patent requests. Why? Why do people keep committing such an offense if its practice is subject to adverse ethical and legal consequences? A practical answer may be that people might have a suspicion about the illegality of the action but, in general, they are not taught about its serious implications. In many cases, reputations are tarnished and personal lives are devastated, which clearly points out to the need for young students entering the academic environment to have a broader education that includes topics such as ethics and the potential societal impact of their work.

Robert Moses was the head of the New York Transportation Department from 1920 to 1970. Such a long period allowed him to enhance the city infrastructure in many ways, through the construction of parks, bridges and parkways. He even had many of these developments named after him. However, some historians claim that his work was somehow associated with bigotry. The reason for this claim was that he had allegedly ordered the Southern State Parkway's bridge to be built very low to prevent black Americans and Puerto Ricans from using the parkway. Also, he vetoed the extension of the railway that could allow low-income people to go to Jones beach. This story is detailed in [6], and even though a debate may arise about his real intentions, his actions are certainly worthy of discussion. In this sense, Engineers must be aware of the political and social consequences of their works. The personal characteristics of Robert Moses should not matter, but his alleged actions, intentionally or not, may have prevented a portion of society from enjoying some technological and natural benefits that everyone had the right to enjoy. Even more complex, the social implications of engineering may involve the workers, and not only the end-users. In this case, alcoholism, diseases, and social disruption may need to be considered to plan, conceive, and run a project. Other problems may be related to pollution emission and transportation lines in low-income communities, which may increase social exclusion [7]. The advent of smart cities poses an additional challenge to Engineers, who must consider sustainability and social inclusion as fundamental components of their projects. As a whole, the cases above lead to a discussion about the moral principles of Engineering.

This chapter is not at all meant to assert that Engineering is an evil aspect of society because no one denies its amazing benefits. On the contrary, the idea is to propose the incorporation of ethical aspects into its scope in a multidisciplinary manner, so that smart grids and smart cities will focus on their end users. Many universities are dealing with this problem using a case-study approach that promotes discussing (un)ethical acts. These cases involve situations and ethical dilemmas, for example, in business, medicine, technology and government. In addition, merging Engineering and social inclusion has also become a matter of concern recently. The Engineers without Borders project [8], for example, is a noble initiative that promotes social and global development and inclusion. The first goal of the project is to create a new generation of global Engineers. For this sake, social inclusion is one of their focal points, as mentioned in their webpage: "The member groups of EWB-I share the mission to partner with disadvantaged communities to improve their quality of life through education and implementation of sustainable engineering projects while promoting global dimensions of experience for engineers, engineering students, and similarly motivated non-engineers". EWB-I creates links between these like-minded organizations and cuts across national borders. In Brazil, they ran a program to teach low-income students to build cheaper solar water heaters. The idea was teaching the principles behind the development process and taking the experiment to a poor community in the city. In Argentina, they promote projects involving sustainability, energy, and community infrastructure.

Other examples involve Engineering students working on social activities to help poor students who want to enter a university. In one case, some students in Brazil created courses free of charge to prepare students for the unified university's admission test. They take care of the administration, teaching, and selection process. The idea has spread throughout the country, benefiting thousands of young students. This makes clear that Engineers may make a difference by promoting gender and social inclusion. Elmina Wilson made history in 1892 by completing her degree in Civil Engineering in Iowa and, for this reason, women became numerous in Engineering classes everywhere nowadays. Before that, Edith Clarke placed her name in the pantheon of great Engineers and became the first woman engineer-teacher in a university in the United States. Hence, Engineering can be an area that supports social inclusion in many different ways, so that projects consider the end-users' characteristics and cultures, and people of different races, ethnicities, genders, social classes and physical abilities are all encouraged to become Engineers.

1.2 Motivation

The cases above show that Engineering practice may lead to both positive and negative consequences. One could argue that the majority of Engineers fulfill their daily activities with little social, or political concerns because they have a specific technical target to reach in each of their tasks. This is a key point of this chapter, as we agree with a strong trend in the philosophy science which claims that technology is not neutral and should be viewed in a broader, holistic perspective. This perspective introduces new concerns about Engineering education and practice. Based on these observations, in this chapter we focus on a holistic approach, and both on how smart grids may enable smart cities and how smart cities will shape professional practice.

1.3 Smart Cities as a World Policy

Several international organizations, including the World Bank, are working on projects that promote inclusion and take into consideration the increasing urbanization and the ever greater number of refugees migrating into urban areas [6]. The World Bank has introduced an approach to smart city planning based on three connected dimensions. The first one regards spatial inclusion. Unplanned cities may have a poor occupation of spaces, yielding to further poverty and social exclusion. This is linked to economic inclusion, which is more easily achieved when a city is well planned and economic opportunities and clusters of companies arise as a result. Finally, it is proposed that no one must be left behind and, for this purpose, gender issues must be addressed. The high rate of women in informal jobs is a concern as well as the fact they are prone to violence in urban areas. People with a disability also deserve special attention. In this case, the planning of a city must consider people, for example, who use wheelchairs, are blind, the elderly, or any others who may be adversely affected by the lack of social inclusion.

Several ongoing projects [6] span some initiatives sponsored by the World Bank. For example, in the city of Tbilisi, Georgia, social media data and semantic analysis are employed to map the use of public space, whereas in Port-au-Prince (Haiti) cell-phone data records combined with machine learning techniques, are used to identify the most common traffic patterns and the vulnerabilities of the transport network subject to flooding risk. In La Paz, Bolivia, the creation of an SMS/online citizen engagement platform (Barrio Digital) helps citizens to identify the needs for infrastructure improvements and interventions in the city. Finally, in Dar Es Salaam, Tanzania, the use of OpenStreetMaps and other open source platforms together with local volunteers collect detailed terrain information and develop flood models that supported resilience infrastructure plans and preventive flood measures in the city.

The initiatives described above, supported by society and funding agencies, show that a holistic background is mandatory for Engineers. This is explored in the next sections, where social consequences of an energy supply failure are reported, and some projects are discussed within this inclusive approach.

1.4 Towards a Holistic Approach to Smart Grids

In July 1977, New York went through a blackout that caused riots, loot, fires, and violence all over the city [9]. Investigations on the technical nature of the problem showed a cascade of events that finally caused the system to fail. From 8:37 PM, when a lightning tripped out two circuit breakers in Buchanan, until 9:36 PM, only one hour later, several technical issues, such as an overload of transmission lines, generators unable to meet the demand and voltage sags, worked in combination to create a perfect storm that drove the city to darkness. Also, the load shedding scheme was not enough to alleviate the system, and a further combination of human and automation failures worsened the problem. A core question remains: Why did a blackout trigger such chaos? The first answer lies in the fact that it all happened following the major fiscal crisis of 1975, which created an atmosphere of tension and a feeling of anger amid suburban communities. Though, why some people looted, while others volunteered to help the traffic to flow safely? Figure 1 illustrates some of the effects of a blackout of New York [10].

We understand, in this chapter, that the lack of electricity may drive some people to unexpected social behavior, given that energy supply is a vital resource of daily life. The interruption of energy supply in New York created several social problems whose types must be addressed by Engineers, e.g., food spoiling in refrigerators, (an aggravated problem for needy communities), public transportation disruption, streets

Fig. 1 Effects of blackout of New York

in darkness (increasing the risk of crime), among other problems. Because electricity should be acknowledged as a right, needy people could receive subsidies so that they can have access to this fundamental asset. A holistic and practical view of electricity as a common good must consider the different realities of the communities involved. The following examples illustrate this statement:

The Brazilian program "Light for all" [11], a rural electrification program, was meant to provide electricity to poor rural communities. Initially, the idea was to provide electricity to 10 million people. Launched in 2003, in 2016, almost 16 million people were benefited. The social impacts may be understood by a poll among the benefited, that showed that 81.8% told that electricity improved their life conditions, 56.3% felt safer, and 40.5% had better job opportunities.

– Despite the huge number of people without electricity in Africa (about 600 million people), the increase in access to electricity surpasses the growth of the population. In this case, replacing the lighting from kerosene to solar panels or conventional distribution systems, besides increasing the comfort, reduces the risk of fire from kerosene, still present in a large number of villages.
– In Canada, over 200.000 people live in remote communities, so off-grid supply is the only option. In this case, the diesel-driven generator is the main source of energy in many places, but many projects to consider renewable electricity generation are underway.

The examples above may trigger different reactions according to the perspectives of each reader. We understand that business interests are relevant, but these examples show that disregarding the reality of a specific community may produce catastrophic results in case social good is forgotten. A city should be considered smart as long as it provides the best to its population. This is in accordance with the definition of smart cities, which claims that smart cities "are those that use technology to promote the well-being of residents, economic growth, and, at the same time, improve sustainability". Such a concept spans a wide variety of expertise that should be considered together in the planning iof a smart city [12]. In this sense, a holistic approach focuses on the users, considers the specificity of each region, and favors people who have disabilities or are underserved, constituting an inclusive methodology.

2 Holistic Approaches to Engineering Education

Holistic approaches to engineering education aim at understanding society from a system-oriented perspective [13, 14]. In order to understand complex systems, these approaches claim that there is a need to understand not only the technical aspects of the problems (e.g., mathematics), but also human nature and and its complex social-technical interconnections in the world. This complexity becomes evident when we consider, for example, human decisions in complex systems such as those that focus on the function and operation of smart grids.

Several authors have advocated the adoption of a more systemic research-oriented method to support continuous improvement and innovation in engineering education, as seen in references [15, 16]. Engineering education, they argue, should recognize the importance of several approaches that can serve the diverse needs of society. These approaches, which are sometimes called engineering education for social good, take into account not only the global issues that society faces, which include health, energy, food, and water, but also social issues related to human rights, equality, inclusion and justice. To realize this perspective, engineers are encouraged to understand that within a more systemic approach they can use their skills to find solutions that directly contribute to solving major social issues.

Systems thinking can be seen as a powerful catalyst for social change [17, 18]. First, systems thinking motivates people to see their responsibility for the current reality and see themselves within the context of the problem they are trying to solve. Second, systems thinking promotes collaboration because people learn that the how their current ways of interacting actually result in the unsatisfying results that compromise in the end not only their individual but their collective performance as well. Third, by assuming a system-oriented perspective, people can work on a few coordinated changes that leads to system-wide significant and sustainable results. Finally, systems thinking promotes continuous learning as people learn that their actions matter and that they need to learn from the consequences of these actions.

Overall, systems thinking leads to collective impact [17]. This impact is caused by developing mutually reinforcing activities (e.g., a better understanding of the individual impact to a problem), building a common agenda (e.g., a shared understanding of the root causes of a problem and how people contribute to it), defining shared measurement (e.g., better performance tracking with respect to systemic theories of change), and promoting continuous communication (e.g., the need for communication based on continuous learning). These characteristics can be illustrated with respect to several aspects and provide a number of relevant benefits [17, 18], such as those listed in Table 1.

2.1 How Smart Cities Shape Professional Practice

Technological progress changes the structure and the way professions are exercised. As an example, truck drivers nowadays can drive more easily thanks to the modern features of heavy vehicles that were not available a few years ago. Even the GPS helps these drivers to move around in places they have never been before. Similar examples that illustrate technological benefits may be given with respect to the majority of professions, rendering technological changes as a major factor affecting professional activities. The next sections describe how some professions may be particularly impacted by the advent of smart cities. Other professions could be included, but the ones discussed exhibit a clear impact in their daily routines. In common, they share the demand that professionals must always be up to date in their areas because of

Table 1 Characteristics and benefits of a system-oriented holistic approach

Characteristic	Benefit
Relies on reinforcing activities	• Improves trust and vulnerabilities through a more comprehensive awareness about the unintended consequences (e.g., social problems)
	• Promotes a better understanding about the impact of individuals and groups
Supports a shared agenda	• Relies on a shared language that takes into account not only local consequences, but also systemic intra- and inter-dependencies, delays and consequences
	• Supports a shared willingness to change that makes the benefits of the status quo more recognizable
	• Relies on a theory of change that is systemic and not specific to single domain
Supports a shared assessment process	• Relies both on qualitative and quantitative data
	• Assesses progress based on multiple time intervals
	• Takes into account both intended and unintended consequences (e.g., social consequences)
	• Assesses performance in terms of system-oriented theories of change
Relies on continuous communication	• Improves communication because of a stance that demands increased personal responsibility for the consequences (e.g., social consequences), stronger alignment based on a shared agenda, and increased awareness that allows to take into account not only short-term but also long-term consequences
	• Relies on continuous learning because of the continuous communication aspect of the approach

the frequent technology changes. Smart grids may also help defining the shape of these professions. The following subsections briefly describe the potential changes that smart cities may impose on professional practice.

2.1.1 Information Technology

The way a passive distribution system becomes a smart one depends on the existence of distributed generation and the level of automation. Regarding distributed power generation, communication technologies enable, as a fundamental component, the creation of local controller of a microgrid. This local control involves regulating primary voltage and frequency. Information technology will play a major role to improve the efficiency, control and management capabilities of smart grids. In addition, regarding the level of automation, information technology will also help support decision making by providing intelligent and proactive methods (e.g., neural networks) to support the estimation of electricity demand, forecast energy production and consumption, and predict system risks and failures.

2.1.2 Machine Learning Scientists and Engineers

Smart cities require, for most of their features, a high level of automation. In this sense, machine learning seems appealing. Machine learning is an application of artificial intelligence (AI) that provides systems the ability to automatically learn and improve from experience without being explicitly programmed. Several applications may be identified, such as self-driving cars and face recognition. Thus, as novel smart city applications emerge, some of the professions not related to information technology will need to deal with machine learning. As for machine learning itself, scientists and engineers will have a myriad of opportunities to introduce new approaches and applications. Machine learning scientists typically can focus on new smart algorithms, while a machine learning engineers can provide new robust and intelligent software solutions.

2.1.3 Cybersecurity Analysts

Smart cities demand a huge amount of data to be processed, which range from traffic lights control to energy management. In this sense, it is important to keep the system secure with the help of cybersecurity especialists. Cybersecurity is originally meant to protect networks in such a way that hackers can not invade and harm the system. Private issues are also a concern, since fraud in bank accounts and private data are constantly reported and feared by system users of all ages and backgrounds. Smart cities are composed of a high degree of automation, which includes the physical safety of people and domestic appliances remotely controlled, among other features. However, it is important that CCTV cameras work properly and with their data protected in a privacy-friendly way. The same concept is applied to traffic lights and domestic appliances, since they involve public security, privacy and comfort. Smart cities are also related to smart grids. Cybersecurity attacks to power systems are a major concern, and some countries have already reported suspicious activities regarding their transmission systems, and even nuclear facilities. Coordinating a smart grid in a good way enables a healthy smart city operation, since the provision of electricity enables most of the daily vital services to society. The conditions described previously make cybersecurity specialists a vital profession in smart cities.

2.1.4 Geospatial Scientists

Global Positioning Systems (GPS) and the popular map-based applications available in internet have changed the way people move around from place to place, especially in unknown places, making travels safer and faster. They rely on Geospacial science, which uses remote sensing, Geographic Information Systems (GIS) technologies to provide accurate and useful data. The scope of this field, however, is much broader. The professionals working in this area may play a crucial role in the development of novel applications. They can, for example, help to improve the operation of waste collection vehicles, so that these vehicles follow an optimal route in an established region. As a consequence, law enforcement agencies may map critical areas by using this tool. Pollution control may also be enhanced by using GIS, enabling the identification of the best (and worst) locations with respect to air pollution, water contamination and waste accumulation. Such professionals must be incorporated into the daily activities of a smart city for planning and operational purposes, so that critical issues are considered. Operational applications involve real time data exchange between different city sensors and devices, and can provide valuable data to support public agents and policy makers to make the best decisions in a specific scenario.

2.1.5 Health Care Professionals

Any realistic definition of smart city needs to take into account inequalities, hunger and the general well-being of the population—that is to say that smart cities must work for people. In this sense, health care disparities may be reduced if technology is deployed for this purpose. Health care needs to provide access to physicians in a preventative manner, so that the basic health concerns of the public can be directly addressed by family doctors using appropriate technologies. Regarding preventive approaches, technology may help individuals to locally monitor their health with equipment that may flag some health problems, alleviating the need for emergency rooms in local hospitals. In this sense, technology may help to remotely monitor the elderly. These examples showcase worthy possibilities, since ordinary people will be able, with no medical knowledge, to have access to real time information regarding their health. In case of an emergency, a call requesting hospital transportation can be automatically made and not only the patient but also the cause of the alert can be identified.

These promising scenarios for patients require an important action from health care workers. They will benefit from the technological advances, but they will need to be open to new resources as well. Diagnoses will be subject to Artificial Intelligent (AI) processes, helping medical doctors to infer the conditions of a patient. This still relies on medical knowledge, since feeding the software and interpreting correctly its output will require a strong medical background. Medical procedures may also be helped by software and hardware, enabling a doctor to execute a remote surgery. This environment, though revolutionary, demands that medical professionals be humble enough to agree to be helped by intelligent machines and incorporate these solutions. The telehealth system adopted by many countries due to the pandemic in 2020, however, shows that medical doctors tend to be open to new automated approaches to health services.

2.1.6 Engineers

Engineering is certainly among the most influential (and affected) fields of work related to smart cities. For this sake, some areas could be exploited. Because this chapter deals with the problem of how smart grids may enable smart cities, renewable energy generation is argued to be a key issue. Microturbines (wind or diesel-driven) may be present in smart cities, which demand the knowledge of an electrical engineer to take care of their operation and maintenance. Note, however, that their construction depends on civil and mechanical engineers, since they need to be incorporated into the city landscape in a safe way, so that people and animals are not jeopardized by the presence of generation equipment. In the islanded mode of operation, in which a smart grid must be able to regulate internal frequency and voltage, the grid also needs proper supervisory control. This control can depend on multi agents or traditional system operators.

The major point of concern regarding how engineers fit smart cities, however, is not their ability to deal with the technical challenges. It is vital that the syllabus of Engineering courses incorporate holistic aspects in the courses. Note that creating new courses on holistic aspects of Engineering may produce poor results. Alternatively, we claim that holistic aspects may be incorporated into existing courses, so that the students will have a broader view about the social consequences of Engineering.

2.1.7 Architects

As discussed previously, smart cities must use all their resources to improve the well being of their citizens, reducing inequalities and improving access to goods and services. Architecture is essential in this scenario. Architects will be requested to design increasingly sustainable buildings, which can provide provide comfort to its occupants while demanding less energy. Thermal comfort and access to people who have disabilities are factors to be considered in the architectural designs. Public spaces must also improve urban mobility and include recreational areas, optimizing the transportation time to work and leisure locations. As mentioned previously with respect to Engineers, Architects are not typically trained to cope with these scenarios. Actually, the debate on the aesthetics and function has been going on for a long time among the professionals of this area, but the advent of smart cities makes this discussion still relevant because smart cities should be both functional and visually attractive.

2.1.8 Elementary Teachers

Special attention must be paid to elementary teachers. Actually, most of the discipline and safety protocols practiced by children are taught in schools. Further, teachers will be the primary source, along with families, of knowledge about new ways of learning and socially interacting in society. Thus, teachers must be prepared to cope with these trends by using new computational tools and proposing novel playful games to enable children to handle a range of daily activities that smart cities may offer.

Smart schools, which focus on the students and their realities, will become a necessity. This will be a challenge for new teachers, who will need to integrate social and technological skills to provide inclusive methodologies in their classrooms. This will lead to improved cities, where, ideally, all the resources in a city will be put available to its citizens. For this sake, virtual reality, internet access and digital innovations will be important tools to enhance the learning process, enabling children to visit museums, archaeological sites, and other places otherwise difficult to access. These advances will enable young students to have contact with different realities, which creates empathy and promotes novel strategies to improve social inclusion throughout the world.

3 Holistic Smart Grid Projects

Smart cities demand smart grids to make them viable [19]. The holistic and practical nature of smart grids embraces several concepts that go beyond the basics of Electrical Engineering. Thus, this section discusses some technological projects that, thanks to the Internet of Things and communications infrastructure, add the concept of smart grids to the smart city paradigm. The goal is to provide a brief presentation of projects that enhance the quality of life of the population through solutions that depend on electric energy.

3.1 Smart Buildings and Smart Elevators

An important question regarding smart-anything is how to make smart a traditionally designed project. Buildings fit this concern, because outdated buildings may become smart with the addition of some design-embedded smart features. For example, the problem of urban floods could be mitigated if smart buildings had cisterns to collect rainwater, which would be easy to set up during the construction stage. The thermal comfort may also be enhanced during the project and construction since appropriate materials and comfort-driven architectural aspects should be considered. It should be noted that a smart building, in so many aspects, mimics a smart grid. Hence, some considerations about the normal operation of smart buildings may be summarized as follows:

Optimized cooling and heating. A central controller automatically adjusts the temperature of different locations of the building, taking advantage of the information about how many people need the service, and reducing the costs of electricity.

Matching occupancy patterns to energy use. Connected to the item above, not only cooling but also the intensity of lighting is determined according to the number of people present.

Proactive maintenance of equipment. This enables equipment to be proactively maintained before any problems occur. This concept may be further expanded to include fire alarm alerts related to maintenance problems.

Dynamic power consumption. It takes into consideration the market prices, which optimizes the building consumption and even enables to sell to the grid the surplus of energy in case solar panels are available.

A smart building has an overall structure that integrates all the involved technology to share information in such a way that comfort is maximized whereas operational costs are minimized. That may be costly since a smart building requires sensors to identify how many people are circulating in specific areas of the building. Automation and data collection are directly linked to sensors, and they help a building to adjust its operation for any condition. The employment of sensors enables the cooling system to adjust the temperature in different parts of the building as a function of solar incidence and local temperature. Another interesting option is the use of smart windows since they help the cooling or heating system as well as the lighting process. In both cases, the energy savings and well-being of the users are taken into consideration. The following aspects should be considered to install smart windows: The solar heat gain coefficient, that is, how much heat is conducted through a window (U factor, which should be as small as possible), and the amount of visible light that can pass through a window (between 0 and 1, and the higher, the greater the amount of visible light).

Smart elevators are another concept that smart buildings embrace [20]. Smart elevators differ from conventional ones by not having a button board that allows people to click it during the trip and make unprogrammed stops. Thus, central controller groups people according to their destination floors, saving the number of stops and reducing the travel time. Besides, if the elevator is fully packed, it does not stop at any further floor, saving energy and reducing the travel time. They provide a number of functions as described in Fig. 2.

Some flaws, however, may be pointed out. The first one regards the fact that a user is given the information about which elevator they are supposed to ride. Such information may be misleading to some users, who may become confused when interpreting the visual displays. Another flaw is, ironically, the automation of smart elevators, since some users would like to change their destiny floor during a ride, which is not possible in a smart elevator. The economical and ergonomic gains of smart elevators, however, surpass most of the problems identified by some users.

Smart buildings and elevators in emergency conditions. A smart grid must provide a continuous and reliable service to its users, and so must a smart building. Some strategies are proposed to help people to evacuate a building in an emergency [19]. A similar approach is proposed in [21], where a fuzzy-based methodology is proposed. Emergency lighting provided when there is a lack of supply from the main system is also a possibility. In this case, batteries may be used along with sensors, so that occupied halls are automatically illuminated by emergency lamps. As for elevators, holistic procedures are particularly necessary. This is because some people may have claustrophobia, leading to major health problems in emergency conditions. Besides energy recovery, which allows injecting into the system the surplus of energy from the elevator, a scheme that drives the elevator to the immediate lowest floor in case

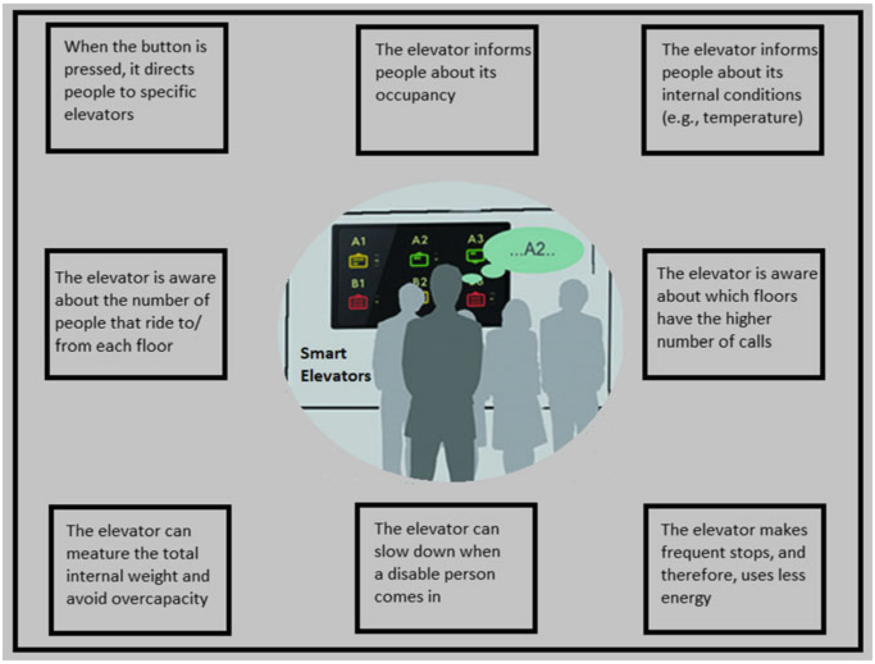

Fig. 2 Some smart elevator functions

of emergency has also been adopted. This allows users either to leave the elevator and wait in the hall the return of energy supply or walk up or down the stairs to their final destination.

3.2 Electric Vehicles and Improved Mobility

Electric vehicles are about to change the way mobility takes place in cities. Some challenges, however, must be overcome to make this a viable reality. In this sense, recharging stations and battery improvements play a crucial role as well as are subject to criticisms. This section describes the changes electric vehicles may bring, including some advantages and disadvantages, and explains how smart grids are connected to this concept of mobility. The first advantage of electric vehicles regards their clean operating conditions. They make no noise, increasing the quality of life in cities, especially for pedestrians, who are commonly affected by the high levels of decibels produced by vehicles. The other advantage comes from the nonpolluting motor drive of these vehicles. This, although considered an advantage, also places a concern regarding the way car batteries are recharged.

Thus, before considering projects that enable car owners to take the advantages of electric vehicles, concerns about how to recharge electric vehicles must be addressed. Indeed, if the primary source of energy comes from diesel or coal, for example, the pollution consequences remain, and the emissions of polluting residues are not reduced. Thus, the advent of electric vehicles is appealing if connected to the increase of renewable non-polluting energy sources, which is exactly the trend we are currently witnessing. As for recharging a car battery, indeed, it is not as fast as fueling a tank of gasoline. Faster recharging is now being proposed, but it may take about 30 min. Hence, charging electric vehicles overnight seems to be a good strategy, as long as they have good autonomy. Since the number of vehicles connected to the grid may be a burden, special operating actions must be implemented [22]. Another important issue regards battery disposal, since it may create an environmental problem. Recycling batteries could be a good alternative, despite its high cost. Reusing old batteries, however, may be a promising practice. In this sense, some manufactures are using old batteries to power streetlights, backup for elevators, storage of solar generation, and support domestic uses. This places electric vehicles as an excellent option for mobility purposes.

3.3 Smart Traffic Lights

Smart traffic lights are a vehicle traffic control system that enhances traditional traffic lights with sensors and intelligent techniques to support the traffic of vehicles and pedestrians [23] (Fig. 3). They provide several benefits as illustrated in Table 2.

Fig. 3 Smart traffic lights

Table 2 Some benefits of smart traffic lights

Item	Benefit
1	Reduce congestion
2	Reduce travel time and fuel consumption
3	Make roads safer by reducing accidents
4	Improve transportation using collected data
5	Reduce pollution
6	Prioritize traffic flow
7	Improve response time for solving traffic problems
8	Support data analytics
9	Support other applications (e.g., smart parking, smart roads)

Smart traffic lights can significantly reduce traffic congestion, which is one of the major problems in urban areas as they adversely affect productivity and fuel consumption. By relying on sensors and surveillance cameras, they can provide a more detailed real-time picture of the traffic situation, providing information, for example, on the number of cars (e.g., waiting in specific lanes, taking turns), their location and speed. By relying on sensors and intelligent methods they can help minimize travel time of the vehicles by coordinating the movement of vehicles at road intersections, and, by learning from measured demands, change traffic signals depending on the specific traffic demand at some time during the day and the night. The application of intelligent techniques such as continuous learning allows constant adaptation with respect to traffic patterns and flow. In this way, they can adapt in a more timely way to specific situations to keep the flow of vehicles at efficient rates, cutting down travel time, reducing pollution from idling cars, and making the roads safer. They can also adapt to the time of night and season, so that energy usage is optimised with respect to changing circumstances and situations, which lead to significant energy savings energy savings for both drivers and governments. In addition, the data collected by smart traffic light systems can be used to improve transportation in general as they can be used for valuable data analytics. In case they are coupled with sensors, they can even facilitate real time alerts and benefit other applications such as smart parking and smart roads as well as help deal with issues such as electrical outages and possible accidents.

Some smart applications involve traffic lights that are distributed in a simulated neighborhood that rely on neural networks to enable them to make decisions based on the data collected from the environment [24]. These applications are critical in areas such as environmental monitoring, energy consumption and health.

4 Technology Solutions and Smart Grids Enabling Smart Cities

The previous sections have described some projects that are relevant to the design a smart grid and a smart city. It was argued that a smart city should be one that aims to have no exclusion or hunger, while promoting social justice for all its inhabitants. In summary, life in urban crowded smart cities depends on several dimensions (Table 3), including smart energy, smart transportation, smart environment, and smart waste management. In conjunction, these dimensions can be seen as a thermometer of the well-being of a city. One should note, however, that energy may help a society to handle many of these dimensions, including the ones related to transportation and waste management. Note that, even garbage, if well managed, may become energy. Indeed, energy is the core of how smart cities operate and one of its main dimensions.

Governments play a central role in planning of smart cities. Projects regarding the use and design of different infrastructures may be embraced by academics who can consider technical and holistic features involved. In this sense, governments need to provide policies direction and financial incentives to society, whereas policy thinkers must consider the reality of the society to which they belong. The infrastructure itself considers all the existing framework, so that they are made as smart as possible. In contrast, telecommunications may be used for health care by the means of enhancing the telehealth services, alleviating hospital occupancy and addressing minor medical conditions remotely. The public space may also be redesigned in such a way that public transportation and leisure areas may help to change the aesthetic of cities. Note that new projects should take into consideration these demands, as well as others not previously addressed. For example, it is reasonable to require that new

Table 3 Some dimensions of smart cities

Item	Dimension
1	Smart environment
2	Smart energy
3	Smart transportation
4	Smart education
5	Smart healthcare
6	Smart safety
7	Smart economy
8	Smart waste management
9	Smart emergency management
10	Smart infrastructure
11	Smart people
12	Smart policies
13	Smart resource consumption

buildings collect the rain water, mitigating the risk of flood in crowded urban areas. All of these characteristics enable one to plan and design cities that are safe and have a high quality of life, collaborating to the well-being and inclusion of their citizens, who are the the major end-users of a smart city. Thus, a smart city does not fit exclusion, and social inclusion projects are a vital part of a successful smart city endeavours. We emphasize that the local culture and specific city characteristics should also be incorporated into a smart city project. This will enable designers to respect the local realities and plan according to people's real needs. In this sense, a remote village may be considered a smart city because it fights hunger and provides full access to electricity and water that is considered safe to drink. These concepts stand for large cities as well, but they also focus on improvements in mobility and telecommunication technologies. All of these concerns must be addressed by a design of an inclusive-smart city.

4.1 Smart Grids and Self-Healing Systems

One of the main aspects of smart cities regards self healing [25], and electricity is one of the main infrastructures involved. The concept of self-healing may be connected to smart grids, one of the main infrastructures to keep running after a disaster takes place. Preventing problems plays a special role in this process. Thus, drones may help to monitor distribution lines and execute minor repair in public lighting, for example. Robots may make inspections in tubes that are hard to humans to execute, while sensors may trig automatic actions to preserve the integrity of the system while supplying energy to high priority consumers.

Electricity shortages may cause several problems to society. They may range from simple problems such as traffic lights going out to serious issues such as hospital blackouts. Microgrids may become an alternative in these critical conditions, as part of the energy load is supplied by them. In this sense, local communication and control schemes, usually employed in smart cities demands, are adapted to emergency conditions, along with local generation. Hence, batteries, solar panels and microturbines may supply priority loads. Note, however, that the concept of priority loads may change according to the time of the day. The blackout of New York described above shows that public lighting and traffic lights are important features that help people to remain calm in some situations.

Establishing the necessary, or even vital aspects of a smart city in emergency conditions is only properly achieved by taking into account energy supply considerations. Note that, even water supply depends on electricity, at least, in the final stage of the distribution process. Hence, a smart city depends on a smart grid in normal operating conditions, but the infrastructure of a smart grid may be quite important for emergency conditions as well.

4.2 Vehicle and People Mobility Approaches

In spatial-temporal data analysis, location data and its evolution through time are investigated with the goal of uncovering important information to provide novel insights [26]. These insights may involve, for example, congestion identification in transportation, which affects fuel consumption, mobility patterns in urban computing, and storm prediction in weather forecasting. These issues can be directly related to emergency conditions in smart cities. Also, predicting the demand for ride-sharing services based on spatial-temporal factors, such as the history of orders, tracking of rides through GPS, and the weather, is a spatial-temporal data analysis task of great value to organizations supplying these services and to the general public.

Clustering, one data analysis technique, groups spatial-temporal data based on location. Some intuitive examples are clusters of people and vehicles, but clusters of animals or even stars are moving clusters too. Cluster relationships are interpretations of the movement between clusters and elements or other clusters, such as enter, or merge. Current spatial-temporal data analysis techniques fail to investigate relationships between spatial-temporal clusters, such as splitting from a cluster and merging with another one because of a change of properties over time. These relationships can hold valuable information about the existence of a cluster and its interactions with other clusters and trajectories. We have introduced a framework to identify, process, and analyze relationships between clusters of spatial-temporal data (e.g. enter, merge, or split).

We have described its architecture and components, as well as the clustering technique used, the different approaches for distance calculation that take into consideration Earth's curvature, and how we calculate cluster similarity of temporally separated clusters. The result of these operations are used in the identification of cluster relationships over space and time. Analysis of these relationships helps uncover hidden values that could support novel approaches to more effective decision-making. We evaluate our framework with two case studies, based on truck and human trajectories.

Supported by the massive amounts of data collected in modern cities, based on clustering methods, exceptional changes related to the mobility and flow of people and vehicles can be identified in real time in an automated way [27]. These methods can support managing a wide variety of emergency situations and crises. They can be the foundation for models that can help cities to improve their emergency management capabilities related, for example, with disease transmission, traffic problems, pollution, and flooding.

5 Conclusions and Future Work

This chapter advocates that Engineering should adopt a holistic approach that relies on a more comprehensive perspective for problem solving. According to this perspective not only the technical aspects should be considered, but also social issues related to equality, inclusion, social justice, and human rights. Our focus in this chapter is a holistic approach to smart grids enabling smart cities and, as we have illustrated, how the adoption of such an approach has been shaping many professions and the way they are exercised.

Holistic approaches are expected to transform the way we tackle global challenges and have a significant impact on science and engineering research, practice, and education. The field of smart cities in general and specifically smart grids can highly benefit from such approaches, as students and practitioners are enable to make relevant contributions to the social good of communities and the world.

Finally, because of the broad nature of the subject, this chapter is not meant to be comprehensive, and much future work is needed to pave the way for progress in the application of Engineering-oriented holistic approaches. Future work includes the provision of methods and practices for the migration of traditional projects to holistic approaches, curriculum extensions to support specific educational goals, and the exploration on how other types of emergent technologies, besides those that support smart grids and cities, can benefit from holistic viewpoints.

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The Coming Trends and What to Expect

Antonio Carlos Zambroni de Souza, Bala Venkatesh, and Pedro Naves Vasconcelos

1 Introduction

The intriguing topics addressed in the foregoing chapters may drive the reader to wonder about the power systems of the future. Indeed, such a challenging scenario places a lot of opportunities to young engineers as well as prosumers. In this sense, it is important that faculties be aware of the changes, so that the syllabus of their courses may follow this trend and anticipate the required changes to form new professionals. On the other hand, the industry is invited to play a role, since Research and Development projects will be a constant need, requiring a strong interaction between academy and productive sectors.

People, in general, tend to take electricity (and more recently, the internet), as a grant. This is a barrier to acknowledge the revolutionary impact of electricity in society. Rural and remote areas are transformed when access to electricity is provided. Such a transformation is visible to these people since new basic habits are incorporated into their daily lives. This is about to happen in the near future, when power systems will change drastically in comparison with their present shape, helping the advent of smart cities and posing new habits to everyone.

It is worth noting that the basic theoretical principles behind engineering practice still stand, and more importantly, it is vital that they are emphasized. At the same time, however, a myriad of new concepts are necessary. Also, old concepts, usually

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neglected, have now growing importance. This chapter briefly discusses some issues regarding the expectations of future power systems.

The next sections are not meant to propose new methodologies or describe some test cases. The idea is just to discuss some topics about this new scenario, provoking a philosophical interest in this fascinating process.

2 The New Old—Current War, DC and AC in Harmony

The war of currents was a defining moment in our history, shaping power systems and the way engineering is taught and practiced. Analyzing that war demands a visit to the DC and AC principles. Since this is a concluding chapter, we rather focus on the consequences of that war and the trends that may, somehow, "pacify" the battle. This is because future grids may be a combination of both DC and AC systems. By pacifying the battle we don't mean to forget the mistakes and the ethical implications of that war. In this sense, recognizing the talent of bright professionals and the potential of emerging technologies still has a place in the modern era. Thomas Edison acknowledged the superiority (for that period) of AC current shortly before his death, but would certainly be amazed by the current opportunities of joint AC–DC systems. On the other hand, sacrificing animals was not acceptable then and unforgivable now. Not to mention the experience with human beings on the electric chair, certainly the most repugnant of all actions in that era.

It is important to mention that when AC prevailed, Thomas Edison already supplied DC energy to local markets, where the distance between generation and consumption was minimal. AC finally prevailed because of the blocks of energy remotely generated, yielding the use of transformers and allowing the building of huge power plants. Note, however, that DC current had some advantages at that time already:

- generators could work in parallel
- DC managed well electric motors
- DC enabled the use of batteries
- DC provided reliable home lighting source

It sounds familiar to the reader since the items above were addressed in detail in the previous chapters. Indeed, a joint AC–DC world approaches. Ordinary users will be able to migrate from one world to another without realizing the technical implications associated with it. On the other hand, future engineers will need to enhance their skills in order to handle issues that nowadays are neglected.

One should not overlook, however, the dramatic way current war was fought. Some ethical dilemmas arose, as mentioned above, and they should be considered in current discussions of adopting technologies and designing projects.

Thus, future engineers will have the opportunity to have a holistic view of engineering, understanding how it evolved and adapted to different conditions. This deserves to be better explored, so a brief discussion on the skills of future engineers is carried out next.

3 New Profile of Future Engineers

Electricity is a vital piece of infrastructure, and supplying the end consumer in a safe and reliable way demands some miracles of engineering. This is certainly a room that fits mechanical, civil, energy, environmental, electrical engineers. The advent of smart cities and self-healing made electricity even more important. For self-healing purposes, it is an “island of infrastructure” that helps society to keep running basic devices following a disaster. It may be the borderline between survival and chaos of a neighborhood. As for smart cities, local distributed generation, electric vehicle issues, deployment of energy storage systems and connection with control and internet of things will turn passive distribution systems into active networks.

The examples above show that an electrical engineer must know some theories that nowadays, though important, are faced as secondary. Power electronics is acknowledged as crucial for HVDC transmission, but inverters demand an application of DC in medium and low voltage levels. This is also true for communication and control structures since they demand an understanding of new theories and devices. Just like in the lunar program speech of President Kennedy, future engineers will certainly deal with theories that have not been invented yet.

But technical issues are not a serious barrier to engineers. They can learn and propose new approaches as a consequence of dedication and focus on specific projects. The most important aspect of future engineering practice regards the holistic view of projects. Smart cities must be inclusive, and managing smart grids in islanded mode also demands a social empathy that must be considered during the design of new projects and their operation. Hence, future engineers are going to be, very soon, social actors with a strong theoretical background [6].

4 Energy Storage and Low Inertia Issues

Traditional power systems are based on high inertia rotational generators. Also, they are not intermittent-type of generation, which allows the planners to design a long term horizon of systems and operators to plan a day ahead with a good level of confidence. On the other hand, the circumstances of a blackout may demand long periods of reconfiguration [7].

This reality is about to change, since renewable energy sources may be associated with a high degree of intermittency and low inertia. Thus, engineers must consider this characteristic in planning scenarios, since the load must be supplied at all times. At the same time, even though local producers – or prosumers, as discussed in the next section—will play a central role, utilities still have their importance. The new grid will consist of several players of different sizes, but the generator park and the transmission grid have vital importance to make sure the load is supplied and also in providing ancillary services. How they will be remunerated and how the technical issues will be addressed by a central planner will be a matter of discussion in a short term [18].

When it comes to operating such systems, energy storage devices have growing importance. Some important aspects are addressed in the next subsections.

4.1 Frequency Adjustment

The intermittency of renewable sources tends to introduce frequency variations in the system. Normally, for huge rotational machines, the local controller and the overall frequency act to restore the frequency to its nominal value when an imbalance takes place. On the other hand, the massive amount of generation from low inertia sources may be a problem. In this sense, storage devices help the system to keep its nominal frequency, working as a frequency regulator.

This problem may be particularly tackled with the help of the droop method and optimization techniques, which may include evolutionary techniques. The problem of demand response may be incorporated into the formulation, so that prosumers may adjust their generation/consumption to balance the system, as long as the energy demand is met in the period of interest. The role of inverters, that emulate the inertia of machines is also important, and demand attention from engineers. Note the solution to this problem may consider technical and economical aspects that must be fairly analyzed by engineers.

4.2 Hosting Capacity

Another important role of storage devices regards microgrids application. In this case, the hosting capacity may be a problem. Thus, storage devices may work to store power during surplus periods, regulating the voltage level in connected mode. However, the advent of smart grids enables engineers to conceive systems in islanded mode. This places further importance on storage devices, since they may help to supply the load and increase the autonomy of the disconnected system.

Hosting capacity may help to mitigate problems in active networks, becoming a solution to some problems that engineers currently do not need to focus on. In this sense, defining the optimal location of batteries and playing system reconfiguration will play a significant role in microgrids operation. Actually, reconfiguration of microgrids may an appealing action to avoid overvoltages and reduce system losses, and hosting capacity may also be addressed in this context. Then, taking this problem into consideration is going to be mandatory.

4.3 Isolated/rural Microgrids

The islanded microgrid cited above takes place as a consequence of a contingency. In this case, the load is supplied according to a priority class previously established. In some countries, however, remote systems are a reality. Depending on the social condition of the country, diesel generators help, while in others, rudimentary sources of energy are found. Emerging power systems must be inclusive. In this sense, a combination of diesel generation, renewable sources, and batteries work to supply the load continuously in isolated mode. Batteries, in this case, may store the energy during the surplus time (if PV panels are deployed, for example) and work as generators when needed [9].

Some countries may adopt rural microgrids if topological issues pose a constraint in the expansion of the distribution grid. Note that, in this case, utilities may not want to participate, in case the investment is not found profitable enough. Thus, the social aspect of electricity places the government in the central spot of the arena, including people and enabling the infrastructure necessary for a reliable operation of these grids. Nevertheless, utilities should pay special attention to this process. This is because some of the challenges to build a rural microgrid may demand creativity and engineering solutions that may be mimicked in urban areas.

5 The Internet of Things and Cybersecurity

As in electrical power systems, a transformation is underway in information and communications technologies, which dawned the concept of the internet of things. Having all objects interconnected through modern platforms and over the internet enables a myriad of smart and autonomous solutions in almost all areas of expertise.

Some projects meant for impaired citizens rely on GPS and the internet of things [24]. Examples like visual and elderly mobility may also use these technological advances [22]. Thus, professionals involved in the development of "smarter" devices will need to acquire interdisciplinary knowledge that meshes different areas of concentration.

In power systems, once the very energy demand is satisfied and as the number of affordable cyber-enabled devices increases, more reliable, secure, cost-effective, and sustainable control and management actions could be performed [19]. The enabling of zero net energy buildings and better communications between utilities and customers, with real-time feedback capabilities, are also on the way [10]. Moreover, the implementation of the internet of things in power systems relies on the usage of big data for line-monitoring and real-time control in all aspects of the grid operating parameters. Some examples include predictive controls, dynamic and steady-state analysis, asset management, and increased demand-side flexibility [5].

Eventually, increasing the coupling and dynamic interaction between cyber and the physical power systems will also rise other alerts. Malfunction on the cyber side may reduce the reliability of the power system operation. Furthermore, large scale cascading failures can be originated by malicious cyber-attacks. Therefore, the enabling of communication-based applications that depend on and generate massive amounts of data also opens a window of opportunity for the development of solutions against actions that renders the system vulnerable to threats from security breaches and data leaks in the communication networks [21].

6 Advancements in Power Electronics

The increased number of energy-hungry applications call for enhancements in power management technologies. Without advances in power electronics, the spread of applications such as data centers, electric vehicles, digital health systems, and modular, automated manufacturing cells will certainly be hampered. Thus, engineers will continue being required to design circuits with ever higher energy densities, better efficiencies, and greater reliability while at the same time providing smaller form factors.

Large-scale integration of renewables, vehicle electrification, and 5G communications will continue to be major topics. Electric vehicles present many new opportunities for power semiconductor products and for decreasing the transport sector's carbon footprint by replacing combustion engines. 5G is also starting to spread, and it is not only base stations that require power solutions; but local small cell installations also require efficient systems [1].

From generation and transmission, all the way to distribution and industrial networks, power electronics knowledge is of utmost importance for the consolidation of key technologies, such as High-Voltage DC and Flexible AC Transmission Systems, adjustable speed drives, converters with extreme energy density and efficiency, wireless power transfer, energy storage systems, smart management systems, and so on [11].

Finally, the hybridization of microgrids, as mentioned before, with large-scale AC–DC and ultra-high voltage networks, will also be enabled through the development of modern power electronics and materials science. Moreover, concerns related to reliability and safety and hazards of the integrations of power converters and machines also continue to be relevant, once the electromagnetic thermal effects of high-power and high-frequencies in the human body are still under study [23].

7 Electric Vehicles and Integration to the Grid

When automobiles were introduced in France and Germany in the late 1800s, the infrastructure for them was very rudimentary. It was a change of habits which caused curiosity and fascination at first since it was not accessible to the working class in general. Mass production in the USA changed this reality and helped to shape urban life and bloomed the suburbs all over the country. Nowadays, two major changes about automobiles are about to take place: electric vehicles and driverless vehicles [4]. These changes, though dramatic, are not as surprising as the advent of automobiles was. As for driverless vehicles, the intelligence behind them may be applied to both oil and electric-based sources. Then, we discuss briefly the challenges and benefits of electric vehicles.

Electric vehicles, however, will bring sharp changes in the infrastructure. In this sense, technological advances in batteries, regarding cycles of life, autonomy, and weight, yield the need and amount of charging stations in cities and highways. Also, charging vehicles during the overnight will change the load profile of distribution systems, requiring control actions to avoid overload and keep voltage level within limits [17].

On the other hand, the advent of electric vehicles may help the active systems in emergency conditions, since the enabling of bidirectional power exchanges will turn electric vehicles into battery solutions and energy sources, according to an agreement previously established between the owner and the utility [16]. In other words, the bidirectional, autonomous use of electric vehicle batteries will enable utilities and customers to make the best use of the existing infrastructure and population of vehicles.

8 Environmental Changes

Electric vehicles bring an appealing call for users when it comes to polluting aspects. Silent and non-polluting vehicles may change the environment and create an encouraging trend of responsible consumption. In this sense, a new critical consumer may arise, demanding fair prices and clean generating sources. Note that this inhibits making electric vehicles viable in the urban center at the expense of polluting generating sources to supply these vehicles.

The concern over clean sources to supply electric vehicles yields a chain of actions regarding the whole process of energy. Thus, disposing of aged batteries is also a concern, as well as PV panels. These items should be recycled as much as possible, and a responsible disposal process must be made available in order to respect the environment. On the other hand, even garbage treatment may help energy production [13]. The literature describes several works that consider biomass as the primary source of electricity generation. But, even more important, garbage itself may be better treated with the help of electricity, preventing thousands of emission per year, and also eliminating the shaming problem of garbage export. In this sense, plasma arc recycling seems to be a good and promising option [12]. Opponents to this idea argue that this is a new term for incineration, while supporters claim that this is a non-polluting recycling process. Super high temperatures are used to turn the garbage into gas that can be burned for energy and rocky solid waste that can be used for building.

Actually, society tends to benefit as a whole from clean energy production. In this sense, tourism may create new opportunities, since some amazing cities are not a touristic destiny because of their air quality and traffic conditions. Also, the health care system will be alleviated, as respiratory problems will be strongly mitigated by cleaner air. The literature shows that the elderly and children are affected by the air quality and have their health compromised [14].

This aspect of engineering is about to be addressed by the syllabus of all universities, and also invite researchers to consider a holistic and disciplinary approach to energy planning [2].

9 The Role of Prosumers and Social Inclusion

As a whole, the new emerging power systems will be completely absorbed by smart cities. This will create a new pattern of consumption, that is partially already taking place. For example, domestic consumers manage the time to use their appliances in order to take advantage of better prices. The advent of prosumers will change the way domestic consumers play. They may go to local batteries in order to increase their autonomy or decide to sell their surplus to the utility. This is all upon the educational process behind these changes. Then, a prosumer will be well informed about the cost of electricity as a producer and also as a consumer in order to come up with the best decision.

Note, however, that the role of prosumers should go beyond market issues. It is important to emphasize that holistic approaches may help all the players involved to make better decisions for society as a whole. Hence, it is expected that market-driven decisions are taken in normal operating conditions. But emergencies may happen, and in this case, a priority of loads should be considered, and that should be common sense so that the well being of the system is preserved. This discussion, it is important to mention, does not overlook market aspects, but invites people to consider holistic aspects.

The paragraph above drives one to think of social inclusion, or the social role of electric systems in society. As previously stated, electricity may be faced as an asset, so that a responsible system planning is executed. But it may also be considered as a fundamental right, that should be available to isolated communities in the North of Canada, rural poor areas in Africa and South America, and poor urban communities [3, 15]. People educated themselves very rapidly to use the internet and mobile phones, and will certainly learn the technical and market aspects of smart grids/cities [20]. Inequality in the world, however, has presented growing discrepancies, and that needs to be faced by all social actors, and smart cities/grids are not an exception. Thus, political measures to include people urge to be taken, enabling the excluded to become part of the process, if not as prosumers, at least as passive consumers, but exercising their citizenship. Planning a fair and balanced society demands urgent actions considering this concern.

Considering social inclusion in designing microgrids will demand a holistic background from engineers. The authors in [8] describe some implications of philosophy of technology in the design of microgrids. It is understood that designing such systems requires scientific, political, economical, architectural, juridical, and ethical aspects. Sometimes these aspects may even overlap, bringing a conflict between parts that must be properly addressed. Thus, special knowledge may be required, but above all, the ability to dialogue with different professionals and hearing the demands from society will be vital. This kind of background urges to be considered by universities and companies, in such a way no one is left behind in this new and, most likely, better world.

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