Dilan Jayaweera   *Editor*

Smart Power Systems and Renewable Energy System Integration

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Preface

This book aims to provide wider knowledge to researchers, engineers, postgraduates and policymakers in research and development in the area of smart grids and integration of renewable energy systems. The operating paradigms of traditional power grids are advancing towards smarter operations to face the current and future challenges and to supply electricity to consumers in a smart grid environment. Power systems are stressed to accommodate increased volumes of renewable power generation with limited resource corridors. With the developments of smart grids, information on the frequency, magnitude and duration of the occurrence of the future power system load demand is expected to be widely available with advances in the forecasting, smart metering and control techniques. The increased accommodation of smart appliances and the autonomous operation of power plants may increase efficiency; however, the security of supply at major power and cyber network incidents may not necessarily be limited due to interaction of highly intelligent systems within a power system environment, owing to the increased risk of restoration process of power supply following large system disturbances and cyber security threats. Thus, it is vital to understand the past, present and anticipated future of power system developments, challenges and needs in order to effectively address planning and operational needs of a smart grid environment. This book attempts to give a solid framework surrounding these problems, research challenges, current and anticipated developments, and the regulatory frameworks through in-depth explorations and case studies. The book covers these aspects through ten chapters.

Chapter "Fundamentals of Power Systems" presents the history, evolution and fundamental analysis frameworks of a power system. Power systems started modestly as small-scale DC systems. As the dependence on electricity increased, the complexity and demands placed on electricity have also increased. The chapter starts with a description of the history of power systems and then describes the major events that have shaped the modern power industry. A description of basic power system components are presented along with analysis techniques such as

load flow, optimal dispatch and transient stability. The chapter fundamentals will aid in better understanding of the remaining chapters.

Chapter "Modelling and Simulation of Power Systems" presents major modelling and simulation techniques used in power systems research. As smart grids will be a journey through the modern power system environment, it is vital to know how these models and techniques are applied in a traditional power grid environment and how they can make advances to realize smart grid objectives. The chapter particularly addresses optimization techniques applied in power systems research, is extended to incorporate stochastic elements, and ends with a brief exploration into the Monte Carlo simulation-based research.

Chapter "Micro Grid Planning and Operation" investigates specific challenges in a micro grid, planning and operation, control strategies and case studies of micro grids. A micro grid is a smaller entity that can intelligently control and coordinate distributed energy resources with the support of intelligent controllers and other necessary architectures. However, achieving such objectives that lead to smart operation require significant advances to planning and operation of the micro grids as their collective operation can potentially provide business cases. Roles of micro grids include improving reliability, resilience and security at normal and emergency operating conditions of the utility power grid. Each mode of operation presents challenges such as frequency control in an islanded mode and voltage control in a utility grid connected mode.

Chapter "A Preliminary Study on Conversion Efficiency Improvement of a Multi-junction PV Cell with MPPT" presents a preliminary study conducted to improve photovoltaic cell conversion efficiency using MATLAB/Simulink platform. The study uses multijunction solar cell and investigates the maximum performance compared with the conventional silicon PV cell. Maximum Power Point Tracker is applied to assess the conversion efficiency of the PV system. The study integrates thermoelectric generator with PV cells, as these work by converting high frequency irradiation, whereas a thermoelectric generator has the ability to convert wasted low frequency heat into electricity. The combination drives to enhance energy efficiency.

Chapter "Grid Integration of Renewable Energy Systems" explores the technical and regulatory framework, planning and operation challenges, and the roles of balancing technologies in the context of grid integration of renewable energy systems. There are short-term operational challenges as well as long-term planning challenges due to the presence of intermittent power generation. The chapter also investigates the optimal technical and regulatory framework that can effectively manage the short- and long-term challenges with large-scale renewable power penetration. Operational challenges addressed in the chapter include the maintenance of frequency and voltage stability due to intermittency of power generation and network congestion. Planning challenges included long-term capacity credit allocation of wind and solar power generation.

Chapter "Technical Challenges, Security and Risk in Grid Integration of Renewable Energy" focuses on technical challenges associated with the grid integration of renewable energy systems. PV power generation is typically integrated at

the power distribution system level, while wind power can also be integrated in the power transmission system level depending on the level of power generation. Utilities around the world are discussing and conducting feasibility studies of 100 % renewable energy-based power systems. Although a very high penetration level of renewable energy looks plausible, the technical challenges associated with them could be a hindrance to seamless integration. This chapter also highlights security concerns and associated risks, which are categorized in this chapter as technical and non-technical issues. At the end of the chapter, the way forward for renewable energy integration in a power system is also summarized.

Chapter "Dynamic Modelling, Simulation and Control of a Commercial Building Microgrid" presents the dynamic modelling of a commercial building micro grid system and conducts stability analysis of the micro grid under various operating conditions. Commercial building micro grids depict unique characteristics due to generation mix and various types of loads connected at the commercial building installations. Therefore, these micro grids require distinct consideration during the operation and control stages. Thus, the chapter addresses these aspects in detail and uniquely distributes the dynamic models of a micro grid for researchers in this area to investigate the operational performance and control techniques before the control schemes are implemented in the micro grid system.

Chapter "Probabilistic Methods Applied in Power and Smart Grids" presents an investigation into the probabilistic methods applied in power and smart grids. The chapter explores the existing probabilistic methods in traditional power grids and then looks at the extended framework for the smart grid environment. In a stochastic-natured and increasingly uncertain smart grid environment, probabilistic methods have been applied in a growing number of research areas, and have shown their increasing importance for handling the uncertainties involved in system stability, reliability, forecasting, and optimization. The chapter also extends to cover the need for tools and techniques to manage novel risks and uncertainties in smart grids.

Chapter "Planning and Operational Challenges in a Smart Grid" presents smart grid challenges in particular in the context of planning and operation. Smart grid is a pathway to achieve smarter objectives, thus one can expect a significant number of challenges that should be addressed throughout the journey. The chapter at first gives the reader an introduction to planning and operation in a traditional power grid environment and then explores the added needs for smart grids to achieve their objectives. It comprehensively covers generation, transmission, and distribution system planning and operation prior to embarking into each stream of smart grid planning and operation. As the key success of a smart grid will be the cyber network operation, its challenges in terms of integration with the physical power system and interoperability are discussed. The chapter explores load forecasting in a smart grid context in detail as the detailed knowledge of load at the smart grid customers is vital in planning and operation of the smart grid. The chapter ends with a discussion of the potential interaction of a smart power grid with other smarter networks and the need for cross-disciplinary research.

Chapter "Applied Research in Energy Storage" presents applied research in the area of energy storage. The development and incorporation of energy storage into large electricity networks, micro-grids and partially or fully islanded energy supplies have numerous applications as the sustainable energy generation uptake increases. The notions of sustainable energy supplies are driving energy storage in two distinct directions. First, there will be large-scale energy storage such as pumped land or sea-based hydro-energy that can absorb excess renewable energy for later discharge when there is a deficit in dispatchable energy available. As an alternative to such large industrial scale units, there is also potential to develop smaller but numerous distributed smaller energy storage systems that are based on inertial or electrochemical battery storage. These developments present huge opportunities to change the way the sustainable energy uptake continues. The chapter also briefly looks into the interdisciplinary research on energy storage in other potential areas.

Contents

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About the Editor

Dilan Jayaweera obtained his Ph.D. and M.Sc. degrees from University of Manchester Institute of Science and Technology (UMIST), UK, in 2003 and 2000 respectively. He is a Senior Lecturer in Electrical Power Systems in the Department of Electronic, Electrical and Systems Engineering, School of Engineering at the University of Birmingham. He was with Imperial College, London and University of Strathclyde, Glasgow for his postdoctoral research careers and was at Curtin University, Western Australia, as a Senior Lecturer in power transmission and distribution systems. He was in the industry for a number of years prior to commencing his postgraduate studies. His total research, academic and industry working experience spans over 16 years.

He has supervised a number of Ph.D. students in the areas of power system planning and operation. He has published a significant number of research papers in scientific journals, conference proceedings and book chapters in the fields of power system security, reliability, active distribution network operation, smart grids and risks in power systems. He has also significantly contributed to technical reports in his academic and industrial careers. He is a chartered engineer in the UK, chartered professional engineer in Australia, Fellow of Higher Education Academy in the UK, and a Senior Member of IEEE.

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Fundamentals of Power Systems

Binayak Banerjee, Dilan Jayaweera and Syed Islam

Abstract The chapter describes the history, evolution, and fundamental analysis frameworks of a power system. Power systems started modestly as small scale DC systems. As the dependence on electricity has increased, the complexities and demands placed on electricity have also been increased. The chapter begins with a description of the history of power systems and then describes major events that have shaped the modern power system industry. A description of the basic power system components are presented along with analysis techniques of load flow, optimal power dispatch, and transient stability. The chapter fundamentals will aid in a better understanding of the remaining chapters.

Keywords Deregulation · Load flow · Optimization · Power system components · Transient stability

1 The Evolution of Power Systems

1.1 History of Power Systems

Electric power systems were initially developed as small direct current (DC) systems that were sold to factories for industrial and mining use. The first electric power system was established in 1882 by Thomas Edison. It was a DC system designed to power the area of Lower Manhattan in New York City. The main drawback of the DC electricity was that the voltage level was low and resistive losses were high so the power could only be transferred to a short distance

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from the point of generation. However, the invention of the transformer in 1885 and the induction motor in 1888 made it more feasible to shift DC power system to an alternating current (AC) power system. Transformers change voltage levels which resulted in using high voltage for transmission over long distances and reduced the resistive power losses. Further, AC induction motors were brushless and were more durable than DC motors with brushes which further strengthened the case for an AC system. The development of rotary converters and mercury arc valve rectifiers allowed conversion from AC to DC electricity which ensured DC loads could still be serviced (Edison Tech Center 2014).

For long distance transmission in excess of distances of 500 km, high voltage DC systems were used and still continue to be used. Power systems in the early part of the 20th century were largely passive systems designed to transfer power from the point of generation to the end customer. However, growing demand for the electricity, changing consumer needs, and the development of a number of enabling technologies have resulted in gradual evolution of power systems.

The developments of semiconductors and power semiconductors have played an important role in modern power systems. Power semiconductors allow large amounts of power to be switched easily. Power semiconductors such as field effect transistors (FETs) are used in building various types of power converters that can allow a great deal of flexibility to the power system.

Development of semiconductors has also resulted in advances in computing and telecommunications technologies which have influenced the way power systems are monitored and controlled. Technologies such as programmable logic controllers (PLC) and supervisory control and data acquisition (SCADA) have enabled transmission systems to be operated and monitored effectively. Further, advanced computing and communication technologies are expected to be used to increase the level of intelligence in the future grid.

In the UK, Charles Merz was the first to adopt Tesla's three phase AC power system in 1901. This resulted in the development of a number of smaller interconnected grids. In 1925, an effort was undertaken to improve the efficiency of the fragmented UK electricity network which resulted in the Electricity (Supply) Act in 1926. As a result of this Act the Central Electricity Board standardised the nation's grid which was operated at a voltage of 132 kV and 50 Hz. Following this, the regional grids were gradually started operating in parallel with the main grid which resulted in formation of the National Grid in 1938 (Electricity Council 1973).

1.2 Deregulation of Electricity Markets

In traditional power systems with a single utility provider, the electricity market was not necessary as electricity was a monopoly regulated by the government. One of the key events in the UK was the privatisation of electricity sector under Margaret Thatcher in the 1980s. The process involved privatisation of a number of state

owned electricity companies and the dismantling of the Department of Energy. This was followed as an example around the world and many countries started deregulating their electricity industry.

Transmission open access and network deregulation started in the 1980s and 1990s with an aim to increase competition in the electricity market. However, due to network congestion, competing entities could not have equal access to customers thus affecting the level of competition (Singh et al. 1998). Prior to the deregulation, generator dispatch schedules were set such that line limits were not exceeded. Marginal pricing signals could be used as an indicator of congestion and persistent congestion would drive generation or transmission expansion projects (Glatvitsch and Alvarado 1998). In the post deregulation, the absence of a method for determining equitable allocation of increased transmission cost due to congestion became a key factor that reduced the competitiveness of market participants (Glatvitsch and Alvarado 1998; Fang and David 1999). In order to ensure that the objectives of deregulation and open access were realised, modern methods of managing the electricity market were required. Sources agreed (Glatvitsch and Alvarado 1998; Shirmohammadi et al. 1998; Singh et al. 1998; Fang and David 1999) that one of the solutions would be to have an independent system operator (ISO) to efficiently manage the operation of the competitive electricity market. Other specific solutions proposed were to have pool and bilateral markets (Singh et al. 1998; Fang and David 1999). Bilateral markets allow suppliers and consumers to directly arrange power transactions without the intervention of a third party. In a pool market, a central operator receives price and quantity bids from generators and then selects the most efficient sources to satisfy current demand. Price bids are adjusted by the pool operator to reflect the locational value of a generator thus the bids are weighted by the level of congestion.

Conejo et al. (2002) discusses the limitation of pool operated markets since network constraints and losses were neglected. They compare three alternative methods for allocation of transmission loss. These are pro rata (PR) allocation of cost to generators and consumers proportional to their energy generation or consumption; marginal allocation based on incremental transmission loss (ITL) coefficients of each generator or load; and proportional sharing which is based on the principle that loses associated with a line that enters a given bus are transferred to the lines (or generation/loads) which leave the bus. These losses are distributed proportional to the exiting flows. It is shown that the PR method allocates cost inequitably and the ITL method leads to volatility and allocation imbalances. The proportional sharing method is shown to have the best performance over the other methods in terms of equitable cost distribution and volatility. Tengshun and Tomsovic (2003) proposed a probabilistic alternative to incorporate transmission constraints in the bidding strategy which better reflects market operation. Firstly, the bidding strategy is modelled as an optimisation problem and the influence of congestion is included explicitly in the objective function. Subsequently, a probabilistic method for large systems is developed which shows similar results to the theoretical approach.

1.3   Climate Change and Modern Power Systems

In the early 2000s, serious concerns started to be raised about the effect of climate change. Many industries including the electric power industry had to review the long term environmental impacts of power generation practices which revolved mainly around combustion of fossil fuels at the time.

The UK joined a number of other countries in a commitment to reduce greenhouse gas emissions. The Energy White Paper (Department of Trade and Industry 2003) released by the UK government was the first major policy to address climate change. It contained a target to reduce greenhouse gas emissions by 60 % by 2050. A draft Climate Change Bill was published in 2007 which was later passed as The Climate Change Act (2008). In the same year the Committee for Climate Change whose powers are invested by the Act was formally launched. This committee advises the Department of Energy and Climate Change in the UK.

Since 2010, an average of £7 billion/year has been invested in renewable power generation in the UK. At the end of 2014, there was an installed capacity of 4.4 GW of offshore wind, and 8.1 GW of onshore wind (DECC 2015). Additionally, current pipeline projects will ensure that 2020 deployment targets are satisfied. According to a recent parliament statement on 18th of June 2015 by the Secretary of State, the wind generation targets are close to being fulfilled and hence there are reductions to subsidies. At the end of 2014, the estimated PV installed capacity was 5 GW, with approximately 5 GW in the pipeline (DECC 2015).

High penetration of renewable energy leads to a large variation in power generation over a short period of time and the effect on security of energy supply is one of the numerous challenges facing the existing electricity grid. Due to the recent severe weather events and threats of terrorism, there is a challenge of meeting increasing demand to build a more resilient grid that is also cost effective and future-proof. Resilience is different from reliability in the fact that it mitigates against low probability high impact events. Electric Power Research Institute (EPRI) in the USA has identified means of enhancing resilience using both hardening and smart measures (EPRI 2013). Additional challenges to the grid have been identified in an assessment of future challenges by the Department of Energy and Climate Change (DECC). There will be a significant change in generation and demand profile in the UK driven by the electrification of the heating and transport sectors. The locational profile is also expected to change as per residential customers' demand for electricity for charging of Electric vehicles (EVs) and home heating.

Traditionally, reliability has been assured by designing redundancy in the system and maintaining adequate spinning reserves to cover intermittency due to renewable energy sources. However, as penetration of renewables increases, the utilisation of assets would decrease significantly. It has been estimated that the asset utilisation in an integrated European energy market would decrease from 55 to 35 % by 2025 (Strbac et al. 2015). Thus asset utilisation degradation is also a challenge and is contrary to the objective of providing high reliability and resilience through built in

redundancy. There are calls to develop smarter and more cost effective methods of providing reliability and resilience.

Fang et al. (2012) and many others describe a smart grid to be the future of power systems which uses two way exchange of electricity and information to create an automated and intelligent electricity network that is also distributed. Fang et al. (2012) states that a smart grid will consist of smart infrastructure systems, smart management systems, and smart protection systems. Smart infrastructure covers the energy, information and communication underlying the smart grid. This smart infrastructure will support all smart grid functions including advanced metering. Smart management is a subsystem for the management and control of the smart grid. Smart protection system is also critical to ensure that a smart network is reliable, resilient and self-healing.

The modern power system has rapidly evolved from previous versions driven by changes in demand. Thus, the operational and planning needs of the modern power system can be summarised as:

- The power system must be capable of accommodating bi-directional flow of power.
- The network should be dynamic and have adequate capacity to accommodate increasing volume of electricity trade between multiple stakeholders.
- The power system must not only be reliable but also resilient against natural disasters and the effects of climate change. This includes the capability to be self-healing.
- Dispatch and unit commitment decisions have to be undertaken much more dynamically than traditional power systems. Decision making must be carried out in near real time since generation and load change occur continuously.
- Reliability and dispatchability of generation must be maintained even under large scale penetration of intermittent power generation (e.g. from renewables) that cannot be dispatched as in the traditional way.
- Risk assessment in a power system has gained increasing importance. Risk assessment can include a wide range of risks such as risk of outages and financial risk of investments.
- The biggest challenge of the modern power system is that it must meet the contradictory objectives of being reliable, resilient and secure, while assuring low cost of electricity. Accurate quantification of the risks and benefits is crucial to meet this objective.

2   Power System Components

Generators form one of the major components in a power system. Traditional generators are of the synchronous type which consists of two rotating magnetic fields. The rotor is excited by a brushless rectifier which supplies DC power to the rotor excitation. The stator is excited separately. AC generators do not require a

commutator and can generate power at a high voltage. The rotor of a generator needs to be moved by an external source called a prime mover. Prime mover technologies can cover hydraulic turbines which are driven by waterfalls, wind turbines which are driven by wind, or steam turbines which are driven by the high pressure steam created by combustion of natural gas, coal or nuclear fuel. In the last few decades, the growth of wind turbines has also increased the use of induction generators which rotate slightly above synchronous speed.

Transformers are another important component of an AC power system since they allow voltage levels to be changed (step up or down) easily. Most transformers are located within substation compounds along with protection infrastructures and capacitor banks for the reactive power compensation. Transformers are located in generation plants to step up the generated voltage to the transmission voltage level. Transformers in terminal or zone substations reduce transmission voltage levels to sub-transmission levels or further step down to distribution voltage levels. Distribution transformers are smaller and usually reduce primary distribution voltage to the secondary voltage level.

Delivery of the generated power to customers is done through the transmission and distribution networks. The transmission network transfers large quantities of power from the generators to distribution networks. Some large industrial customers may be directly connected to the transmission network. Interconnection of neighbouring utilities is also done via the transmission network. Transmission lines typically terminate at substations where they interface with the distribution network and other auxiliary accessories.

A distribution network is that the part which connects the zone substation to the customers. The distribution network consists of a primary network or high voltage network which carries power from the zone substation to a relatively large geographical area. Some small industrial customers may connect directly onto the primary feeder. The secondary network is in low voltage and typically delivers electricity to residential and commercial customers. Distribution substations consist of transformers and switchgear that convert the primary voltage level to the secondary voltage level and protects the feeders and transformer.

Loads can be broadly classified into industrial, commercial, and/or residential. Industrial loads may be connected to the transmission network or primary distribution network while commercial and residential loads are connected to the low voltage distribution network. Loads vary throughout the day and thus additional generation may be required to meet the peak demands. The Load factor is defined as the ratio of average load to peak load and 0.5–0.7 is a typical value. Another important concept for load is the diversity factor since not all loads will necessarily peak at the same time. Thus, the peak load that substations are designed for can be lower than the sum of all the peak loads served by the substation. Diversity is higher if a given region consists of a mix of different types of loads e.g. commercial and residential or industrial and residential. Diversity also improves the overall system load factor.

3 Principles of Power Systems Analysis

3.1 Load Flow Methods

Load flow analysis is described in detail by Saadat (2002) and many other power system analysis books. Load flow analysis or power flow analysis forms the basis for many types of decisions such as contingency analysis and transient stability analysis. Typical load flow involves analysis of a power system in the steady state under balanced conditions. Due to the assumption of balanced conditions, the problem can be solved as a single phase system. There is also an unbalanced power flow technique which incorporates unbalanced conditions of the system.

In a load flow assessment, it is assumed that there are three types of nodes or buses in a power system. They are known as generator buses, load buses and the swing (or slack) bus. At a generator bus, the voltage magnitude and real power are specified (or given). Voltage angle and reactive power are not known. At a load bus, the real and reactive powers are typically specified but voltage magnitude and voltage angle are unknown. The swing bus acts as the reference bus which balances the real and reactive power at the other buses. As a result, the real and reactive powers at the swing bus are not specified however the bus voltage magnitude and angle are considered as known. In a real power system, the bus with the largest generators can be considered as the swing bus. The voltage magnitude and the angle at the swing bus are typically assumed as 1.0 per unit and 0° respectively. The aim of load flow analysis is to determine the voltage magnitude, voltage angle, real and reactive power at each bus in the system and then to calculate other unknown parameters of the power system.

The system itself is represented by the bus admittance matrix. Each element of the bus admittance matrix is the admittance in the branch connecting the buses that are defined by the row and column of the matrix element. The network state is described by the equations for the injected active and reactive power (P_i and Q_i) as a function of bus voltages at each node and is given by (1) and (2) respectively.

$$\sum P_i = P_{gi} - P_{Di} - P_{sch} \quad \text{At each bus 'i'} \tag{1}$$

$$\sum Q_i = Q_{gi} - Q_{Di} - Q_{sch} \quad \text{At each bus 'i'} \tag{2}$$

where P_{gi} (Q_{gi}) represents the real (reactive) power generation as bus i and P_{Di} (Q_{Di}) represents the real (reactive) power demand at bus i. P_{sch} and Q_{sch} can be determined by (3) and (4) respectively.

$$P_{sch} = V_i^2 G_{ii} + \sum_{\substack{j=1 \\ j \neq i}}^{N} \left[V_i V_j G_{ij} \cos\left(\delta_i - \delta_j\right) + V_i V_j B_{ij} \sin\left(\delta_i - \delta_j\right) \right] \tag{3}$$

$$Q_{sch} = -V_i^2 B_{ii} - \sum_{\substack{j=1 \\ j \neq i}}^{N} \left[V_i V_j B_{ij} \cos\left(\delta_i - \delta_j\right) - V_i V_j G_{ij} \sin\left(\delta_i - \delta_j\right) \right] \qquad (4)$$

V and δ represent voltage magnitude and angle respectively. G_{ij} and B_{ij} represent the conductance and susceptance between bus i and j respectively. However, the number of unknowns (voltage magnitude, angle, real and reactive power) is greater than the number of equations. Additionally, power injection is a nonlinear function of bus voltage. Thus, iterative techniques are required to find a solution to the load flow problem. The common solution methods to the power flow problem are as follows.

- Gauss Seidel—This technique involves expressing the complex bus voltage at a node as a function of bus voltages at other nodes and power injections. In each successive iteration the complex bus voltages are determined which are then used in the next iteration to update the bus voltages. When the change in bus voltages between iterations is lower than a specified tolerance, the process is stopped. This process is also called the method of successive displacement and the number of iterations required to convergence is usually quite large. Thus, the technique is suitable for smaller power systems.
- Newton Raphson—This is the most popular method for solving load flow equations. It has quadratic convergence properties and this reaches a solution in a much fewer iterations than Gauss Seidel. However, the computation effort in each iteration is higher. The Newton Raphson algorithm uses the Jacobian matrix to extrapolate the gradient at successive estimations of the solution as the next estimate. Determining the Jacobian for large systems can require high computational effort and the algorithm relies on suitable choice of initial solution to guarantee convergence.
- Fast Decoupled Method—This method simplifies the Newton Raphson method by assuming that most transmission systems have high X/R ratio. For such systems real power is mostly sensitive to changes in voltage angle and imaginary power is sensitive to changes in voltage magnitude. Thus, the off diagonal elements of the Jacobian can be set to 0 and the real power and complex power equations become decoupled. The solution process is similar to Newton Raphson but the dimension of the matrix to be inverted is halved. It should be noted that this is an approximation but for most practical purposes it does not lead to significant loss of accuracy.
- DC load flow—This method is the only load flow solution that does not require an iterative solution. The DC load flow method makes the further assumption that angular separations in a power system are typically small. Thus, trigonometric functions in the power balance equations can be removed. For example when x is small $sin(x) \approx x$ and $cos(x) \approx 1$. These approximations lead to a set of linear equations which can be solved by a single matrix inversion.

While a detailed description of load flow analysis is beyond the scope of this book, these concepts should illustrate the capability of load flow. For a detailed treatment of load flow the reader is referred to power system analysis books including Saadat (2002).

3.2 Optimal Power Dispatch

The objective of optimal power flow (OPF) is to determine a steady state operating point that optimises the use of system resources while maintaining operational constraints such as voltage regulation, generator limits and line flow limits. It is formulated as a constrained optimisation problem where the overall system cost is modelled by the objective function of the optimisation, and the load flow equations and voltage regulation requirements are modelled as constraints. In traditional OPF, the objective function represents the total cost of generation and can be described by (5).

$$C_i(P_{Gi}) = a_i P_{Gi}^2 + b_i P_{Gi} + c_i \tag{5}$$

where P_{Gi} is the generated power and $C_i(P_{Gi})$ represents the generator fuel cost which can be represented as a quadratic function. The coefficients a_i, b_i and c_i are coefficients that are constant for a given generator and determine the nature of the cost function. In addition to the objective function, the constraints of the optimisation problem must also be satisfied. Some of constrains are described as follows.

3.2.1 Power Balance Constraints

Power balance constraints model the fact that the total power at any bus must be equal to zero, i.e. all incoming power flows must be equal to outgoing power flows. This is modelled by setting the power injection Eqs. (1) and (2) equal to 0.

3.2.2 Generator Limits

Every generator has real and reactive power limits which can be modelled by inequality constraints. Thermal generators also have a minimum level of output that must be maintained to ensure system efficiency, stability and the security.

3.2.3 Voltage Constraints

At each bus, the voltage magnitude is not allowed to fluctuate beyond a fraction of the rated voltage. They are defined by the statutory voltage limits of the network. This is represented by inequality constraints.

3.2.4 Line Power Flow Constraints

Every transmission line or branch of the network has a maximum rated power carrying capability. There are two ratings that determine the power limit. Firstly, the real power flow limit places an upper limit on the maximum power flow in the line. This limit represents the stability limit of the line. Secondly, the thermal limit is proportional to the resistance and square of current magnitude and is represented as an inequality constraint. In a real system, stability limits determine the line rating for long lines while short to medium lines are determined more by thermal limit.

The standard formulation of optimal power flow assumes a balanced three phase configuration. For unbalanced systems, a three phase representation is required using the sequence component or phase frame of representation. In the sequence component frame, the unbalanced system can be represented as the sum of three independent balanced systems. Each of these balanced systems is a sequence. In the phase frame of reference, each phase is represented independently. In both the sequence component and phase frame, mutual coupling between sequences and phases must be considered.

Three phase power balance equations for each phase considering flows due to mutual coupling are given by (6) and (7).

$$P_i^x = \sum_{k=1}^{n} \sum_{m \in \{a,b,c\}} \left[V_i^x V_k^m G_{ik}^{xm} \cos\left(\delta_i^x - \delta_k^m\right) + V_i^x V_k^m B_{ik}^{xm} \sin\left(\delta_i^x - \delta_k^m\right) \right] \quad (6)$$

$$Q_i^x = \sum_{k=1}^{n} \sum_{m \in \{a,b,c\}} \left[V_i^x V_k^m G_{ik}^{xm} \sin\left(\delta_i^x - \delta_k^m\right) - V_i^x V_k^m B_{ik}^{xm} \cos\left(\delta_i^x - \delta_k^m\right) \right] \quad (7)$$

where x is the phase and i is the node. Similarly, the load flow equations in sequence component frame can be determined from the same set of equations but x represents the sequence instead of the phase.

3.3 Transient Stability

Stability issues arise in a power system whenever there is a momentary imbalance between generation and load. Traditional synchronous generators cannot change their power output instantaneously to match the load and as a result, they speed up or slow down to supply the shortfall until the speed changes. The momentary change in speed causes changes in frequency.

Renewable sources fluctuate widely and thus present a control challenge to the grid. For small quantities of renewable integration, it is common practice to treat them as negative loads. Most power systems have enough inertia in the rotating machines to adjust for small variations in load. However, as the penetration of renewable energy increases, the variations are likely to get larger and the reserve

capacity of synchronous machines may not be able to cope with it. Thus, measures need to be taken to ensure that the impact of these variations on system frequency is minimal.

Bevrani et al. (2010) produces a comprehensive review of the challenges and possible solutions on frequency regulation in systems with high renewable penetration. The new generation of variable speed, large wind turbine generators have high moments of inertia from their turbine blades and thus can provide some form of filter to power and frequency fluctuations. The rotating mass can also provide short term frequency support to the power system. Longer term frequency support can be achieved by using wind in conjunction with storage technologies such as fuel cells. These methods are classified as primary frequency control. Variable speed turbines which are electrically coupled to the grid using power electronics converters will not be able to utilise the primary frequency control capabilities of the wind turbines.

Supplementary frequency control is based on maintaining balancing reserves and implementing effective control systems. Electrically coupled renewable energy systems usually interface to the grid via a power electronic converter. This converter is usually capable of monitoring the grid frequency and adjusts output accordingly. Supplementary control is essential for Photo Voltaic (PV) systems which do not have inertia.

Bevrani et al. (2010) suggests that every fluctuation in renewable energy source (RES) output does not need to be matched and regular variation due to RES output and load variation cancel out. As long as large penetration of DG is geographically dispersed it is unlikely that the impact of overall system frequency will be significant. However, this can be an issue in islanded micro grids where system size is smaller and there is a less inertia available.

Power electronic converters that are used to interface between renewable generation and the grid can significantly improve the level of frequency stabilisation. There can be three broad categories of wind turbine generators in terms of power electronics converters (Blaabjerg et al. 2004). These are those systems that do not have power electronics, those with partially rated power electronics and those with full-scale power electronic converters.

There are also solutions without power electronics for variable speed wind turbines and they include:

- Power limiting by stall, active stall or pitch control.
- Soft starter to reduce inrush current.
- Reactive power compensation by continuously switching capacitor banks.

An example of a partially rated system would be a system with a wound rotor induction generator where the power electronics are used to control rotor resistance. A reactive compensator and soft starter would also be implemented in such a scheme. These systems typically use power electronics to provide an additional level of control in some aspects compared with the systems with no power electronics.

A full scale power electronic converter would involve power electronics to interface between generator and the grid without any direct connection. This provides the highest level of control and flexibility.

4 Summary

Power systems have evolved significantly since they were first implemented at the end of the 19th Century. Most aspects of modern life depend on electricity and sectors such as transportation are also expected to be added into the mix. The grid has evolved from its original function of supplying electricity to being a platform for various independent generators and customers to trade electricity. Electricity markets developed as a result of deregulation at the end of the 20th Century and trading mechanisms have advanced to allow greater flexibility to participants in the market. One of the biggest revolutions occurring in the power industry has been due to the influence of climate change and the limited availability of fossil fuels for the power generation. The need for sustainable energy is driving smarter grids and new paradigms in grid control and operation to manage intermittent renewable generation.

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Modelling and Simulation of Power Systems

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Abstract This chapter presents major modelling and simulation techniques applied in power systems research. As the smart grids will be a journey through the modern power system environment, it is vital to know how these models and techniques are applied in a traditional power grid environment and how they can make advances to realize smart grid objectives. The chapter describes optimization techniques applied in power systems research and then extended to incorporate stochastic elements. The chapter ends with a brief exploration into the Monte Carlo simulation based research.

Keywords Deterministic approach · Monte Carlo simulation · Probabilistic techniques · Stochastic optimization

1 Introduction

Power systems are complex and dynamic and they employ advanced mathematical techniques for planning, operation, control, and analysis. One of the biggest challenges of power systems is that the physical experimentation and observation is not practical and thus planning and operation decisions rely on accurate replication of experiments using mathematical modelling and simulations. It is thus critical that simulation techniques are robust and reliable. Power system simulations incorporate robust mathematical representations of real life systems by utilising advanced modelling techniques to assess the interactions of individual component models.

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In addition, most power system analysis methodologies require solving highly non-linear and non-convex problems which necessitates the use of a large amount of computational resources. While advances in numerical computing and processing speed have resulted in significant benefits, it is still necessary to make models as efficient as possible to minimise computation times and to capture realistic effects.

At the same time, power systems consist of a number of expensive assets which can be damaged if operated incorrectly. A number of industries rely on electrical power and outages would result in huge financial losses. Thus, the consequences of incorrectly planning or operating a power system can have severe consequences. Additionally, due to the modern power systems are becoming increasingly dynamic, and real time modelling, state estimation, real time decision making requirements are placing added demands on power system modelling and simulation techniques. Thus, modelling and simulation techniques must meet the contradictory objectives of being fast, computationally efficient yet robust, secure, and reliable.

While some of the modern requirements of power system modelling and simulation are covered in the relevant chapters, this chapter discusses some of the developments in basic methodologies that form the basis for all analysis. This includes various forms of analytical and heuristic optimisation techniques as well as the application of probabilistic techniques for analysis under uncertainty.

2 Optimisation Techniques

Optimisation techniques are widely used for power systems analysis. The objective of optimal power flow (OPF) is to determine a steady state operating point that optimises the use of system resources while maintaining operational constraints such as voltage regulation, generator limits and line flow limits. It is formulated as a nonconvex, nonlinear constrained optimisation problem and a variety of algorithms have been used to solve it.

Reviews published by Hunealt and Galiana (1991) and by Zhifeng et al. (2009) describe the evolution of OPF from its development till the present day. While attempts at establishing the OPF problem can be traced back to the 1940s, the first official publication on the subject was by Carpentier in 1962, who formulated the optimality conditions from the Kuhn-Tucker conditions for optimality for a mathematical function. Much of the research in the area for the next couple of decades focussed on finding efficient algorithms to solve the OPF problem. One of the earliest proposed methods used linear approximation of the nonlinear objective function and constraints and applied linear programming techniques to solve the problem (Wells 1968). The drawbacks of this include the final solution is not necessarily being optimal and constraint overloading due to rounding error (Zhifeng et al. 2009). Nonlinear programming techniques were developed shortly after with Dommel and Tinney (1968) representing the first successful attempt at using a gradient based method combined with penalty functions for violation of constraints.

In the 1970s quadratic programming (Nabona and Freris 1973; Nicholson and Sterling 1973) was used for the solution of the OPF formulation which involved using quadratic functions to approximate the objective function and linear functions for the constraints. Compared to linear programming, it offered a more flexible algorithm and higher reliability in terms of convergence but the computation time was increased with larger system scale.

In parallel to the aforementioned techniques, the interior point method was also used for solving the OPF problem. It can solve both linear and nonlinear problems and has robust convergence characteristics. There was renewed interest in the interior point method after Karmarkar (1984) devised an efficient algorithm to solve interior point problems. The subsequent development of the predictor-corrector technique by Mehrotra (1992) further improved the utility of interior point methods. Even in present day OPF problems, the interior point method is a very common algorithm for solving the OPF problem either in purely analytical or hybrid techniques due to their robustness and convergence characteristics (Jabr et al. 2002; Jabr 2008; Jabr and Pal 2009; JunHua et al. 2012; Zhang et al. 2005). Jabr et al. (2002) proposed an enhancement of existing primal dual interior point methods for OPF which involves a filter technique to guide the choice of the step length and search direction in order to avoid convergence to a non-minimizing stationary point. The proposed method addressed the issues of global convergence of interior point methods resulting in robust convergence characteristics and reduced computational time.

Another significant enhancement to reduce the complexity of the OPF problem was made by Torres and Quintana (1998) who expressed the bus voltages in rectangular form which resulted in a quadratic objective function and quadratic constraints. The rectangular form allows for ease of matrix setup with incorporation of higher-order information which improves tractability by predictor corrector nonlinear interior point methods. The modified power balance equations are shown as follows where the voltage at the bus $V_i = e_i + jf_i$. e_i represent the real part and the f_i represent the imaginary part of the voltage at bus i. P_i and Q_i represent real and reactive power at bus i respectively and V represents voltage magnitude. G_{ij} and B_{ij} represent the conductance and susceptance between bus i and j respectively.

$$P_i = \sum_{j=1}^{n} G_{ij}\left(e_i e_j + f_i f_j\right) + B_{ij}\left(f_i e_j - e_i f_j\right) \tag{1}$$

$$Q_i = \sum_{j=1}^{n} G_{ij}\left(f_i e_j - e_i f_j\right) - B_{ij}\left(e_i e_j + f_i f_j\right) \tag{2}$$

Following on from the rectangular formulation of the OPF problem, a nonlinear interior-point OPF method which substitutes the bus power mismatch formulation with a current mismatch formulation in rectangular coordinates was proposed by Zhang et al. (2005). The advantage of the current mismatch formulation is that some constraints become linear which improves ease of implementation. Results indicate that the two methods are comparable in terms of CPU (central processing

unit) time with the current mismatch formulation method having less computational complexity per iteration.

Jabr (2006) proposed the formulation of the OPF problem as a second order cone program which transforms the optimisation problem for radial distribution systems into a convex optimization problem. This method is used in a separate study (Jabr and Pal 2007) to determine the load capability of the radial system, thus avoiding the need for running a sequence of load flow solutions. The conic objective function yields a voltage stability indicator which quantifies the maximum percentage by which the current load profile can be uniformly increased before a voltage collapse occurs. Conic programming was extended to meshed networks by Jabr (2007) by including a trigonometric functional constraint for the voltage angle spread on each line in the network. As a result, the load flow solution of a meshed network can be obtained from a sequence of conic programming solutions. A complete extended conic quadratic OPF (ECQ-OPF) formulation was developed by Jabr (2008) to solve the economic dispatch and active power loss minimization problems including control devices such as tap-changing transformers, phase-shifting transformers, and unified power flow controllers. Reported advantages of the ECQ-OPF approach include easy integration within optimization routines that require the evaluation of second-order derivatives, efficient solution using primal-dual interior-point methods, and use of linear programming scaling techniques for improving numerical conditioning.

The extended conic quadratic (ECQ) form using the transformations is defined in (3) (Jabr 2008; Jabr and Pal 2009).

$$
\begin{aligned}
R_{in} &= V_i V_n \cos(\delta_i - \delta_n) \\
T_{in} &= V_i V_n \sin(\delta_i - \delta_n) \\
u_i &= \frac{V_i^2}{\sqrt{2}}
\end{aligned}
\tag{3}
$$

where δ and V represent the voltage angle and the voltage magnitude respectively. R_{in}, T_{in}, and u_i represent ECQ variable representing real component of flow between buses i and n, ECQ variable representing imaginary component of flow between buses i and n, ECQ variable representing voltage at bus i respectively. When these transformations are applied, the power balance constraints are expressed as follows.

$$
P_{sch} = \sqrt{2} G_{ii} u_i + \sum_{\substack{j=1 \\ j \neq i}}^{N} \left[G_{ij} R_{ij} + B_{ij} B_{ij} T_{ij} \right]
\tag{4}
$$

$$
Q_{sch} = -\sqrt{2} B_{ii} u_i - \sum_{\substack{j=1 \\ j \neq i}}^{N} \left[B_{ij} R_{ij} - G_{ij} T_{ij} \right]
\tag{5}
$$

where, P_{sh} and Q_{sh} give the scheduled real and the reactive power respectively. Thus, the power balance constraints are transformed into linear equality constraints. The transformed equations are constrained by the following relation

$$2u_i u_n = R_{in}^2 + T_{in}^2 \tag{6}$$

The above formulation is sufficient to describe the power flow equations for a radial network. For a meshed network, the arctangent equality constraints must also be included.

$$\delta_i - \delta_n = \tan^{-1}\left(\frac{T_{in}}{R_{in}}\right) \tag{7}$$

Adding the rotated conic quadratic in (6) and arctangent equality constraints in (7) captured the nonlinearity of the classical OPF problem (Jabr 2008; Jabr and Pal 2009). All other constraints are transformed into linear expressions making the ECQ-OPF problem easily tractable by primal-dual interior point methods.

While the Optimal Power flow (OPF) problem has been a challenge for many decades, recent evolution of the electricity grid has further increased the complexity of this problem. Additional challenges include issues such as transient stability constraints, large scale renewable energy penetration, dynamic line ratings and use of flexible AC transmission system (FACTS) devices. While traditional OPF has considered only the steady state performance of the system, the transient performance is equally important to ensure reliability and quality of supply. Dynamic transient stability constraints including rotor angle limits during contingencies must be included which require the use of algebraic as well as differential equations (Zhifeng et al. 2009). One of the first efforts to effectively approximate the dynamic nature of the TSCOPF (transient stability constrained optimal power flow) problem using numerically equivalent algebraic equations was by Gan et al. (2000). Yue et al. (2003) modelled transient stability constraint under multiple contingencies by using interior point methods (IPM). Instead of approximating dynamic characteristics by equivalent algebraic equations, Cai et al. (2008) used artificial intelligence techniques based on evolutionary programming to solve the TSCOPF problem thus demonstrating the effectiveness of artificial intelligence techniques for OPF incorporating dynamic characteristics.

Incorporation of FACTS devices present similar challenges to TSCOPF as new control variables must be incorporated which results in increased power transfer across lines and the need to consider system stability constraints (Zhifeng et al. 2009). Early work on FACTS devices (Ge and Chung 1999; Taranto et al. 1992) used methods that approximate the characteristics of the devices using simplified linearized models. In modern power systems, the increased complexities due to FACTS devices require a more versatile modelling method. Some attempts at improving the modelling of FACTS devices include use of the thyristor firing angle

as a state variable (Ambriz-Perez et al. 2000) or by real and reactive power injections due to FACTS devices as additional independent variables in the OPF problem (Ying et al. 2002). Modern power systems include devices such as static VAR compensators, solid state synchronous compensators, thyristor controlled compensators and unified power flow controllers. Jabr et al. (2008) proposed transforming the OPF problem into a second order cone program with constraints for FACTS devices such as the UPFC (unified power flow controller). While there are some efforts such as these to create better power flow models for FACTS devices, existing algorithms still need further development to be versatile or reliable enough to adequately deal with new constraints arising from FACTS devices.

More recently the use of artificial intelligence techniques and heuristic methods have overcome a number of challenges associate with convergence of classical optimisation methods, especially for transient stability constrained problems (Hayes et al. 2014; Qi et al. 2013; Rahul et al. 2012; Bhattacharya and Roy 2012). As a result, it is now possible to incorporate a number of factors such as demand management and electric vehicles which have dynamic characteristics that may result in high sensitivity to initial conditions when solving by traditional analytical methods. Hayes et al. (2014) incorporate the effect of demand side management (DSM) into the OPF formulation by quantifying benefits in terms of the ability of demand-responsive loads to relieve upstream network constraints and provide ancillary services, such as operating reserve. It uses a time-sequential OPF applied to typical radial and meshed U.K. distribution networks which suggest that including DSM in the OPF formulation can optimise the benefit. JunHua et al. (2012) develops a hybrid method involving particle swarm optimisation (PSO) and interior point methods to include the effect of plug in electric vehicles (PEHV) in the OPF problem. Qi et al. (2013) formulates the OPF problem incorporating controllable and uncontrollable distributed generators in a power network. Furthermore, they consider single and multiple generator failures and use a particle swarm optimization technique and group search optimizer to solve the problem.

Other artificial intelligence techniques were proposed by Rahul et al. (2012) by using a Genetic Algorithm based approach to demonstrate the improvement over the Particle Swarm Optimization Technique. Bhattacharya and Roy (2012) propose a gravitational search algorithm (GSA) for solutions of multi-objective optimal power flow (OPF) problems demonstrating superior convergence speed and global search ability compared with mixed integer particle swarm optimisation, evolutionary programming, genetic algorithm and biogeography-based optimisation. While artificial intelligence techniques such as the ones presented have a higher likelihood of convergence they cannot still guarantee the global optimisation and solutions from AI techniques may often provide only a local optimum or may not have any physical/practical meaning (Zhifeng et al. 2009). As a result, there is a strong motivation to develop modern analytical techniques such as those outlined in (Jabr 2008; Jabr and Pal 2009) or analytical and AI hybrid techniques such as those in JunHua et al. (2012).

3 Probabilistic Techniques

It should be evident that modern power systems operate under a high level of uncertainty. This uncertainty is introduced by the variations in load, renewable generation as well as unexpected changes in system operating conditions. It is also becoming less economically viable to operate under the large risk margins of past power systems thus risk needs to be quantified quantitatively and more closer to the reality. As a result, probabilistic techniques have seen applications in various aspects of power systems simulation and modelling. This section discusses the use of probabilistic techniques in optimisation and outlines the use of Monte Carlo simulation as it is one of the most widely used simulation technique in power systems.

To incorporate the uncertainty, stochastic optimisation techniques use the expected value of uncertain variables in the OPF problem and minimise the cost of recourse actions (Jabr and Pal 2009; Meibom et al. 2011). As an improvement from conventional day ahead unit commitment methods, Meibom et al. (2011) propose a stochastic model to study operational impacts of future high wind penetrations for Ireland. It considers uncertainty due to load, wind and forced outages using a stochastic mixed integer linear optimization scheduling model with regular updating of schedules as more data becomes available. Jabr and Pal (2009) determine the expected wind power output including the error in wind power forecasts from a probability distribution derived from historical data or estimated by a bimodal normal distribution. It then determines the wind power to schedule by balancing the expected penalty cost for not using all available wind power and the expected cost of calling up reserves because of wind power shortage.

The aforementioned stochastic optimisation techniques use variables with a known probability distribution in conjunction with deterministic constraints. An alternative method of modelling stochastic variables as well as uncertainties in constraints is the chance constrained optimisation where the probability of violating a constraint is limited to a predetermined value (Qianfan et al. 2012; Hui and Pu 2011). Hui et al. (2011) identifies the additional complexity of the chance constrained OPF problem due to nonlinear constraints with multiple uncertain variables as well as uncertain constraints. It uses a back-mapping approach and a linear approximation of the nonlinear model equations to incorporate the chance constrained programming (CCP) approach to OPF under uncertainty. Qianfan et al. (2012) uses a two-stage chance-constrained stochastic program to include uncertainties due to wind power in the unit commitment problem, while maximising wind power utilisation. It develops a combined sample average approximation (SAA) algorithm to solve large-scale power grid optimization problems. Chance constrained optimisation is one the few methods that can use analytical techniques to capture uncertainty in constraints. However, it is required to have standards and guidelines to specify how the predetermined maximum probability of constraint violation is selected. Traditional stochastic optimisation avoids this problem by using expected values and penalties for deviating from the expected value, but it cannot account for uncertainties in constraints. Dynamic line ratings lead to

uncertainties in constraints and more research could be directed towards modelling such uncertainty so that dynamic line ratings may be incorporating into dispatch decisions.

4   Stochastic Optimal Power Flow

Stochastic optimization is the process by which the optimization is undertaken when there is an uncertainty in one or more of the variables. The uncertain variables must have a known probability distribution. The optimisation can then be solved with the expected value of the uncertain variable. To ensure that the expected value of the variable is chosen appropriately by the algorithm, it is assumed that there is a cost of recourse action if the actual value of the variable is different to the expected value. The total cost of the recourse action is included in the objective function. Variations from the scheduled value have a penalty factor associated with them and this ensures the best value is chosen for the scheduled variables.

The method of stochastic optimisation is often referred to as two stage stochastic programming. The first stage refers to the values of the known variables and the second stage refers to variables that are not yet known but will be realised in future. However, the optimisation decision should only account for the information available at the time which is usually in the form of a probability distribution. The general problem definition for optimisation under uncertainty is

$$\min_{x \in X} \big\{ g(x) := c^T x + E[Q(x, \xi)] \big\} \tag{8}$$

where E[.] represents the expected value and Q(x,ξ) is the optimum value of the second stage problem.

$$\min_{y} q^T y \quad subject\ to \quad Tx + Wy \le h \tag{9}$$

The first stage decision vector is x and the set of constraints are in X. The second stage decision vector is y and the second stage data is contained in ξ = (q,T,W,h). The value of ξ is uncertain and a decision must be made based on the expected value when solving the first stage problem. The optimisation of the second stage can be considered in terms of recourse action for when the actual realisation of the uncertain vector is different to the value used for optimisation. The solution of the first stage problem should be such that the expected cost of recourse action is minimised.

The possible realisations of ξ present a challenge especially when there are a large number of outcomes possible. Monte Carlo techniques based on Sample average approximation can be used to reduce the number of realisations to a manageable size.

Sample average approximation (SAA) can be used for optimisation when there is uncertainty in the objective function. In practical scenarios objective functions may not be known accurately and hence the parameters defining the function are modelled as random variables with known probability distributions. The objective function f(x) is replaced by the expected value which is obtained by repeatedly sampling $f(x, \xi)$ for different values of the uncertain vector ξ and finding the average of those samples as $f_N(x)$ for N samples. This is shown in (10) and it is assumed that each sample is independent and identically distributed (i.i.d.).

$$f_N(x) = \frac{1}{N} \sum_{i=1}^{N} f(x, \xi_i) \tag{10}$$

where ξ_i represents the vector that contains all the parameter with uncertainty. In this instance $\xi_i = [cOLp]$ such that it contains Dynamic Line rating (DLR) cost parameter for each line in the system. The objective function of optimization can be replaced by the SAA function in (10). Thus, if the original objective function is denoted $f(x, \xi_i)$ it can be replaced by the SAA approximation $f_N(x)$.

If $f_N(.)$ converges uniformly to $f(.)$ then it is well established that for a given sample size N, the optimal solution, x_N and the optimal value, $f_N(x_N)$ are random variables with normal distribution (multivariate normal distribution in the case of the optimal solution x_N). $f_N(x_N)$ is approximately Normal ($v*$, $\sigma^2(x_N)/N$) and x_N is Normal ($x*$, $H^{-1}\psi H_{-1}$). The true values of optimal solution and optimal value are given by x* and v* respectively. H represents the hessian matrix of the objective function $f(x)$. ψ is the asymptotic covariance matrix of $\sqrt{N}[\nabla f_N(x) - \nabla f(x)]$.

Thus, it should be possible to determine a $(1 - \alpha)$ confidence region for the optimal solution in terms of a tolerance ǫ. We can then state with probability $(1 - \alpha)$ that any estimator of the optimal solution based on N samples, will be within a tolerance of ǫ from the true solution. The value of ǫ can be expressed as a percentage and be made smaller for a more accurate solution by choosing a larger value of N as long as uniform convergence characteristics are satisfied.

It should be noted that for a multivariate normal distribution the confidence region is an ellipsoid. Thus, the tolerance ǫ is defined in terms of the boundaries of the ellipsoid. As the worst case scenario, we may only consider the largest axis of the ellipsoid which represents the furthest distance a possible solution can be from the true solution.

An example of OPF under uncertainty occurs when wind generation output is considered. The OPF problem can be represented as a stochastic optimisation problem since the output from a wind farm is a random variable with a known probability distribution. The expected wind power output is determined from the probability distribution at the scheduling stage. During the operational phase any deficit or excess in actual wind power output compared to scheduled output, must be balanced by additional reserve generation or by curtailing excess wind. Thus, reserves and wasted wind are the recourse actions which account for any differences between expected wind output and actual wind power output. The wind power

intermittency cost ($C_w(P_w)$) is modelled using stochastic optimization by discretizing the probability distribution of wind power and balancing probabilistic reserve cost with cost of wasted wind (Jabr and Pal 2009) as shown in (11).

$$C_w(P_w) = \sum_{j=1}^{N_W} \left[e_j P_{Wj} + c_{Wj} \sum_{k=1}^{M} f_{jk} s_{jk} + c_{Rj} \sum_{k=1}^{M} f_{jk} t_{jk} \right] \quad (11)$$

where the power output of wind generator j is P_{Wj} and the unit feed in cost is e_j. The cost of wind in (11) is subject to the constraints in (12).

$$\begin{aligned} t_{jk} &\geq P_{Wj} - w_{jk} \\ s_{jk} &\geq w_{jk} - P_{Wj} \\ t_{jk} &\geq 0, s_{jk} \geq 0 \end{aligned} \quad (12)$$

where (f_{jk}, w_{jk}) is the kth ordered pair (out of a total of M) representing the discretised probability distribution of wind generator j. N_W is the number of wind generators in the system and c_{Wj} and c_{Rj} are the unit cost of wasted wind and reserve generation respectively at wind generator j. Based on the constraints in (12), the probability distribution of reserve generation is represented by the set of ordered pairs (f_{jk}, t_{jk}) and the probability distribution of wasted wind is represented by the set of ordered pairs (f_{jk}, s_{jk}). The cost of wasted wind represents the opportunity cost of not being able to sell the energy generated.

4.1 Monte Carlo Simulation

Monte Carlo Methods are commonly used for modelling inherent variability in systems of which a closed form analytical expression cannot be obtained or is complex. Monte Carlo simulation is based on simulating the value of uncertain parameters using random number generators to determine the sampled statuses and estimating the outputs. After a large number of simulations (trials) are performed, it is expected that the probability distribution of the outputs will be obtained with a degree of confidence to the confidence interval. In contrast, a deterministic method may use the mean value of uncertain parameters and hence obtain the mean value of the output. This method may provide an accurate representation of the mean value of the output but does not capture the variability or in other words it assumes that each event has a same level of probability. Alternatively, some methods may attempt to evaluate every possible combination of uncertain parameters to obtain an exhaustive range of outputs. Such a method is complex, resource intensive, and often unnecessary as some combination of parameters is highly unlikely to occur in a practical scenario. Monte Carlo simulation considers different combinations of inputs and corresponding outputs, based on the likelihoods of these conditions occurring in a practical scenario (Rubinstein and Kroese 2008).

In power systems, Monte Carlo simulation has been used in a wide range of applications when there has been an uncertainty. One of the traditional applications of Monte Carlo simulation has been in reliability and security evaluation (Billinton and Peng 1999; Rios et al. 2002). A typical example of distribution system reliability using Monte Carlo techniques is presented by Billinton and Peng (1999). It is argued that considering the mean value of system reliability indices does not reflect the reliability seen by the customer due to the inherent variability of these indices. A time sequential Monte Carlo method is then used to obtain both the mean value and probability distribution of a range of system reliability indices. Rios et al. (2002) examines similar techniques for transmission system security where deterministic criteria have traditionally been used. It is proposed that the cost of the security margin should be weighed against the benefit obtained by using probabilistic techniques. This method also accounts for time dependent phenomena such as cascade tripping due to overloads, unreliable operation of protection devices, and potential power system instabilities. The advantage of this type of approach is that it can prevent over-designing of a system to meet deterministic security criteria where the added benefit may be minor.

Unit commitment is closely related to reliability and security at the transmission level and Monte Carlo analysis can be applied in modelling uncertainties (Lei et al. 2007, 2008, 2010; Zhai et al. 1994). Earlier studies on stochastic unit commitment (Zhai et al. 1994) considered the uncertainty due to load while more recent studies (Lei et al. 2007, 2008, 2010) consider effects of wind and other renewable generation in addition to likelihood of outages. These studies clearly demonstrate that Monte Carlo simulation captures not only uncertainties due to outages and component failures in the system but also the variability of load and renewable power generation and hence present a more accurate and comprehensive evaluation of unit commitment risk.

Probabilistic load flow is another application of Monte Carlo simulation techniques (Allan et al. 1981a, b). Allan et al. (1981a, b), Chun-Lien (2005) developed an improved method for probabilistic load flow using the results of Monte Carlo simulation. More recent studies used Monte Carlo simulation for probabilistic load flow with integration of renewable power generation and distributed generation (Jorgensen et al. 1998; Ruiz-Rodriguez et al. 2012). When wind integration is considered, reserve allocation in the presence of wind can also be determined by Monte Carlo techniques (Ortega-Vazquez and Kirschen 2009; Zhai et al. 1994).

5   Conclusion

Modern power systems rely on advanced modelling and simulation techniques to facilitate decision making. Increasing complexity of power systems has resulted in developments in advanced and innovative modelling and simulation methodologies. Most power system decision making involves determining the optimal configuration for operating system resources under a wide spectrum of static and

dynamic constraints. Modern optimisation techniques include both analytical and heuristic and often a combination of both to improve the solution efficiency for such problems. Probabilistic modelling can account for the uncertainties and associated risks of decision making. Stakeholders in the power system can thus plan contingencies accordingly.

The area of power system modelling and simulation is an active and wider area of research. There are a number of key areas that could further increase the effectiveness of the existing methodologies. Analytical and artificial intelligence based techniques continue to improve and new developments in mathematics are often applied to power systems. Improved understanding of risk and uncertainty continue to influence decisions which will lead to less built in redundancies in systems thus resulting in lower overall costs. These developments coupled with improvements in computing technologies will ensure that the power systems of the future will be flexible, robust and reliable.

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Micro Grid Planning and Operation

Binayak Banerjee, Dilan Jayaweera and Syed Islam

Abstract Increasing penetrations of renewable power as well as deregulation of electricity markets have seen a rise around the world. A Micro Grid is a smaller entity that can intelligently control and coordinate distributed energy resources with the support of intelligent controllers and other necessary architecture. However, achieving such objectives that lead to a smart operation require significant advances to planning and operation of the Micro Grid as the collective operation of Micro Grids can potentially provide business cases. Roles of Micro Grids include improving reliability, resilience and security at the normal and emergency operating conditions of the power grid. Each mode of operation presents challenges such as frequency control in islanded mode and voltage control in grid connect mode. Micro Grid control strategies may be classified into grid following and grid forming and further into interactive or non-interactive. Most control hierarchies combine centralised as well as decentralised control. This chapter investigates specific challenges in a Micro Grid, planning and operation, control strategies as well as realistic studies of micro grids.

Keywords Grid connected micro grids · Islanding · Micro grid control · Micro grid standards · Real time state estimation

1 Introduction

The traditional approach of centralised electricity generation is gradually being replaced by decentralised generation. Traditional centralised generation took advantage of economies of scale which were not applicable for loads to be supplied in remote areas. It was more economically feasible to use smaller generators to

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supply such loads locally. The accompanying steady growth in the penetration of renewable energy generators and deregulation of electricity markets has resulted in high levels of interest in distributed generation not only for remote area power but also power in stronger parts of the grid. Renewable generators are usually small scale and thus it is easier to connect them to the grid as distributed generators. Market deregulation has resulted in smaller independent generators connecting to the grid at various points.

These factors have seen a rapid growth in distributed generation (DG). DGs have a number of benefits since they are close to the customer and can improve reliability, power quality and voltage profile. The distributed generation systems combined with energy storage and other balancing technologies are collectively called Distributed Energy Resources (DER). While there are a number of benefits of DERs they pose new control and operation challenges at higher levels of penetration. Thus the concept of Micro Grids was proposed to coordinate DERs in a more decentralised fashion.

There are a number of definitions of a Micro Grid available in literature. A few common ones include:

- A micro grid is formed when a region capable of autonomous operation is islanded from the grid (Katiraei et al. 2005).
- From the grid perspective, a micro grid includes LV or MV locally controlled cluster of DERs that behave as a single generator or load both electrically as well as in the energy market (Hatziargyriou et al. 2007).
- Micro Grids can disconnect from the traditional grid, operate autonomously, and help mitigate grid disturbances, serve as a grid resource for faster system response and recovery, and hence strengthen grid resilience (Strbac et al. 2015).

The key feature of a Micro Grid is that it can be treated as a single entity with respect to the overall grid. However, it must also be capable of autonomous operation in case the main grid is not available. It is important to note that a distribution system with DERs is not necessarily classified as a Micro Grid. One of the distinguishing features of a Micro Grid is the level of intelligence and controllability. Micro Grids appear as a controlled and coordinated unit of the upstream in a network. A typical structure of a micro grid is shown in Fig. 1.

One of the first groups to undertake practical research into Micro Grids was the Consortium for Electric Reliability Technology Solutions (CERTS) in the United States of America and the project was titled the CERTS Micro Grid. The CERTS group comprised of multiple national laboratories across the United States and the purpose of the CERTS Micro Grid was to provide an alternative means of integrating small scale distributed generation (less than 500 kW) into distribution systems.

The definition and function of Micro Grids has changed over time from a necessary means to coordinate DERs and operate autonomously to a grid resource that can be used to improve the overall resilience, reliability and security of the grid. The evolution of Micro Grids has been aided by the development and application of smart grid concepts which expect grids to be operated more dynamically, securely, efficiently, economically with a greater flexibility.
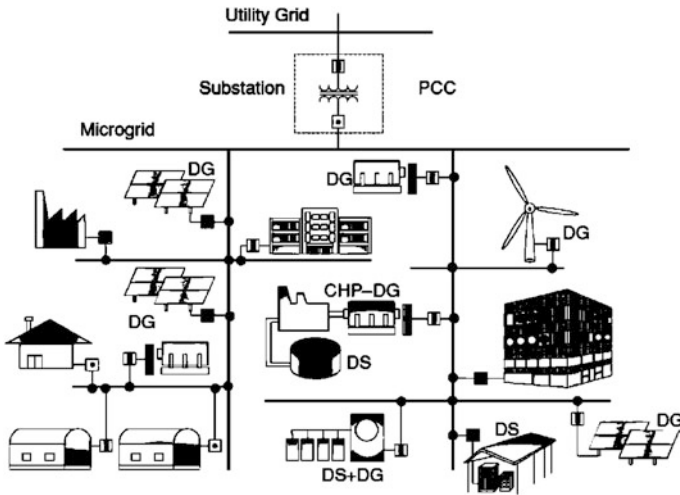
Fig. 1 Typical micro grid structure (*Source* Katiraei et al. 2008)

The Department for Energy and Climate Change (DECC) is developing policies as part of the Energy Efficiency Strategy (DECC 2012) which will support distributed generation. The opportunities in the area of distributed generation include:

- Increased generation mix
- Reduced requirement for transmission infrastructure
- Reduced transmission losses.

However a number of challenges also need to be overcome including;

- Rise in voltage and fault levels
- Thermal ratings of equipment being exceeded
- Possible reverse power flows
- Power quality being affected.

This chapter outlines the state of the art in micro grid components as well as some of the challenges and opportunities in Micro Grid planning and operation. It discusses Micro Grids in grid connected as well as islanded mode. It also presents relevant standards on micro grids as well as presenting a few case studies of practical micro grid projects. It concludes the chapter by discussing future directions which micro grid research can take.

2   State of the Art of Micro Grid Components

One of the key components of a Micro Grid includes DG sources. There are two fundamental types of DGs that most technologies can be classified into.

- Conventional DGs are those which involve rotating machines connected directly to the grid. These typically do not require a power electronic interface. Examples include small hydro or fixed speed wind turbines connected to induction generators.
- Nonconventional DGs are those which usually require a power electronic interface. The source side of the power electronic converter may be AC as in the case of variable speed wind turbines or microturbines, or DC as in the case of PV arrays or fuel cells.

Distributed storage (DS) also forms a major part of a micro grid. There are two types of DS technologies

- Long term storage e.g. batteries are used to store energy to be supplied later and this prevent loss of load due to fluctuation in generator output.
- Short term storage, e.g. supercapacitors or flywheels, can be used to balance short term fluctuations in frequency when in islanded mode. Some short term storage such as flywheels can provide the inertia of rotating mass that is usually missing in Micro Grids and thus maintain grid frequency.

DS usually requires a power electronic interface for connection to the grid. Details on storage can be found in Chap. 5.

Sector customer loads are also key components in a Micro Grid. In Micro Grids, loads need to be flexible since in the autonomous operating mode, loads/generation may have to be curtailed to ensure the power balance and voltage and angle stability. In the grid connected mode, such a provision is not necessary as the grid accounts for any imbalances. Thus, it is important that the control strategy prioritises critical loads to ensure they are supplied at all times. Part of nonsensitive loads can be considered controllable from the grid perspective and can be used for the demand response strategy when required.

3 Current Micro Grid Challenges and Opportunities

3.1 Voltage Control—Grid Connected Mode

In a Micro Grid, there can be multiple micro generators operating in parallel. The circulation of reactive power between these sources causes fluctuation in voltage and reactive power. Voltage control is necessary to mitigate against these voltage fluctuations. In a traditional power grid, the impedance is sufficiently high to prevent circulating currents between sources. Since micro grids are typically operated in a radial configuration this problem is pronounced further. Due to the high sensitivity, small errors in voltage set points can increase circulating currents beyond the ratings of the generators. Thus voltage set points need to be adjusted in real time.

In conventional power systems, the real and reactive powers are both coupled through the magnitude of the voltage at the generator and the grid and the voltage

angle difference. For small changes, real power (P) is typically dependent on the voltage angle and reactive power (Q) is dependent on the magnitude of the terminal voltage. Converter based micro-sources can use the same basic principle of P-Q control to regulate real and reactive power.

However, Micro Grids typically involve the interconnection of a large number of micro-sources. In such case, there may be circulating currents between micro-sources which leads to oscillations in the voltage and reactive power magnitude. Thus, some form of local voltage control is necessary to ensure system stability. This problem is evident in the traditional grid between synchronous generators; however, the high impedance of the grid reduces circulating currents. Since distribution systems are operated radially, the circulating currents can be very high and often exceed ratings of the micro-sources even for small error in voltage set points.

Voltage droop control (Lasseter 2002) is one of the fundamental methods of controlling local voltage that avoids circulating currents. The reactive current is measured and the voltage set point is adjusted accordingly. The set point is reduced for as the reactive current becomes capacitive and the voltage set point is increased for inductive reactive current. Voltage droop control allows for load sharing between generators. More sophisticated algorithms also account for sharing of harmonics currents when nonlinear loads are present (Guerrero et al. 2011).

Figure 2 shows the voltage droop characteristics with (Q_0, V_0) representing the nominal voltage at rated reactive power. Dynamically adjusting the reactive power sharing can allow new values of voltage to be set $(1 + \Delta V$ or $1 - \Delta V)$.

Modern voltage control methods such as high angle gain droop control (Majumder et al. 2010) are based on the basic droop control method. Angle gain droop control measures the voltage angle instead of the magnitude and a high value for the gain of the voltage angle in the control loop provides good results in weak grids. However, they can lead to overall stability problems which is solved by using supplementary control loops as proposed by Majumder et al. (2010). The work of Guerrero et al. (2011) proposes a generalised hierarchical droop control for AC and DC Micro Grids which include not only the basic primary droop control but also two more levels. The secondary loop control corrects for deviations from the primary control and the tertiary control manages the power flow between the Micro Grid and external distribution network.

Fig. 2 Voltage droop characteristics for load sharing amongst DERs
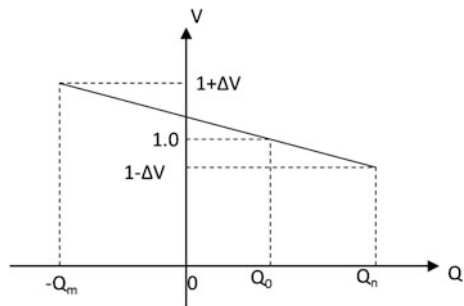
3.2   Frequency Control—Islanded Mode

A Micro Grid is islanded usually following a disturbance or fault in the system to ensure that supply can be maintained to customers. However, most utilities do not allow autonomous operation of micro grids in an islanded mode due to safety requirements. They require that all downstream components are de-energized following a fault or disturbance. To fully realise the benefit of micro grids it is essential to allow islanded operation of Micro Grids. Utilities and policy makers must be convinced of the benefits of islanded operation and all associated risks should be mitigated appropriately.

Micro grid islanding can be due to pre-planned or unplanned incidents. In the case of pre-planned islanding, transients can be minimised since loads can be shared equally between DGs. An example of pre-planned islanding would be isolating a line at both ends for maintenance. During pre-planned islanding, micro grid set points can be adjusted prior to islanding and there will be minimum transients.

For islanding due to faults and disturbances, a change in control strategy is required to ensure that transients can be minimised. Disturbances will result in frequency variations and power swings in a Micro Grid. On the other hand, fast control action of converter interfaced DGs can damp such oscillations.

Most distributed generators cannot respond to load changes fast since they are inertia less and slow response (10–200 s prime mover). Thus when any load changes occur, there is no initial energy balance and the frequency begins to fluctuate. In a traditional grid, synchronous generators have inertia and it can accommodate load changes without affecting the frequency greatly. The storage technologies discussed previously are critical components of a Micro Grid and comes in many forms including flywheels, supercapacitors, electric vehicles, and batteries that are connected local or centralised to micro generators.

Frequency droop control can also be utilised similar to voltage droop. The frequency droop control strategy is shown in Fig. 3. The rated frequency is at (P_0, f_0) and changing the real power sharing can allow new values of frequency to be set.

Fig. 3 Frequency droop characteristics for load sharing amongst DERs
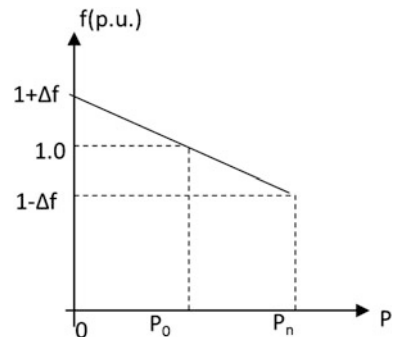
3.3 Real Time State Estimation

Another challenge for operation of Micro Grids is real time state estimation of components. The state of a system is typically determined based on a finite number of observations or measurements. Real time state estimation is undertaken for transmission networks using SCADA systems to record measurements at regular intervals. However, transmission system state estimation practices cannot directly be applied at the distribution level since distribution planning and operation has a different philosophy. For example, one of the challenges identified in state estimation at the distribution level is the lack of available data on real time load variations for individual customers (Hu et al. 2011). Also, in a Micro Grid the state depends almost on infinite number of factors whereas there is limited number of measurements. The challenge is thus to use a limited number of measurements to accurately estimate the state of a Micro Grid in real time.

Measurements for state estimation may be based on node voltage measurements (Ghosh et al. 1997) or branch current measurements (Wang and Schulz 2004). Branch current based state estimation is superior in terms of computation speed and resource usage and is also ideal for weakly meshed distribution systems (Wang and Schulz 2004). A number of researchers are making progress on determining optimum measurement locations and it is expected that the uncertainties associated with the real time state estimation will gradually decrease further with advanced techniques and technologies. For example, advanced metering infrastructure due to smart grid will allow for increased visibility at the individual customer level which will facilitate data collection. However, the high cost of metering infrastructure dictates that their use is limited to a finite number of key locations which will allow adequate measurements for accurate state estimation.

Once the optimum locations for measurements have been identified and data has been collected, the process of state estimation can be undertaken. Probabilistic modelling which optimises the estimate of state variables (Hu et al. 2011) will play an important role since there will be some level of uncertainty in the collected data based on number of observations.

4 Micro Grid Control Strategies

The control of Micro Grids can take place centrally or in the form of distributed control. Controllers can be placed on each DERs in the Micro Grid as local source controllers and on loads as local load controllers. There may be a central supervisory controller that coordinates the operation of source and load controllers. The distribution of control between the central controller and local controllers determines whether the Micro Grid is controlled locally or centrally as per the operating requirements.

4.1 DER Controls

A Micro Grid controller may be centralised or embedded in each DG or DS unit. DER controllers can have various strategies. These are typically classified as grid forming or grid following (Katiraei et al. 2008; Rocabert et al. 2012). Grid forming control is used when the Micro Grid is in autonomous mode and the DER needs to regulate the voltage and frequency. In grid following mode, there are no such requirements and the voltage and frequency are set by the grid.

Control strategies can be further classified as grid interactive or non-interactive. Grid interactive strategies involve setting the output power of the DG unit according to a dispatch strategy or the grid requirement. Non interactive strategies involve setting the output power independent of loads and other generators in the grid.

When a micro grid is in grid following non-interactive mode, it has a power exporting strategy. In this instance the DER voltage and frequency limits are defined by the Micro Grid. The reference signals are also synchronised to the Micro Grid frequency.

Grid following interactive control is used when a power dispatch and real/reactive power support is required. Grid following interactive control is applicable to dispatchable DER units. Voltage regulation of the unit as well as power factor compensation is an example of this type of strategy.

A non-interactive grid forming control is used when the Micro Grid is in islanded mode. In the absence of the utility grid the DER attempts to stabilise voltage and frequency while supplying the balance of power. In this scenario, it is necessary for the DER to be dispatchable. Thus, in grid forming mode the DER emulates a swing source in conventional grid.

If there are more than one grid forming DERs it may be prudent to use both of them to share the power and balancing function in islanded mode. In this case a grid forming interactive strategy of operation will be required. Frequency droop and voltage droop control will be required for sharing of load between the DERs. When multiple DERs are in operation in autonomous mode a power and energy management system (PMS) will be required. This is because the DERs can have significantly different characteristics with no clear dominant source or infinite bus. The PMS also ensures that voltage/angle stability problems do not adversely affect the micro grid when there are electronically coupled DERs.

4.2 Micro Grid Supervisory Control

Each Micro Grid has different levels of control. A micro grid will typically consist of a Micro Grid Central Controller (MCC) to coordinate the operation of multiple DERs and loads, and a number of local controllers (LCs) to determine the operation of each DER or controllable load. Decision making is usually divided between MCC and LCs and the level of division determines whether the control strategy is

centralised or decentralised. The LCs receive set points from the MCC and control DERs and loads. Depending on the level of decentralisation, LCs may have a certain amount of intelligence.

When a number of Micro Grids exist in an area they are typically coordinated by the distribution network operator (DNO) and market operator (MO). These are not part of the Micro Grid but typically part of the transmission grid. The MCC is the interface between the Micro Grid and the main grid.

In a centralised control structure, decisions are made by the MCC about the set points and generation that will optimize production. The MCC informs LCs about electricity market prices, generation set points, and load serving or shedding. On the other hand it collects generation bids from the DERs and demand bids from loads. Based on signals from the MCC the LCs adjust their output. The aim of a centralised structure is to optimise the power exchanged with the host system.

In a decentralised control structure, the LCs have maximum autonomy. The objective is not necessarily to maximise the revenue of each unit but also to optimise the performance of the micro grid as a whole. Thus the LCs require a certain level of intelligence and they should be capable of communicating with each other. Decentralised control is typically suited to Multi agent systems (MAS). MAS is an evolved form of classical distributed control with the distinguishing feature that software in each agent can imbed local intelligence. Unlike centralised structure, the agents don't just exchange simple on/off signals. The agents exchange knowledge, commands, procedures and beliefs.

5   Grid Interaction of Micro Grids

5.1   *Transmission Level Analysis*

Transmission level studies of Micro Grids have received relatively less attention compared to the distribution level studies. One of the main reasons is that a Micro Grid has a large number of variable elements and their control and coordination can be a challenging task. These are more immediate challenges that need to be addressed before considering their effect when combined with other Micro Grids at the transmission level. However, techniques for improving Micro Grid control and coordination are improving. A number of projects on implementing and testing Micro Grids have also shown promise.

5.2   *Micro Grid Aided Restoration*

System wide blackouts are rare events that have serious implications and widespread impact. Examples of such events include storms, terror attacks or natural

disasters. Due to the effects of climate change cost effective measures of mitigating against low probability but high impact events has become a requirement for modern electricity grids.

Increasingly, Micro Grids are being identified as a resource for black starts where the grid fails to restore supply to customers. In this scenario, the Micro Grid would isolate from the main grid and restore supply to local loads before synchronizing with the main grid. The Micro Grid restoration procedure requires a sequence of actions that can be automated. The local controllers for generators and loads in Micro Grids, in conjunction with the Micro Grid supervisory controller should be able to execute this sequence of operations without intervention from the distribution network operator.

The Micro Grid should include isolators on LV feeders as well as adequate protection devices on micro-sources and loads to ensure that they are not exposed to fault currents and faults are cleared and isolated. Communications infrastructure needs to have a dedicated power supply to ensure that they can continue to function in the case of loss of supply. The Micro Grid controller also needs the capability to change protection settings as short circuit currents will change since a black start procedure will involve a step by step reconnection of sources.

A typical sequence of events for Micro Grid aided restoration may be as follows (Strbac et al. 2015):

1. The MGCC evaluates the network status both upstream and downstream. The upstream network status check confirms that there is no other alternative to reconnect to the grid except by initiating a restoration procedure. It is also important to check the downstream network for local faults.
2. The MGCC sends control signals to local controllers to isolate loads and microsources from the LV network. This prepares the Micro Grid to start the restoration procedure.
3. Connection of the central Micro Grid storage unit at the MV/LV substation on the LV side. Since the generation and loads are disconnected, the Micro Grid will be operating at nominal voltage.
4. The MGCC synchronises each controllable microsource with the Micro Grid.
5. Connection of loads and non-controllable microsources while ensuring that there are no large voltage or frequency deviations.
6. Micro Grid synchronises with main grid after confirmation from the distribution network operator.

Micro Grid aided restoration is one of the many benefits that micro grids can provide at a transmission level. Wang et al. (2015) suggests that it is challenging to maintain the voltage and frequency profile of a Micro Grid while controlling the operation of distributed generators using remotely controlled switches. If the outage is due to a natural disaster it is likely that the control switches may be partly damaged and operation under these scenarios must be considered.

6 Standards and Policy Relevant to Micro Grids and Distributed Generation

6.1 UK Grid Code

All distribution network operators (DNOs) which are licensed electricity distribution businesses are required to maintain a distribution code (Distribution Network Operators of Great Britain 2014) detailing the technical parameters and considerations relating to use of their electrical networks in any way.

Under the distribution code there are four different categories of distributed generation connection guides.

1. Generators under EREC G59 but less than 17 kW single phase or 50 kW three phase—The connection procedures of these generators are significantly simpler and hence a separate guide is available for them.
2. EREC G83 single premises—EREC G83 covers generators that have a capacity of less than 16A per phase and typically connected to the low voltage network at 230 V single phase or 400 V three phase. This guide is specifically for projects where the distributed generators are located on a single property.
3. EREC G83 multiple premises—This guide is for those projects that otherwise meet EREC G83 but cover distributed generators that are not on a single property. Typically these DG units are located within a close geographical region which can be assumed to be within 500 m as a rule of thumb.
4. Generators that fall under Energy Recommendations (EREC) G59—This includes projects with a capacity of more than 16 A per phase and connected to a voltage higher than 230 V (single phase) or 400 V (three phase). It also covers any projects not being within the scope of EREC G83.

Medium and large power stations are also covered by EREC G591. In England and Wales, power stations under 50 MW are classified as small, and those above 100 MW are classified as large. Power stations between 50 and 100 MW are classified as medium power stations. In Scottish Power Transmission in southern Scotland, any generators less than 30 MW are classified as small generators and greater than this limit is classified as large generators. In Northern Scotland which is under Scottish Hydro Electric Transmission, there is a similar system in place but the threshold is at 10 MW.

Currently all generators between greater than 100 MW require a generation license while those between 50–100 MW may be granted exemption by the Secretary of State for Energy and Climate Change. Conditions in the generation license include compliance with the Distribution Code and relevant parts of the Grid code. It also involves compliance with the Balancing and Settlement Code (BSC) and becoming party to the BSC Framework Agreement.

Additionally, large generators will need to enter into an agreement with the National Grid Electricity Transmission (NGET). This agreement could be in the form of a Bilateral Embedded Generation Agreement (BEGA) which allows the generator

to export to the transport network and participate in the energy balancing market. Developers of smaller power stations also have the option of entering into a BEGA if they wish to trade on the wholesale electricity market. Another type of agreement applicable to Scottish large power stations below 100 MW is the Bilateral Embedded Licence Exemptible Large Power Station Agreement (BELLA). These power stations do not need to hold a generation license as they are under 100 MW and can choose to enter into a BEGA or a BELLA. A BELLA allows power to be exported into the transmission network but not participation in energy balancing.

All distributed generators are subject to connection charge as well as ongoing costs. Connection charge is a one off charge levied by the DNO to cover cost of the new connection including new infrastructure, reinforcement, budget and feasibility studies and administrative costs. Ongoing costs include generation distribution use of system charge, metering charge and a transmission network use of charge where applicable.

Currently, for distributed generators up to 5 MW there are feed in tariff structures for electricity exported to the grid. There are three sources of benefits from feed in tariffs

- Generation tariff which is a fixed price per unit of electricity generated to the grid.
- Export tariff is a guaranteed price for each unit of electricity exported to the grid.
- Import reduction which reduces the supplier's electricity bill by using generated electricity.

In addition renewable generators above 50 kW that are not eligible to receive feed in tariffs due to type of technology, will be eligible for renewable obligations. Generators between 50 kW and 5 MW may be eligible for both ROs and FITs and may have a one off choice between the two schemes. The RO scheme works by issuing generators with Renewable Obligation Certificates (ROCs).

6.2 IEEE 1547

IEEE 1547 series of standards (Basso 2014) cover distributed energy resource interconnection and interoperability with the Electrical Power System. In this field it has been a foundational document and has shaped the ways in which the energy industry does business. Since Micro Grids are based around distributed energy resources and their intelligent coordination and integration with the grid, IEEE 1547 is applicable to Micro Grid operation and control. As a technical standard it has provided local, state and federal policy makers with a technical basis for promoting transparency, openness and fairness with regards to interconnection of distributed energy resources.

The IEEE standard 1547 (2003) was the first in the series and was approved in October 2003. It covered distributed generation and energy storage systems focussing specifically on the technical specifications and testing requirements. The IEEE standard 1547 (2003) was prepared as a single holistic, mandatory set of universal requirements.

In subsequent years separate additions were made to the original standard to account for new development in technologies. In the original standard, intentional islanding and Micro Grids were not covered. In fact the standard included requirements to ensure that distributed generators did not unintentionally provide power to adjacent generators or to the utility grid in the case of loss of the grid power. The IEEE Standard 1547.4 approved in 2011 covered approaches for design and good practices with regard to the operation of Micro Grids and islanded systems connected to the grid. It also addresses the capability to form islands when the utility grid is not available to supply power to a part of the grid.

Developments in technologies through research have surpassed requirements in standards. As a result, a full revision of IEEE 1547 including scope and title is currently underway and must be completed by 2018 as per IEEE mandate. The full revision will address distribution level connected DER and some areas relevant to Micro Grid operation and control such as:

- Generation, storage and advanced functionalities of DERs.
- Supplying adequate inertia to the grid with DER
- Micro Grids
- Intermittency due to very high penetration of renewable generation
- Demand response and load effects including storage as load.

The impact of the fully revised IEEE 1547 will be to enable high penetration of DER and clustered Micro Grids and reduce interconnection costs amongst other benefits.

7   Selected Micro Grid Research and Case Studies

7.1   EU Micro Grid Research Projects

At the international level, the European Union has two main projects which are titled Micro Grids project and More Micro Grids project. While the former investigates the operation of a single Micro Grid, the latter aims to increase the penetration of microgeneration through the use of Micro Grids including the study of multi Micro Grid systems.

7.2   Kythnos Island Micro Grid, Greece

The Kythnos island project is a pilot project for the EU Micro Grids project. Kythnos island is a village scale autonomous Micro Grid consisting of a low voltage network. The main source consists of two 10 kW PV arrays and a 5 kW backup diesel generator. There is also a 53 kWh battery bank for storage. Three inverters connected in parallel master—slave configuration are used to interface to the load which consists of 12 residences. The battery inverter can operate in frequency droop control mode. Majority of the load on this Micro Grid is lighting and water pumping.

7.3   Netherlands

Netherlands' first Micro Grid was built in Bronsbergen Holiday Park in Zutphen (100 km out of Amsterdam). This was part of the EU More Micro Grids project. This location consists of 208 holiday homes for a total peak load of 150 kW. 108 of the holiday homes have been fitted with PV arrays and the total generation capacity is 315 kW. There are also two battery banks to store and resupply energy when PV is not available. During the day, most of the PV power is exported to the MV (Medium Voltage) grid and at night the holiday park requires grid support.

Each of the homes is connected through 4 parallel LV (Low Voltage) feeders. Each feeder has measuring devices for active and reactive power. These measuring appliances are linked to a master controller which monitors the real and reactive power exchanged with the grid. The master controller uses GSM communication to interact with a computer. A 400 kVA transformer is used to connect to the 10 kV MV network via a 630 A fuse. The battery banks are located on the load side of the 630 A fuse.

7.4   CERTS Micro Grid, USA

The consortium for Electric Reliability Technology Solution (CERTS) was established in 1999 with the aim of investigating the impact of modern grid technologies. The emergence of distributed generation was a key focus of CERTS. The CERTS Micro Grid as a concept was developed in 2002. Laboratory scale testing of the viability of the CERTS Micro Grid was undertaken at the University of Wisconsin, Madison. A full scale test system is installed at the Dolan Technology Centre in Columbus, Ohio.

The CERTS Micro Grid is designed to operate while connected to the grid as well as autonomously. It consists of generators such as microturbines and PV panels which are connected through power electronic interfaces. The Micro Grid

also consists of controllable loads and storage in the form of fuel cells. It connects to the grid through a single point of coupling and appears as a single entity to the upstream network. The CERTS Micro Grid does not export power even though in principle it possesses the capability to do so.

Generators are controlled locally by on board power electronics. The controllers monitor frequency and voltage and utilise droop characteristics for control. The generator controllers are capable of operating in grid connected and islanded mode.

The devices use slow supervisory control which enables them to respond to economic dispatch and unit commitment under constraints. This is ensured by an energy manager at the point of common coupling which can be realised by adding onto an existing infrastructure, e.g. building management software.

Generators are physically placed in locations that allow them to take advantage of CHP (Combined Heat and Power) opportunities. For example thermal generators are placed near heat loads. The effective use of CHP can influence Micro Grid economics.

The CERTS Micro Grid is also designed to provide heterogeneous power quality and reliability (PQR). The loads are divided into sensitive loads, controllable/adjustable loads and sheddable loads which are placed on three separate circuits. If the power balance cannot be maintained, then the circuit with sheddable loads is switched off followed by the circuit with controllable loads. The circuit with the sensitive loads is capable of isolating itself and maintaining supply. This ensures that there are three distinct levels of reliability available.

7.5   GE Global Research Micro Grid, USA

The US Department of Energy (DOE) co funds GE global research Micro Grid efforts. The aim of this program is to develop Micro Grid energy management frameworks. As a product, this offers controllers at the device level as well as at a supervisory level. At the device level, GE will provide controllers for generators and loads for low inertia environments. At a supervisory level GE will provide a framework to coordinate and optimise various Micro Grid resources to achieve objectives such as Micro Grid dispatchability, renewable integration, and minimising the operation cost.

Recently GE and the DOE along with National Grid US and the National Renewable Energy Laboratory (NREL) have undertaken a Micro Grid project aimed at improving the resilience of electrical networks in northern New York. A key feature of this project is the development of the enhanced Micro Grid control system (eMCS) which is designed to operate the Micro Grid in the islanded mode.

Projects such as the GE Micro Grid developed control systems complement other Micro Grid projects such as the CERTS Micro Grid.

8 Future Pathways in Micro Grids

Micro Grids are currently a wide and dynamic area for research. The power industry has identified Micro Grids as being one of the few technologies that could potentially address all the challenges and demands of the modern electricity grid. Additionally, the EU has set aggressive renewable energy targets for the next few decades which will require investment in the electricity grid. In line with the European Commission's target areas, the top priorities of the DECC are stated in the Energy Security Strategy (Great Britain. Department of Energy and Climate Change 2012). The challenges and response is based around ensuring the sustainability and resilience under climate change, energy efficiency, enhancing interconnection capacity, and decarbonisation of energy supply. A key element of the DECC response is to guarantee the security of global electricity markets to ensure that when the UK requires foreign energy supply, it is reliable and affordable.

Currently commercial Micro Grids are largely used to power isolated areas as Micro Grid technologies are not cost effective in densely populated areas. The biggest challenge for Micro Grids is operating them in the islanded mode and the grid connected mode and the transition between the two modes with the minimum disruption to customers. Based on the current trends in Micro Grid technology combined with the aggressive political support for energy efficiency measures, it is reasonable to expect that Micro Grid technologies will improve in pace and volume and become widespread in the near future.

The cost of storage and other balancing technologies are likely to decrease and mature. These technologies will then become more widely available. For example, the Tesla Powerwall is providing a low cost storage solution at the customer level. The availability of low cost storage will provide the balance required to account for variations in Micro Grid operating conditions. Similarly, the use of demand response is likely to increase. Currently, a number of newer air conditioner models available with demand response capability. Smart devices are also available that respond to variations in grid frequency. As these devices are made available in the market and customers start realising their value, their impact on the grid will be more evident in the future. Efficient control and coordination of balancing technologies are expected to play an increasingly important role beyond 2020 and even further beyond 2030.

The growth of smart grid technologies will allow for a higher level of sophistication in control and operation of Micro Grids. Micro Grids with a large percentage of smart devices and storage will be flexible and can be adjusted as necessary to maintain the grid frequency and energy balance. As the cost of Micro Grid components decrease, they will become economically competitive with the electricity delivered by the traditional grid. It is likely that Micro Grids will be used in areas not only with weak grid effects but also areas where the grid is available.

The availability of well-defined Micro Grid standards and favourable policies will provide a uniform framework for device manufacturers and the grid operators

with regards to Micro Grid planning and operation. The availability of the revised IEEE 1547 is expected to address a number of current issues in Micro Grid standards. Similarly, utilities and grid operators in various geographical regions also expected to develop and refine Micro Grid standards suits for their businesses. On the other hand, there is also a critical need of standards that are applied to other business areas including the smart manufacturing and heavy engineering industries.

The development of new technologies and standards will lead researchers to address some of the current challenges in Micro Grids. The focus will then likely shift on to the transmission level impacts of Micro Grids. Currently, there is limited knowledge regarding the integration of Micro Grids and the existing grid. If the future grid is to be composed of clustered Micro Grids, it is likely that there will be a transition period when the existing grid is operating in parallel with a number of Micro Grids. A number of key issues should be addressed to facilitate this transition period and they are (Hertem et al. 2010):

- The definition of a technical framework required in order to transform the power distribution network level micro grids to better serve the power transmission system operation
- Identifying the interaction challenges between micro grids that are designed to operate independently or in grid connect mode with the transmission grid. Hence determining what tools should be developed in order limit the negative impacts of interactions in order to enhance the reliability of power supply and network resilience.
- Developing key technical and economical advances in order to accommodate challenging and complex operating conditions in a micro grid based system.
- Determining the impacts of system level operation of super micro grids and strategies for mitigating these in order to minimise the effects of large system disturbances through strategic restoration schemes.
- Defining the role of the macro grid under large scale penetration of clustered micro grids and identifying the critical services it will provide.
- Determining the most effective topology for the macro grid, whether AC, or HVDC or hybrid.

Grids composed entirely of clustered Micro Grids are within the realms of possibility in the near future. In these mega grids (or super grids) there would be no limitations on interregional trade due to political boundaries thus resulting in a fully integrated market. One of the visions of the European super grid is to form a system based on interconnected micro grids with a high voltage direct current (HVDC) backbone (Bompard et al. 2014; Strbac et al. 2015). The existence of smart communication and control in micro grids is a key to achieving the dynamic performance, cost effectiveness and resilience that is required in modern electricity grids. An EU wide integrated electricity grid can exploit the spatial dispersion of renewable resource.

A number of challenges to the super grid have been identified which includes technical challenges such as grid standards, ratings and interoperability as well as control and operation challenges which includes interaction between systems,

islanding and security of supply. Micro Grids with intelligent control are capable of addressing some of these challenges. None of these challenges are identified as being fundamental challenges and they will eventually be addressed by technological advances in the future (Hertem et al. 2010).

Thus, given the current situation, it is expected that Micro Grids will continue to play a significant role in the energy industry. Key factors such as costs, development of standards and policies are starting to shift in favour of these technologies. Micro Grids will potentially be the main vehicle to ensure that the electricity grid of the future are flexible, dynamic, secure and resilient and provides electricity that is reliably and affordable to customers.

9 Conclusions

With the traditional power grid journey towards a smart grid and meeting its prime objectives, it is vital to plan and operate Micro Grids with increased functionalities, flexibility, and resilience. The chapter identifies several key challenges that can be seen in smart Micro Grids. There is a small number of Micro Grid projects currently operate around the world. This number is expected to grow with the complex challenges arising from the smart operation of future power grids. It will also be vital to look at future Micro Grid operation through super Micro Grids in order to mitigate impacts from highly complex operating conditions and component outage interactions in a smart gird environment and to control and coordinate the Micro Grids with their population growth.

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A Preliminary Study on Conversion Efficiency Improvement of a Multi-junction PV Cell with MPPT

Narottam Das, Hendy Wongsodihardjo and Syed Islam

Abstract This chapter presents a preliminary study conducted to improve photo-voltaic (PV) cell conversion efficiency using MATLAB/Simulink platform. The study uses multi-junction solar cell and investigates the maximum performance compared with a conventional silicon PV cell. Maximum Power Point Tracker (MPPT) is applied to assess the conversion efficiency of the PV system. Study integrates thermoelectric generator (TEG) with PV modules because the PV cells work by converting high frequency irradiation where as a TEG has the ability to convert wasted low frequency heat to the electricity. The combination delivers more power and contributes to enhance the conversion efficiency of a PV system. The simulation results show that a tandem cell can provide a considerable higher power with a conventional PV cell operation.

Keywords MATLAB/simulink · Maximum power point tracker · Multi-junction solar cell · Photovoltaic cell · PV cell working temperature · Thermoelectric generator

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1   Introduction

World Bank statistics reported that the global population reached almost seven billion by the end of 2011 (World-Bank 2012) and is set to reach eleven billion by the end of century. The population growth significantly influences the energy consumption on a daily basis. International Energy Agency (IEA) reported that the energy consumption in 2010 reached 535 eJ (1 eJ = 10^{18} J) (IEA 2010) and this number is expected increase considerably over the time. However, more than 80 % of the energy is still extracted from the limited resources such as coal, oil, and natural gases. If this process continues, extinction or even disappearance of some the energy resources may be inevitable in the near future. In order to mitigate long term impacts of dependability on the fossil fueled power generation, renewable power generation should be incorporated in order to share some of the loads which were traditional supplied by the conventional power generation.

Photovoltaic (PV) system is a set of PV arrays that convert the sun light as a renewable energy source into DC voltage. This system is then connected to an inverter(s) in order to convert the generated DC electricity into AC electricity and then to supply households demands. With the demand share by the solar PV array systems, use of fossil fuel for the power generation can be reduced.

Nevertheless, the performances of solar cells are still far from satisfaction. Despite its high initial cost, electrical power generation from them is highly depended on the surrounding circumstances. The most common drawback of generating electricity from PVs is the cloudy day effect in which the PV cells produce less power as compared to a sunny day when the sun is shining at very bright. The installation locations of PV modules are also important as four seasons have varying temperature levels. It can be lower than 0 °C during the winter and can be higher than 45 °C during the summer time depending on the geographical location. It is comparable with the tropical countries with the average temperature of 30 °C throughout a year. The varying seasons may decrease the PV cell performance because it cannot reach out peaks even with the MPPTs.

Nowadays, silicon is one of the most popular semiconductor used in industry because of its wide range of availability, makes it economical to construct and produce the devices. However, the efficiency of a silicon solar cell is considerably low (González-Longatt 2005). The assembly process of the module itself can also affect the performance of PV cells. Manufacturer defects may also create losses through the cell junctions and may earth the connection leading to a loss of power.

This chapter presents a preliminary study conducted to improve PV cell conversion efficiency using MATLAB/Simulink software platform. Due to the limitation of resources and manufacturing facility, the improvisation techniques were based on the most popular demand with simulations. It is also to be noted that all the models given in this chapter are based on the reference value in accordance with standard test conditions (STCs), 1000 W/m^2, 25 °C. Besides, all prototypes are presented in single cell or individual parts only.

This chapter is organized as follows: theory and modeling of multi-junction PV cell using MATLAB/Simulink is in Sect. 2, modeling of hybrid PV cell and thermoelectric generator is in Sect. 3, and installation of MPPT onto the PV cell is in Sect. 4. Finally, the conclusion is presented in Sect. 5.

2 Modeling of Multi-junction PV Cell Using MATLAB/Simulink

2.1 *Historical of MJSC*

Concentrated PV (CPV) cell which was based on the multi-junction solar cell (MJSC) became a breakthrough for solar electric power generation. Currently, most of the MJSC is made of III–V semiconductor materials for terrestrial concentrator applications due to its high conversion efficiency. Tandem solar cell is introduced by the Research Triangle Institute and Varian Research Center in the late 1970s to mid of 1980s. They presented dual-junction devices that are formed by the aluminum gallium arsenate (AlGaAs) junction, interconnected on top of a gallium arsenate (GaAs) junction by a semiconductor tunnel junction (Virshup et al. 1988). Bright future of stacked concentrator solar cell led scientists to continue their research in this area further. Later in 1990s, changes in the top cell thickness and addition of new layer led to a greater conversion efficiency that had never been matched before. A 3-junction solar cell was demonstrated by the combination of gallium indium phosphide (GaInP) with GaAs both on the top of active germanium (Ge) substrate (Yamaguchi et al. 2005).

In 2012, Sharp Corporation's product that was claimed by the Fraunhofer Institute for Solar Energy (Germany based organization) became the most effective concentrator solar cell in the world and it was suggested to have an approximately 43.5 % efficiency from a triple junction compound solar cell. Sharp stated that the CPV cell utilizes the photo-absorption layers made from the compounds consisting of two or more elements, such as indium and gallium. A basic structure of this latest triple junction cell uses proprietary technology that enables efficient stacking method overheads on indium gallium arsenide (InGaAs) (Shahan 2012).

In September 2013, Fraunhofer announced a new breakthrough of CPV cell with an approximately 44.7 % efficiency and findings was later collaborated with Soitec, CEA-Leti and the Helmholtz Center in Berlin (ScienceDaily 2012). They presented that four-junction solar cell is improved in terms of material composition, optimization of the structure and introduction of a new procedure called wafer bonding. This latest connector method had the ability to connect two semiconductor crystals with a very high quality (Mohr et al. 2011).

Due to the concerns of climate change effects and depletion of fossil fuels, increased interest to produce renewable power generation was using MJSC. However, for the past 40–50 years, there was no significant improvement was

reported from first it was introduced. The new model of combined cell that produces very high conversion efficiency significantly reduces cost of a CPV system and makes III–V MJSC as the leading technology in a today's concentrator system (Cotal et al. 2008).

2.2 Basic Criterion for Modeling MJSC

The MJSC is constructed by stacking two or more *p–n* junction semiconductors with different characteristics. It is expected that the MJSC can generate higher PV power compared to the existing or conventional PV power generation. The good candidates to construct the stacks of semiconductors are by gathering the alloys from group III–V of the periodic table. Despite on its high expectation, the MJSC has a few limitations with the aim of choosing materials to generate a high efficiency PV system. To develop the layer of semiconductors to be combined, there are some essential requirements to follow. These are described in the following sections.

2.2.1 Lattice Matching

The first consideration is the material selection to be lattice-matched. In order to produce the maximum conductivity of current between the layers, each layer needs to have a similar crystal or lattice structure. Lattice constant is a parameter that is used to check whether each material is matched to each other or not. This constant value measures the spacing of atom on the crystal structure.

Mismatch on the lattice constant will create dislocations in the lattice which results loss of photo-generated minority carriers. Chain reaction of this dislocation is the decrement in the open circuit voltage (V_{OC}), short circuit current density (J_{SC}), maximum power delivered (MPD), and the fill factor (*FF*). Many researchers put this factor as a secondary concern, but the US National Renewable Energy Laboratory (NREL) researchers reported that even ±0.01 % mismatch on the lattice matching can cause a significant degradation of the PV quality or conversion efficiency (Tobías and Luque 2002; Landis et al. 2011).

2.2.2 Bandgap Energy Matching

Another important aspect on stacking is that each junction has to have a diversity of the bandgap level on each sub-cell (Takamoto 2009). This is because; the sun rays consist of a different spectrum while each of the semiconductor material can absorb only a certain type of wavelengths depending on its substance or materials used.

Therefore, having a wide range of bandgap increases the possibility of absorbing a highest level of spectrum.

The coordination of each layer is put in stack. The first layer absorbs the highest photon energy from the sun. The sub-bandgap light is transmitted to the lower sub-cell and processed further until reaching the last or bottom layer of the cell. However, if the bandgap range is too far, the amount of unabsorbed light will turn into heat and exhaust to the air which cause loses through the crystal junction. In order to reduce loses; the bandgap of the closest junctions is to be tight as possible.

2.2.3   Current Matching

Each sub-cell is connected in series which means it requires same or at least the minimum difference on current characteristics (Bertness et al. 1994). While this condition does not fulfill, the total current read may be decreased by the nature of the series circuit connections. The current generation will be limited to the lowest current produced by an individual layer.

The current of each junction depends on the number of photons that passes through the material's absorption capacity (Yastrebova 2007). When the absorption coefficient is very high, the photon can easily pass through and the material thickness can be decreased. On the other hand, the layer with low absorption capacity is better to be thickening in order to provide some space for the photon passes through during the sunlight captivation.

2.3   Various Combination of MJSC

The process of developing the MJSC also carries limitations or approximations. Each layer must produce a similar amount of current to maintain the performance as they are connected in series. The thickness justification of each material is important in order to ensure that all of them are matched to produce an optimum current. The wavelength absorption capacity is to be in a wider range to convert the light as much as possible for a better performance (Azab 2009). The crystal structure of each stack is required to be matched.

Figure 1 shows a simple equivalent circuit model of a MJSC, which is a series connection between one type of cell and the other cell materials. They can be connectable in any desired number of cells. However, the awareness comes from the connection method, where the defected layer or poor construction may increase the resistance between the layers. The power loses can also affect the generated current which creates an unmatched current flow between the cells and later it contributes for the reduction of the cell conversion efficiency.

Fig. 1 A basic equivalent circuit diagram of a tandem solar cell
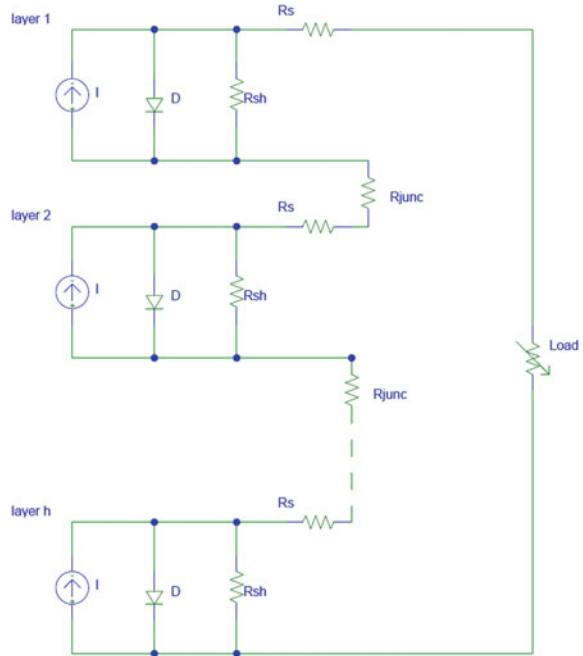
2.3.1 Double-Junction Solar Cell

The most common dual junction tandem cell is the combination of InGaP (Indium Gallium Phosphide) and GaAs (Gallium Arsenate) cells originating from the III–V group alloy. Their bandgap energy coefficient does not vary significantly however it is wide enough to receive more energy intake, which is 1.86 eV (InGaP) and 1.42 eV (GaAs) respectively. The InGaP is almost lattice matched with the GaAs which makes them first option to form the tandem cell (Or and Appelbaum 2013; Bhattacharya and Foo 2010). Currently, both of them are frequently being used in space applications either in tandem form or separately.

The practices on developing the stacked junctions do not always stick to the III–V group, but also merging different kinds of material where ever possible. For example, solar cell from thin film family can be utilized as they are able to create more energy. In this study, copper indium gallium selenide (CIGS) is selected and it would be united with other cells. The CIGS has approximately 1.7 bandgap coefficients and formed by small crystal materials or polycrystalline material. There are numerous advantages of using this thin film. Its absorption coefficient is relatively high and its thickness can be reduced. Besides that, the current density of the CIGS solar cell is also useful for producing higher amount of output current.

In this tandem cell, the CIGS is connected with GaAs which is one of the best options for solar cell performance. Despite using the crystalline cell, GaAs is compressed to form a thin film which is similar to the CIGS. This option is taken not a prioritizing in efficiency increment, but to create a harmonious combination with the CIGS, especially for junction connections (Green et al. 2009). From this approach, it is possible to make a wider range yet thinner MJSC (Solarex-Inc. 2007).

Furthermore, another option can also be designed for lattice matched ZnSe (zinc selenide) and AlAs (aluminium arsenide). The ZnSe is a semiconductor material which rarely occurs in nature as its toxic contents might be hazardous. ZnSe has a very high bandgap of around 2.7 eV. Therefore, connecting aluminium arsenide (AlAs) with 2.12 eV creates a wide range of absorption chances. This arrangement is done with the cross section of II–V material in which ZnSe is created by the combination of II–IV intrinsic semiconductor, while AlAs is almost identical with GaAs from II–V alloy periodic table.

2.3.2 Triple-Junction Solar Cell

This part of the study experienced a greater challenge due to adding more materials on the sandwich stack. Based on data of lattice constant for III–V semiconductor material, it was observed that AlAs, GaAs, and Ge were matched on its lattice constant. Therefore, the materials are being able to grow with a lesser strain. Their bandgap variation is also quite wider to perform a great absorption. Therefore, they can be used on the process for making the MJSC.

However, the researchers reported in the literature that the bandgap variation does not show as a satisfactory choice. An ideal triple junction should be able to produce energy effectively with the combination of 1.89, 1.28 and 0.84 eV materials (Tobías and Luque 2002; King et al. 2007). AlAs with 2.12 eV properties are considered as it has a very high bandgap energy and can be substituted by InGaP. Thus, a three junctions solar cell is designed by stacking InGaP, GaAs, and Ge together with statistic as 1.86, 1.42, 0.67 eV (Spectrolab 2008; Warmann et al. 2011). This is similar to the first double cell experiment but with an addition of germanium. Option of choosing the Ge as third layer is not just by it is lattice and bandgap matched with the other two, but also its characteristic is to be similar with the silicon. Purified germanium can appear close to the elemental silicon (Aiken 2000).

2.4   Simulation Results of Combined MJSC

In order to create a basic model for the PV cell in MATLAB/Simulink, mathematical formulation of current and voltage relationship is necessary. The generated voltage for each cell can be given as in (1).

$$V = V_{sh} + IR_s \tag{1}$$

where, V_{sh} is the voltage that dropped by the shunt resistance, I is the load current, and R_s is the series resistance.

Furthermore, the current flows to the grid can be calculated using (2) (Hernanz et al. 2010; Nianchun et al. 2011).

$$I = \left[I_{SC} + K_i \left(T_C - T_{ref} \right) \right] \frac{G}{G_{ref}} - I_S \left(e^{\frac{V_D}{NV_T}} - 1 \right) - \frac{V_{sh}}{R_{sh}} \tag{2}$$

where, I_{SC} is the short circuit current at ambient temperature (T_{ref}) and reference irradiation (G_{ref}). The cell working temperature and irradiation is symbolized as T_c and G, respectively. K_i is the cell's short circuit current temperature coefficient which is set at 0.065 ± 0.015 %/°C. I_s is the diode saturation current, V_D and V_T respectively represent voltage across diode and the thermal voltage that can be held with a factor of diode ideality (N) which set as 1.0.

The diode saturation current is formulated as in (3) (Shockley and Queisser 1961; Solarex 1997).

$$I_S = I_{RS} \left(\frac{T_C}{T_{ref}} \right)^3 e^{\frac{E_g}{NV_T} \left(\frac{T_C}{T_{ref}} - 1 \right)} \tag{3}$$

where, I_{RS} characterizes diode reverse saturation current. Semiconductor bandgap energy is shown as E_g.

Based on formulations in (1) to (3), the simulation model of a MJSC is created on MATLAB/Simulink platform. Figure 2 shows the sub-layer of a tandem cell which can join with other sub-cells.

The MJSC is able to generate more energy than the conventional PV cell. Figure 3 shows the performance of each stacked cell at the PV power generation.

For the construction of a MJSC, wafer type semiconductor combinations are adapted (Keener et al. 1997). For a comparison, two single junction cells are considered in this study. The performance of a single cell is shown in Fig. 3a. They are Si and GaAs which used broadly for PV cell manufacturing. Si is chosen as its broad availability in nature and cost effectiveness. Nevertheless, based on the experimental results, it produced a lower capacity than GaAs which is also costly.
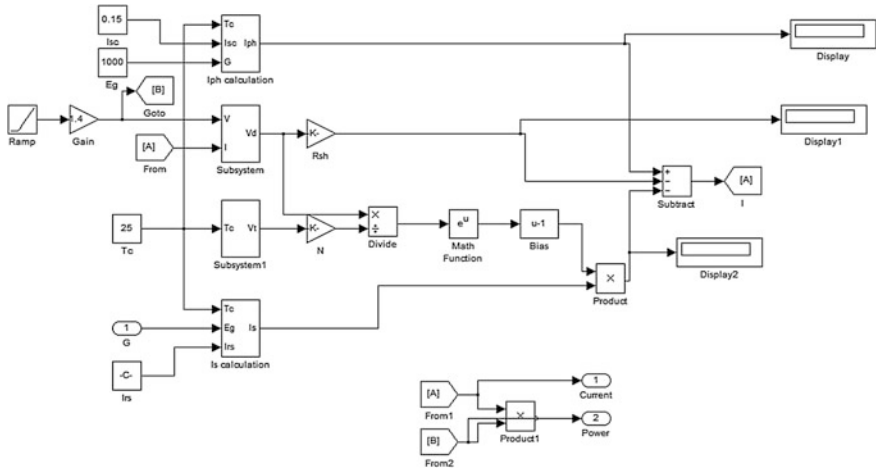
**Fig. 2** MATLAB/Simulink model of a sub-cell in MJSC

Therefore, the latter type is mainly used on solar space which needs a greater energy but it is supported by high capital investment. The GaAs cell has recorded 20 % more effectiveness than the Si cells.

In addition, three types of double junction solar cells are also examined. The performance of a double junction cell is shown in Fig. 3b. InGaP and GaAs are lattice matched well and therefore they can generate more power as per the need. A better result is provided by the new design on thin film coupled a cell, in which it is formed by GaAs and CIGS. They are able to increase the maximum power by 36 % because they are wider enough to absorb more energy without increasing their thickness. Another factor contributing to the feature is that the GaAs is a thin film and had a little better performance.

The combination from II–IV and III–V classes has not provided significant performance. However, ZnSe and AlAs have a larger bandgap, but it is not useful to create a well performed hybrid structure. They are even a bit behind the InGaP/GaAs conversion efficiency. They have deficiencies in their operation because of their bandgap level is far and they do not absorb enough energy but release excessive energy. Besides that, it is difficult to match their current as they are from different material classes.

For the triple junction combination, the first design of AlAs, GaAs, and Ge provided a satisfactory result. The performance of a triple junction cell is shown Fig. 3c. However, when AlAs is changed with InGaP, the whole statistic is increased even though they were not significant. This means that the difference from the first design has a wider range but not closer to each other, which cause more loses.

Fig. 3 Comparison of PV
characteristics with different
junctions **a** single junction,
b double junction, and **c** triple
junction cell
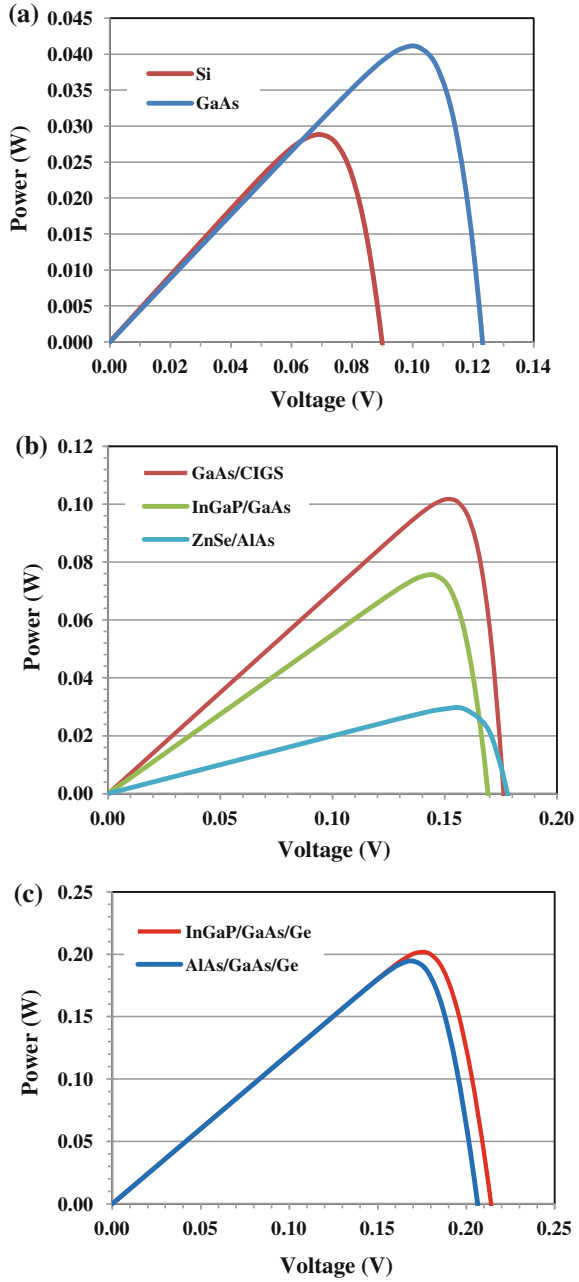
3 Modeling of Hybrid PV Cell and Thermoelectric Generator

Thermoelectric generator (TEG) is simply a solid-state electronic device which has the ability to convert heat alterations into the electricity using the thermoelectric transformation material (Thermoelectric 2011). Basically, it is made with a *p-n* junction material and produced electricity due to the heat differences between the materials, in which the heat flows from hot side to cool side. This thermoelectric behavior first introduced by Thomas J. Seebeck in 1821 (Phillip et al. 2012), which led to call the converter also as 'Seebeck generator'.

The TEG is one of the most environment friendly energy generators since it has no moving parts which make it remains silent during the operation, no emission, has compact size and uses zero fuel consumption. Therefore, it copes well with a PV module. Because of its compactness, Seebeck generator can only produce smaller electricity for 'niche appliances'. However, the TEG device is scalable which make it is possible to be mass produced, modified, and combined with a PV module.

3.1 Thermoelectric Generator (TEG) System Integration

Thermoelectric power is generated by Seebeck to maximize the temperature difference (ΔT) between *p*-type and *n*-type pellet junction and then interconnected by two different metals to form a closed loop. Basically, the gap between *p*- and *n*-type of semiconductors is connected electrically in series and thermally in parallel (i.e., like a sandwich). This device utilizes the heat transfer well and the heat flows from higher to the lower temperature. Consequently, the free charge carriers of material are electrons (*n-type*) and holes (*p-type*), tend to flow from heat absorber material to the cold end (Chen et al. 2009). These movements harvest voltage (V) via Seebeck coefficient (α) in which it is expected to work between 100 and 300 µV/K (Snyder 2008). It is given by (4).

$$V = \alpha \Delta T \tag{4}$$

Seebeck coefficient depends on the electrical resistivity (ρ) and thermal conductivity of materials (κ). The 'figure of merit' can be given by (5).

$$zT = \frac{\alpha^2 T}{\rho \kappa} \tag{5}$$

where, zT is known as the 'figure of merit' which is used as the standard of combining thermoelectric properties to evaluate its performance (Han et al. 2010).

In order to find the current generated by the TEG, ohms' law is applied. Therefore, the current produced is given by in (6).

$$I = \frac{\alpha \Delta T}{2R_m} \tag{6}$$

where, R_m is the matched resistance provided by the manufacturer. In this case, 24CX1 TEG from the *Custom Thermoelectric* is chosen for its high functionality.

For the simplicity of design, the TEG model 'Seebeck coefficient' can be expressed as in (7) (Tsai and Lin 2010).

$$\alpha = \frac{2V_m}{\Delta T} \tag{7}$$

where, the matched voltage (V_m) is different from each TEG to another. To stick with the design constant, V_m of *24CX1* product is being used. The voltage V_m is dependent on the temperature difference ($\Delta T = T_h - T_c$). Here, T_h is the hot-side temperature and T_c is the cold side temperature which is constant at 25 °C (Ortiz-Rivera et al. 2010). The expression of matched voltage V_m is given by (8).

$$V_m = 0.0148 \times T_h \tag{8}$$

3.2 Hybrid PV Cell-Thermoelectric Generator

Both the solar cell and Seebeck generators were introduced in the market for a long time. However, the combination is still to be developed to have a high PV conversion efficiency.

Theoretically, sunlight hits directly on top of the solar cells or panels and they convert the absorbed light energy into electrical energy, but depending on the PV cell material, not all the input energy from sun is converted into the electrical energy. The rest of the lights whose frequency is greater than cell's absorption coefficient are reflected back to the open air. This property is known as excess heat or loss of energy. Seebeck generator has the ability to produce power using this excessive energy when the other side of the TEG is at a lower temperature (Bobean and Pavel 2013).

Seebeck generators do not cope well with the solar panel and a new design is required to pair them together for a higher conversion efficiency PV system. The proposed design was made by keeping both the TEG and solar cell efficiency as possible and without distracting the effectiveness of the PV systems.

Figure 4 shows the design of a new hybrid PVT system. This modified design does not connect the solar cell and TEG in series, but connect them together in
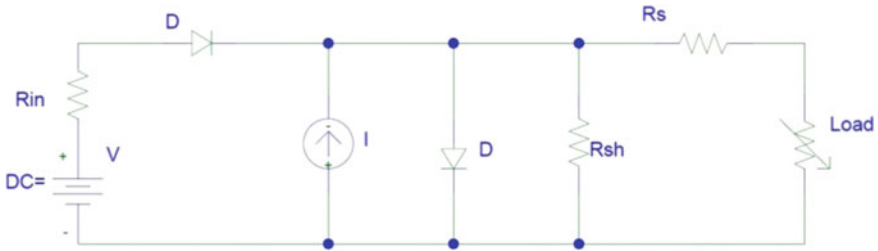
Fig. 4 Circuit diagram of a new hybrid PVT system design with the combination of TEG and PV cell for a higher PV conversion efficiency

parallel conjunction with a reverse blocking diode. Essentially, Seebeck generator is simplified as a voltage source with the internal resistance R_{in}. Therefore, it is presented as a set of DC voltage source in series with a small value resistance.

A blocking diode is connected together with them to prevent the over charged current flow from the solar generator because of small power produced by the Seebeck generator. If this is connected directly to other power generator with higher efficiency, a higher current will flow into the Seebeck device and it limit acting as source, instead of it behave as a charger. This is not a favorable condition because of the risk of damage pose on the Seebeck device. With an addition of extra diode, the TEG performance can be reduced and it may also have similar characteristics with the solar cell.

Figure 5 shows the proposed design of Seebeck generators which are attached with a PV module for the use of heat extraction.

The sun radiation is absorbed by the PV cell. At the illumination, a part of heat of solar cells is passed through and flowed directly onto the hot side of Seebeck generator. In order to keep the cold side in a lower temperature, a contact with the
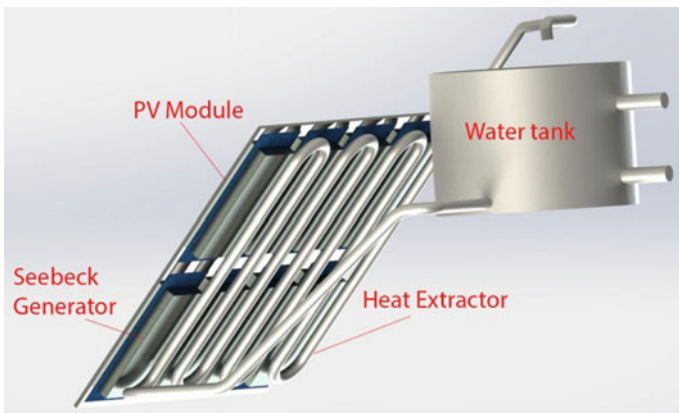
Fig. 5 Proposed design of a new model of hybrid PVT system
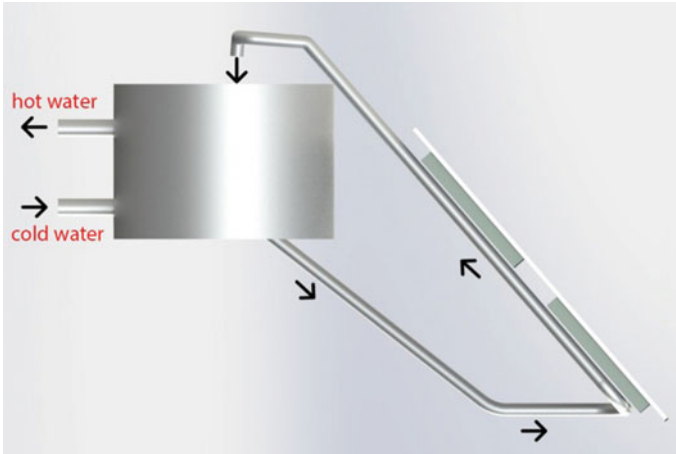
Fig. 6 The side view of water circulation scheme for a hybrid PVT system

heat extractor was designed. This heat extractor uses the cold water as its heat collector which is supplied from the water tank. With this approach, it is expected that the solar cell can work well without any interruption while the TEG maximizes excess heat from the cell into electricity as its hot side has direct contact with heated back of semiconductor and its cold side temperature is kept cold by the heat extractor.

Figure 6 shows the schematic diagram of the heat extraction process for a hybrid PVT system (side view). Initially, the cold water is supplied through a pipe and it will flow directly into the conductive pipe. The water will flow with the up-down motion in accordance with the shape of the pipe. Afterwards, the heated water is sent back to the water tank. This hot water can be used for home appliances or other usages. If nothing happens with the hot water, it is just stored in the tank and waits until the temperature decreases. Furthermore, if hot water is used or evaporated, another amount of cold water is supplied to the tank again. This re-supply process can be done either manually or automatically using a sensor which is controlled through a Programmable Logic Controller.

3.3   Thermoelectric Generator MATLAB/Simulink Model

Figure 7 shows the basic Matlab/Simulink model of the TEG system for simulation.

The model shown in Fig. 7 is for the calculation of voltage and current generated by the TEG. The cold side temperature of the Seebeck generator is set at 25 °C. This value always varies in reality, but during computer simulation, it is achieved by varying the hot side temperature accordingly. Therefore, the simulation result
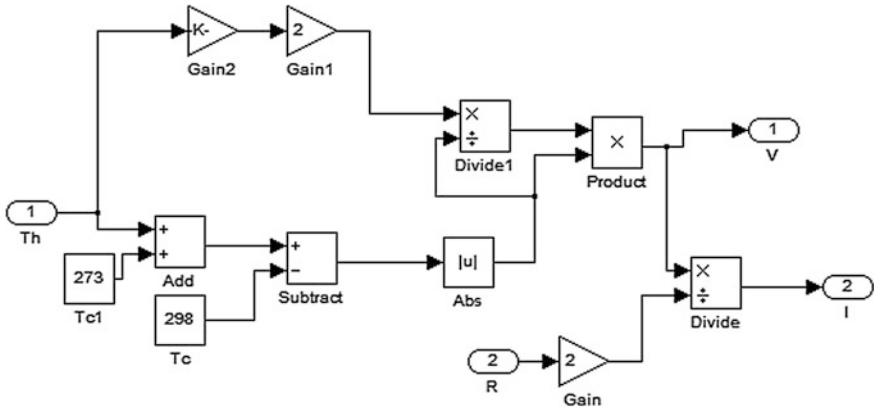
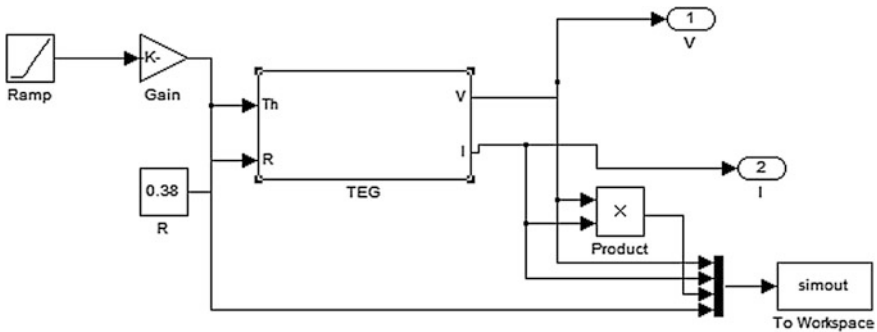**Fig. 7** A basic Matlab/Simulink model of the TEG for simulation

Fig. 8 A complete system of the TEG in Matlab/Simulink

will not only base on the higher temperature but also based upon the temperature differences.

There are two *gains* that are connected with the T_h model input. These were added to obtain the generated voltage. *Gain1* was set as 2 in order to increase the matched voltage value in accordance with the formulation. *Gain2,* which is specifically designed to obtain the matched voltage from the manufacturer specification, was set as 0.0148.

Figure 8 shows the full system block diagram of the TEG block model. The performance of the system was assessed by varying the hot side temperature using a ramp voltage as shown in Fig. 8.

The input of the Seebeck generator block is the hot side temperature and internal resistance. The high side temperature is varied to check the behavior of the generated voltage and current in accordance with the temperature difference between the two layers. The internal resistance is taken from the manufacturer's specification sheet.

3.4 Simulation of the Hybrid PVT Systems

Figure 9 shows the simulated results of the TEG block diagram. Note that the cold side temperature of TEG layer is kept constant at 25 °C.

Figure 9 is plotted using the Eqs. (5) to (8). It shows that the power produced by the device is rising steadily as the temperature on the hot-side layer is increased. The power and temperature relationship can be given by (9).

$$P_{TEG} = 0.0012T_h^2 - 2 \times 10^{-15}T_h \qquad (9)$$

The comparison of a conventional PV cell and a combined PV cell with the TEG is shown in Fig. 10. The simulation is performed when the hot side temperature of the TEG is at 25 °C. To keep the simulation simpler, the PV system is made with silicon solar cells.

Fig. 9 Performance of the TEG system based on the hot side temperature
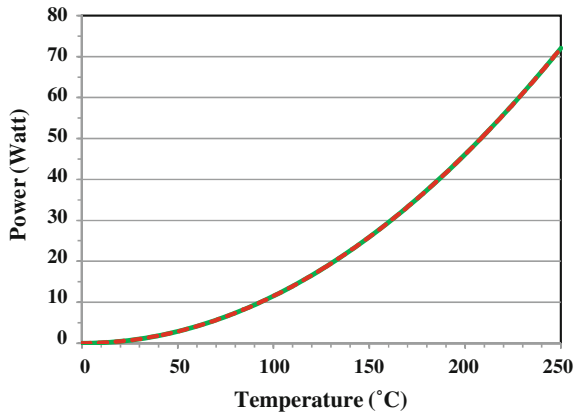
Fig. 10 Power versus voltage characteristics for the conventional Si PV cell with and without the TEG
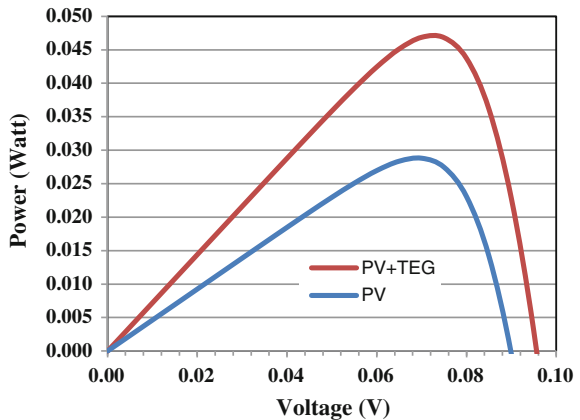
Thermoelectric module can transform the heat difference between its p–n junction into electrical energy. This occurs by the movement of atoms inside the p–n junction. The working principle of a TEG is almost the same as PV cell without the presence of a photoelectric semiconductor.

The increment of the power delivered by TEG is not a linear. Figure 9 shows the change in power at hot side with the temperature increases. If the temperature difference is larger, the power tends to increase exponentially. Therefore, it is recommended that the material on each side should not have the same level. Cold side must use a semiconductor which has the low absorptivity to let the electron moves more frequently.

The simulation of hybrid system is done with the Seebeck generator is at the hot side temperature. Because of that there was an increment in the I–V characteristics, but it does not show a satisfactory result. This is an obstacle for designing a PVT system. Hot side temperature of a Seebeck generator cannot be at a very high temperature as the heat penetrates from the excess energy that is wasted by the PV cell. The cold layer is considered as the same with the ambient temperature.

The results plotted in Fig. 10 shows the combination of silicon PV cell and the Seebeck generator. When a conventional PV cell is changed with other cell, such as a CPV cell, more excess heat can be delivered to the TEG and their combined performance can potentially improve.

The Seebeck generator may not be on its best performance because of the small differences between the layers, but it is still able to increase the PV cell production. The I_{SC} of the hybrid system is approximately 0.23 A larger than the conventional PV cell. The maximum power they can deliver also larger than the stand-alone PV cell. The PVT generates power up to 0.048 W. Compared with a single silicon cell, that only offers approximately 0.029 W in its maximum; the proposed design offers a better performance. Results also suggests that the proposed PVT system can provide approximately 66 % additional power than a conventional PV system.

4 Installation of MPPT with the PV Cell

MPPT plays an important role in a solar cell system as it can optimize the power output of the generator for a given set of weather conditions. Thus, the number of arrays connected in a module can be decreased which can also reduce the cost and optimize the number of modules involved to produce electricity.

Numerous MPPT techniques have been proposed in the literatures. These methods can be classified either into (i) *look up* method, (ii) *perturb and observe* method or *increase conduction* method (Qin and Lu 2012; Hohm and Ropp 2003; Revankar et al. 2010). Each of these algorithms has its own merits, which allow them to be utilized in a variety of applications. Some techniques can work better to maximize the energy. However, among all of them, perturb and observe techniques are the most popular compared to the other algorithms due to the high tracking accuracy at steady state conditions.

4.1 MPPT Algorithm

The observed techniques are for tracking the electronic system to vary the operating point of modules and not the mechanical system, which can shift the PV modules to obtain the maximum sun intensely.

4.1.1 Fractional Open Circuit Voltage

The basis of this method is about observing the percentage of MPP voltage (V_{MPP}) as an open circuit voltage (V_{OC}) of the I–V curve. This ratio is known as K_1, which is expressed by (10).

$$V_{MPP} = K_1 V_{OC} \tag{10}$$

where, V_{OC} is the extracted open circuit voltage when the PV array is isolated from the MPPT. Based on that V_{OC} voltage and V_{MPP} are calculated in accordance with the constant value K_1. However, there is a complexity in deciding what the real value of K_1 is. It is reported that the value of K_1 can be varied from 73–80 % (Hohm and Ropp 2003). After setting the K_1 value, the MPPT can adjust the operating voltage of the PV array until the maximum voltage is reached. This cycle is repeated for a period of time in order to acquire the maximum power delivered.

During the measurement of V_{OC}, the PV power is interrupted due to the discontinuity of the supply from the PV array to the MPPT point. In such circumstances, exact maximum value of K_1 is still undecided and it needs more adjustment when the variation exists in irradiance and/or in temperature of that specific day or time. In order to improve the performance, the method requires dynamic adjustments while the maximum efficiency is obtained. However, with the automatic adjustment, it will be similar with the Perturb and Observe technique.

4.1.2 Fractional Short Circuit Current

Based on the behavior of a PV cell, there is a fact that the current at MPP (I_{MPP}) is approximately linear to the short circuit current (I_{SC}). Therefore, it is possible for a PV cell to maintain its performance by producing an operating current near the I_{SC}. Similar with operation to find the V_{MPP}, an absolute constant is required, which is represented by the factor K_2. Equation (11) shows the relationship between the I_{MPP} and I_{SC}.

$$I_{MPP} = K_2 I_{SC} \tag{11}$$

The value of K_2 for the current ratio is also undecided. I_{MPP} can be within the range of between 78–92 % of I_{SC} (Hohm and Ropp 2003). In order to find the I_{SC}

value, the PV modules are shorted and then recorded in order for the output power to reduce and then to interrupt. Moreover, the MPP value may or may not be perfectly matched with the optimum performance characteristics.

4.1.3 Perturb and Observe (P&O)

The working principle P&O can be described with "hill climbing method". It checks the basic behavior of the PV cell's operating curve by making small increment in the operating voltage (Das et al. 2012). When the power delivered to the load to rise, it will make further perturbation in voltage until the power reaches to its maximum capacity and start to fall below the *MPP*. In this step, the adjustments are not continued but it will be reversed to move back toward *MPP*. If the change in power is positive, the perturbation is kept at the same direction. Inversely, if the power difference is negative, it means the MPP is in a different direction and next perturbation will be at the opposite direction.

This method is widely used in the MPPT console because of its simplicity and ease of implementation. The method of finding the global maxima of curve will continue throughout the PV operation, so the power generated will not stay on the MPP but will oscillate around. There is also an observation time during which the power output is disturbed. Besides that, it is difficult to discriminate the location of the MPP, when the sun radiation is low, as the I–V curve is flattening out. One way to reduce the oscillations at MPP is by decreasing the perturbation size, but it can make the MPPT working time to be smaller.

4.1.4 Increase in Conductance

The incremental conductance can be symbolized as $\Delta I/\Delta V$. Where, ΔI and ΔV are the increment of current and voltage, respectively. This change affects the power of a PV array which further tells if the MPP is near or not. When, $\Delta I/\Delta V$ becomes closer to the zero, PV system works close to its maximum efficiency. As this method can directly be compared with the PV array conductance, it can track any changes better. However, this way of tracking may still receive some oscillations.

4.2 MPPT MATLAB/Simulink Model

To simulate the MPPT performance, basic PV cell system is combined with the MPPT technique to generate the voltage for its maximum performance. Several methods are being used for this simulation. However, all of them are not implemented using Matlab/Simulink platform.

P&O method is widely used among other techniques. Therefore, in this study, P&O tracker method is designed using Simulink and it is shown in Fig. 11.
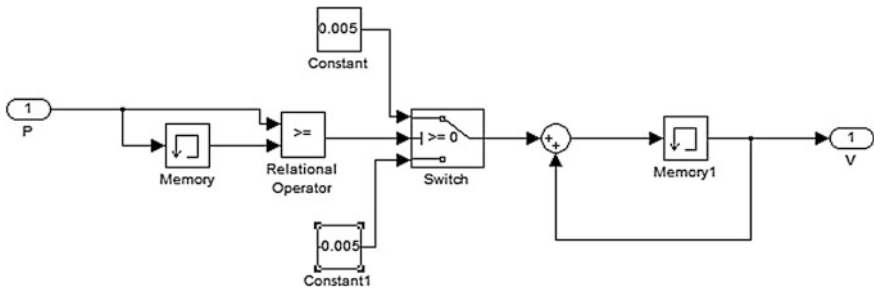
Fig. 11 Simulink model of Perturb and Observe technique
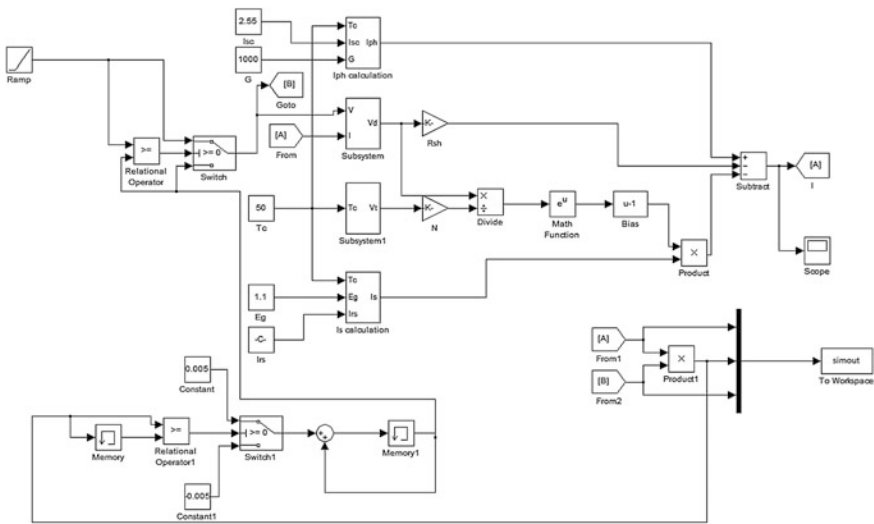
Fig. 12 The combination of a PV cell and the P&O algorithm

In Fig. 11, the power delivered by a PV cell becomes an input for the algorithm. Then, the system is perturbed with a step of 0.005. Afterward, the data is stored in memory and then they are used in the next instruction as shown in Fig. 12 (Revankar et al. 2010; Walker 2011).

Figure 12 shows the combination of a PV cell system and the MPPT technique using P&O method.

4.3 Performance Comparison of the MPPT Techniques

In this section, the results obtained using MPPT techniques were plotted and compared. First two algorithms used the fractional calculation method and plotted
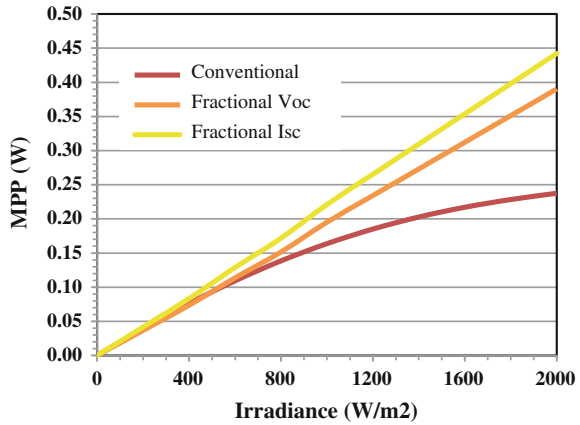
as shown in Fig. 13. For this calculation, the value of K_1 and K_2 are used as 0.75 and 0.85, respectively. Then, these results are compared with the maximum power of a conventional PV cell.

Different designs of MPPT provide different characteristics as they depend on the techniques used for measurement. Constant voltage tracker or fractional process used an open circuit to find the V_{OC} or else shorting the load to find the I_{SC}. Possibly, during this momentary time, some of the energy may be wasted which is not an effective way to generate electricity. Constant values of the ratio also keep changing during the operation of the PV cell which makes them not functioning well. One benefit of the technique is its lower cost and simplicity for the implementation.

As the results suggest, the value of K used in both fractional voltage and current are not stable. When the weather changes suddenly, it may cause the performance to drop further. Thus, this technique cannot cope well to set its constant ratios for a long duration.

Figure 14 shows the power generated using the P&O technique with different time steps, such as (a) 0.01 steps and (b) 0.005 steps.

The P&O technique used a *hill climbing* method to find the maximum power. It increases the step of power to find the operating condition of the module. However, this leads to oscillations around the MPP because it keeps perturbing every specified period, even during the steady state condition.

The results plotted for the P&O design show how the oscillation dominating the generated power. Even when the perturb step is increased to 0.01, the power will suddenly drop because of the higher rate of oscillation. The value of the perturbation step is too high as compared to the voltage value of the cell, which cause the defection during the first experiment. However, when the steps were reduced, the MPP can easily be reached and works around the point. A disadvantage with a smaller step is that it takes some time to find the optimum power compared to the larger steps.

Based on the results, the recommendation comes to try a use variable method. The constant K is set to be as a variable which can cope with the ambient temperature. The relationship will depend on manufacturer's product. This variable method can also be applied to the P&O algorithm to find a better perturbation step. During the tracking period, steps are set to be higher compared to the time when the maximum power was found. When the dark time is coming (i.e., less sun lights are dropping), then the perturbation steps are set to be higher than normal values.

5   Conclusion

This chapter presented preliminary study results of conversion efficiency of multi-junction PV cells with MPPT. The combination InGaP, GaAs, and Ge offers the best performance in tandem cell configuration. The hybrid PVT model has

shown a little disadvantage in the temperature difference between the junctions. The proposed system with water cooling can fulfill temperature diversity issue between the PVT systems. It can also improve the performance of MPPT for a fractional short circuit current and a fractional open circuit voltage. Besides these two, the P&O method showed a better performance among the techniques investigated. This technique highly depends on its perturbation value. When it is very high, PV cells achieve a good dynamic performance, but on the other hand the static performance is not very significant. The smaller steps can lead to better stability but it can also slow down the operation. Thus, the investigation suggests that the multi-junction solar cell can generate a higher power compared with the conventional solar cell and it leads to improve the conversion efficiency of the PV system.

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Grid Integration of Renewable Energy Systems

Binayak Banerjee, Dilan Jayaweera and Syed Islam

Abstract The percentage of renewable power demand met by renewable power generators is increasing rapidly. This growth is driven by environmental concerns, government policies and decreasing cost of technologies. However, as the penetration of renewable power sources increases, new challenges in system planning and operation are becoming evident. There are short term operational challenges as well as long term planning challenges due to the intermittent nature of renewable power generation primarily from wind and solar photovoltaics. The study of grid integration of renewables is concerned with determining the optimal technical and regulatory framework that can effectively manage the short term and long term challenges of large scale renewable power penetration. Operational challenges of this chapter include maintaining frequency and voltage stability due to intermittency as well as network congestion. Planning challenges include allocating long term capacity credits of wind and solar power generation. Currently, the cost of a number of balancing technologies is expected to play a major role in overall viability of renewable power generation. This includes energy storage, demand side management, and dynamic ratings of assets. Smart grids are expected to provide the platform for utilizing the full potential of renewable power generation as well as balancing the technologies.

Keywords Demand side management · Dynamic asset ratings · Energy storage · Grid code · Network congestion · Operational planning

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1   Introduction

It is common understanding that the penetration of renewable power into the grid at both transmission and distribution level is on the rise. A number of factors have accelerated this trend including environmental concerns, decreasing costs of capital investment, technical benefits, and government incentives. In fact, statistics show the market share of renewable energy has been growing rapidly and in some countries they share a significant percentage of the total energy demand.

According to the 2014 Global Status Report on Renewables by REN21, the Renewable Energy Policy Network for the 21st Century (Brower et al. 2014) have concluded that renewable energy provided an estimated 19 % of total energy production in 2012 and 144 countries have already well defined their renewable energy targets. As of 2013, the leading countries, in terms of installed renewable power generation capacity, were China, United States, Brazil, Canada and Germany. Figure 1 shows the global installed capacity of some renewable energy technologies from 2004–2010.

There has been a reduction in the investment in renewable power generation due to the significant decrease in cost of renewable energy technologies, especially PV panels. For example, prices of PV panels dropped by 12 % for installations under 10 kW and by 15 % for installations greater than 15 kW (Brower et al. 2014).

In the UK, there have been a lot of activities to rapidly increase the overall penetration levels of renewable power into the electricity grid. The Department of Energy and Climate Change (DECC) has outlined an 80 % carbon reduction target by 2050. Since 2010, an average of £7billion/year has been invested in renewable generation in the UK. The share of renewable generation in the overall generation has increased from 16 % in 2014 to 25.3 % in 2015 (DECC 2015b). Over the same period, the increase in total energy generated by renewables was 51 %. At the end

Fig. 1 Global installed capacity of various renewable energy technologies from 2004–2010 (*source* REN21)
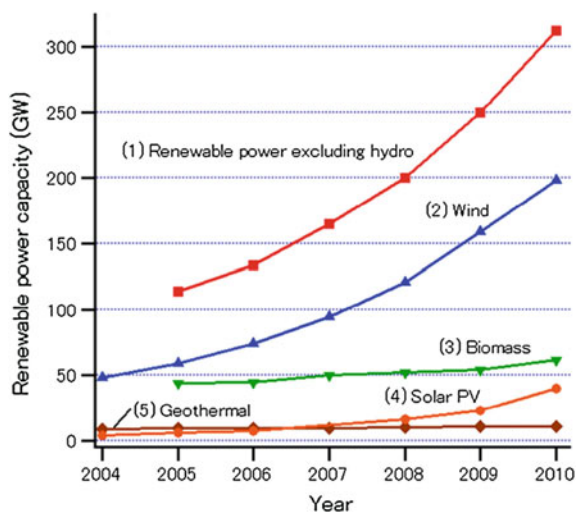
of 2014, there was an installed capacity of 4.4 GW of offshore wind, and 8.1 GW of onshore wind (DECC 2015a). Onshore wind energy production increased by 61 % and offshore wind by 70 %. Solar energy production more than doubled. According to a parliament statement on 18th of June 2015 by the Secretary of State, the wind generation targets are close to being fulfilled and hence there are reductions to subsidies. At the end of 2014, the estimated PV installed capacity was 5 GW, with approximately 5 GW in the pipeline (DECC 2015a).

However, the increasing penetration of renewable power generation leads to the creation of new challenges in system planning and operation. The variability and dynamic nature of renewable power generation, such as PV (Photovoltaics) and wind are a departure from the way the power was generated with traditional generation technologies including coal and gas. In order to accommodate these new technologies, the grid must be evolved and operated in such a way that it ensures the maximum accommodation of renewable power generation and utilised efficiently and economically.

The field of grid integration of renewable energy systems investigates efficient methods of operating the grid that would maximise the utilisation of renewable energy generated. Grid integration considers a number of factors. They are:

- The optimum coordination of balancing resources in the grid.
- Appropriate government and utility regulations to ensure minimum requirements of grid connected systems are met.
- Smart grid technologies to coordinate renewable generation and ancillary services.

2 State of the Art in Grid Integration of Renewables

Renewable energy sources exhibit a high degree of intermittency and often cannot be exported to the grid in that form. Sources such as photovoltaics may also generate DC electricity which needs to be fed into an AC grid. Based on this, renewable energy connection methods may be classified as direct coupled or converter coupled systems. Direct coupled systems are evident in some older wind turbines whereas most modern systems are converter coupled. The following subsections present current available technologies in key types of renewable energy systems.

2.1 Wind Turbine Generators

Global wind power capacity increased from 48 GW at the end of 2004 to 318 GW at the end of 2013 (Brower et al. 2014). The wind industry continues to be challenged by downward pressure in prices, increased competition among turbine manufacturers, and reductions in policy support driven by economic austerity.

At the same time falling capital costs, increased efficiency of technologies leads to higher competitiveness with fossil fuels. Turbines can be classified as fixed speed or variable speed and further into pitch controlled or stall controlled. Turbines may also be directly coupled to the grid or through a power electronics converter.

Fixed speed wind turbines are usually connected to a squirrel cage induction generator and connected directly to the grid via a transformer. Induction generators are asynchronous and require external excitation. The frequency of the rotating magnetic field is set by the grid frequency which makes it possible to connect directly to the grid. Since induction generators do not produce reactive power, fixed speed wind turbines require installation of capacitor banks in order to eliminate the reactive power requirements from the grid (Ekanayake' and Jenkins 2004; Eriksen et al. 2005). These turbines may be pitch controlled or stall controlled (National Instruments 2008; Muljadi et al. 2013). Pitch control adjusts the angle of the blades in response to changes in wind speed to ensure that turbine speed is fixed. Wind turbines with pitch control have the capability to adjust the blade angle to optimise the amount of power produced by the turbine as the oncoming wind varies. Such turbines can also adjust the blade angle to create aerodynamic stall when the wind speed is very high (active stall control). Fixed pitch turbines cannot adjust the blade angle and rely on passive stall control to limit the maximum power during high wind speeds. Pitch and stall control can also be used to ensure that the wind speed remains fixed if required.

Variable speed wind turbines can be of many types and have various control configurations. The simplest type of variable speed turbine uses a wound rotor induction generator (Muljadi et al. 2013; National Instruments 2008; Eriksen et al. 2005). The wound rotor has additional variable resistance which allows for speed control usually through a simple power electronics interface. Additional pitch control is also implemented. The range of speed variation is limited to up to 10 % above synchronous speed (Eriksen et al. 2005). This configuration provides a limited level of variable speed while still ensuring the turbine can be directly coupled to the grid. However, for a larger range of speed variation requires advanced power electronics converter interface.

Most modern variable speed turbines use a doubly fed induction generators (DFIGs) (Eriksen et al. 2005; Datta and Ranganathan 2002; Holdsworth et al. 2003). The DFIG has a separate electrical connection to the stator as well as rotor through a power electronics interface. The advantage of this method is that it allows a high level of control and the mechanical frequency of the rotor can be decoupled from the electrical frequency of the grid. This allows a wider speed range of approximately −40 to +30 % (Eriksen et al. 2005).

Some variable speed wind turbine are connected to the grid through a full scale converter which allows a very high degree of flexibility (Eriksen et al. 2005). The generator can be excited electrically or by a permanent magnet. Thus, it is possible to use synchronous generators in the generation of wind power. Such converters are then capable of supplying reactive power and smoothing out the output of the wind farm.

The first two types are more common in older wind turbines. Most modern wind turbines are variable speed connected to the DFIG. The DFIG provides the added

benefit of being able to provide reactive power to the grid and low voltage ride through capability during grid disturbances. Older wind turbines do not have low voltage ride through capabilities and are likely to disconnect from the grid when the voltage drops below 20 % (Eriksen et al. 2005).

2.2 Photovoltaics

Worldwide PV capacity has increased from 2.6 GW in 2004 to 139 GW in 2013 (Brower et al. 2014). The most growth has been driven by falling costs and increased efficiency of PV modules. China has accounted for nearly a third of the growth. Unlike wind turbine generators, PV arrays generate D.C. (direct current) electricity and usually require a power electronic inverter interface to connect to the grid.

Types of PV-DG (Photo Voltaic Distributed Generation) installations are classified according to their size and interconnection configuration (Katiraei 2011). Utility scale PV-DG is usually large PV plants that are greater than 1 MW and can be connected to the feeder or the distribution substation. The connections can be three phase and require multiple interconnection transformers. Utility scale PV-DG plants also require multiple power electronic inverters operating in parallel. These have protection features, such as anti-islanding, built in.

Medium scale PV-DG arrays are usually placed on roofs of small or large buildings and have capacities in the range of 10 kW to 1 MW. Larger installations, in this range, have similar configuration to Utility scale PV-DG but with lower nominal ratings on equipment. Smaller installations are similar to small scale PV-DG installations.

Small scale PV-DG is usually a single phase rooftop installation on residential customers. They are less than 10 kW and are connected to the low voltage network. They do not require an interconnection transformer.

Some small to medium scale PV installations can also be non-exporting category. These systems do not feed power to the grid and reduce the local demand for grid electricity. These PV systems do not also pose any integration challenges for the utility grid.

2.3 Other Renewable Energy Generation Technologies

A number of other technologies such as mini and micro hydro, solar thermal, bio energy and geothermal also used in practice as distributed generation. However, they may not necessarily present the same grid integration challenges as PV or wind as the demand shares of them are limited. It is common to consider hydro power as a form of storage instead of generation. As such (Brower et al. 2014) presents key renewable energy statistics both with and without hydro power. Due to the

controllable nature of hydro power, it does not present the same integration challenges. Technologies such as solar thermal or bio energy uses renewable energy to indirectly produce fuel which may be used in ways similar to conventional generation. As a result, these technologies are controllable and don't have a high level of uncertainty such as with PV or wind.

3 Challenges and Opportunities of Connecting Renewable Power Systems to the Grid

One of the biggest challenges of renewable power generation is that it is highly variable and not controllable compared with the conventional generation sources. This is especially true for wind generation which experiences large swings with variations in wind speed. Photovoltaic generation also experiences variations especially when there is varying degrees of cloud cover. Forecasting of power output from these sources is challenging and this can pose long term planning challenges as well as short term operational challenges. Some renewable technologies such as biofuels do not exhibit a high level of intermittency and as such do not pose an integration challenge as in wind and PV cases.

Operating reserve is one of the many types of ancillary services that are required to manage the intermittency of grid integrated renewable power generation. Chuang and Schwaegerl (2009) show that the severity of intermittency can be as high as 60–85 % deviation in capacity over a period of 5–12 h. The challenges associated with intermittency of wind power, such as high cost of ancillary services and the uncertainty of wind power output, at large scale wind integration have been well documented in literature (Yi et al. 2011; Barth et al. 2006, 2011; Jabr and Pal 2009). Some of examples of ancillary services are:

- Regulation and frequency stability through reserves (short term fluctuations)
- Operating reserve to meet power balance or load following (longer term)
- Voltage control such as tap changer or reactive power control
- Restoration of supply.

The cost of ancillary services is a significant component of the cost of renewable integration. It is essential to maintain system reliability and prevent outage costs to the customers.

4 Short Term Operational Challenges

A power system is dynamic and the imbalance between generation and load is continuously changing mainly due to load variations. Stability issues arise in a power system whenever there is a momentary imbalance between generation and load. Traditional synchronous generators cannot change their power output

instantaneously to match the load and as a result, they speed up or slow down to supply the shortfall until the speed changes. The momentary change in speed causes changes in frequency. However, due to the large number of rotating machines in a power system there is a high inertia which can absorb momentary changes in load. Most generators have some capability to speed up or slow down which results in spinning reserve. Furthermore, the variations in load are fairly predictable as human energy use follow patterns. Based on this, system operators can allocate additional rapid response generation units during expected periods of high demand.

The fluctuations produced by the presence of small quantities of renewable generation (5–10 % penetration) can be absorbed by the spinning reserve capability of most power systems. Most renewable generators of this size do not have a significant impact on the generation profile of the system. The usual effect of small scale renewable power generation is to offset some of the local load. Thus, for modelling purposes it is prudent to consider them as negative loads due the effects of low inertia machines. However, as the penetration of renewable energy increases, the fluctuations observed by the system are likely to get larger and the spinning reserve capacity of synchronous machines may not be able to cope with the intermittency. Thus, further measures are required to be taken into ensure that the impact of these variations on system frequency is minimal. They include:

- Installing balancing technologies in the system.
- Installing short term and rapid response storage such as flywheels or supercapacitors.
- Demand management in real time to ensure that system frequency does not fluctuate significantly.

Most measures to account for the intermittency come at a high cost to the system and then to the cost of electricity. While renewable energy generation is fairly inexpensive compared to conventional generation, cost of balancing resources can become prohibitive (Wedde et al. 2007). Thus, the challenge of grid integration of renewables lies in minimising the overall cost of balancing resources. This can take the form of effective coordination and management of existing technologies, or researching new low cost technologies for balancing resources.

5   Long Term Capacity Planning Challenges

Apart from short term balancing of intermittent systems, renewable power generation experience challenges in predicting long term (day ahead or greater) generation capacity. The variability coupled with the challenge of accurate forecasting makes it impossible to use renewable generators as sources of capacity without significantly increasing the risk of loss of load. As a result, reserves must be maintained to guarantee the reliability of power supply beyond some thresholds. When renewable penetration increases, the cost of reserves may grow significantly disproportionately. This cost limits the amount of renewable power that can be connected (Wedde et al. 2007).

Medium to long term predictability of renewable power generation is necessary for adequate investment planning in generation capacity, and good management in scheduling the system (Xie et al. 2011). Unit commitment (UC) with renewable generation relies to a great extent on the quality of forecasting. Wind and PV forecasting can both be obtained for a time period of 6 h with accuracy. Wind power exhibits a higher degree of variability and forecasting techniques are capable of accounting for local influences of roughness, obstacles and height variations. UC decisions need to be updated more frequently when renewable generation is present. The frequency may be as low as 6 h compared to 24–36 h for conventional generators (Xie et al. 2011).

Improved wind forecasting technologies are based on persistence based modelling, numerical weather prediction and artificial intelligence techniques. Persistence methods (Billinton et al. 1996; Palomares-Salas et al. 2009; Peiyuan et al. 2010) may involve time series analysis based methods to predict power output. Numerical weather prediction (Khalid and Savkin 2012; Jiang et al. 2011; Xiaohong et al. 2012) takes into account the nature of the local terrain on wind speed and wind power output. Artificial intelligence techniques (Jie et al. 2011; Bhaskar and Singh 2012; Gao and Billinton 2009) are highly advanced and use methods such as neural networks to analyse and predict the pattern in wind speeds and power output. The successful implementation of forecasting reduces uncertainty associated with wind power output. PV power output exhibits a much lower level of intermittency and forecasting is not as challenging.

Geographical dispersion and decentralization of renewable generation also reduces the intermittency and allows the spinning reserve to be reduced (Asari et al. 2002). The combined effects of dispersed renewable resources can be used to provide a stable supply to some extent. The unpredictability of long term capacity of renewables has resulted in interest in evaluation of capacity credit of renewable power generators specifically wind farms. Some methods of calculating capacity credit of wind are (Amelin 2009):

- Equivalent firm capacity (EFC)—This is the capacity of a hypothetical 100 % reliable unit that would provide the same improvement in loss of load probability as the wind generator in question.
- Load carrying capability—This method defines capacity credit as the amount of system load that can be increased, without increasing the risk of loss of load when a generating unit is added.
- Equivalent conventional power plant—This is similar to the EFC definition but instead of a hypothetical 100 % reliable unit, the renewable generator is compared to a conventional power plant with "realistic" level of reliability.
- Guaranteed capacity—This definition considers the minimum capacity that the unit can provide at a specified probability level referred to as the level of supply reliability.

While the aforementioned methods have been discussed in the context of wind generation in literature, they can also be applied to PV and any other form of renewable generation. Amelin (2009) used an empirical study to compare the

methods and concluded that the obtained capacity credit is highly dependent on the choice of method. All the methods consider different aspects of capacity e.g. the first three methods consider the effect on system load whereas the last definition considered the effects on available generation.

6 Network Congestion

Network congestion occurs when the transmission system constraints cannot accommodate all physical flows within the system. In traditional power systems with a single utility provider, network congestion was managed by setting generator dispatch schedules such that line limits were not exceeded. Marginal pricing signals could be used as an indicator of congestion and persistent congestion would drive generation or transmission expansion projects (Glatvitsch and Alvarado 1998). As a consequence of congestion, generation had to be redispatched such that the overall generation cost was higher than in a congestion free system.

Transmission open access and network deregulation started in the 1980s and 1990s with an aim to increase competition in the electricity market. However, due to network congestion and the limited availability of transmission capacity, competing entities could not have equal access to customers thus affecting the level of competition (Singh et al. 1998). The absence of a method to determine equitable allocation of increased transmission cost due to congestion became a key factor that reduced the competitiveness of market participants (Fang and David 1999; Glatvitsch and Alvarado 1998).

A number of researchers proposed market based mechanisms that could be used to determine more equitable allocation of the increased transmission cost. These include:

- An independent system operator (ISO) to efficiently manage the operation of the competitive electricity market (Fang and David 1999; Glatvitsch and Alvarado 1998; Shirmohammadi et al. 1998; Singh et al. 1998).
- Bilateral markets allow suppliers and consumers to directly arrange power transactions without the intervention of a third party (Fang and David 1999; Singh et al. 1998)
- Pro rata (PR) allocation of cost to generators and consumers proportional to their energy generation or consumption marginal allocation based on incremental transmission loss (ITL) coefficients of each generator or load; and proportional sharing which is based on the principle that losses associated with a line that enters a given bus are transferred to the lines (or generation/loads) which leave the bus (Conejo et al. 2002).

While the aforementioned methods addressed the challenges of network congestion in deregulated markets, they do not necessarily reduce the level of congestion. In a congested network, there will be a reduced level of competition and prices will be distorted compared to the uncongested case. However, schemes such

as the aforementioned ensure that in the event of congestion, the added cost is allocated as equitably as possible amongst market participants to ensure that competition is not hindered excessively.

The rapidly increasing penetration of renewable energy, particularly wind has added to the network congestion problem (Yingzhong et al. 2011; Jianhua et al. 2011; Muneender and Kumar 2009; Zhang et al. 2007). The large penetration of renewable generation has increased the focus on congestion management for transmission system operators (TSOs) without which further renewable integration will be impeded. During periods of high congestion, significant amount of wind farm output is curtailed in real time operations to ensure that network thermal constraints are satisfied and system security and reliability are not compromised. Many ISOs have incentives to offset the risk of curtailment and encourage market participation of wind power producers during times of excess wind power production. However, providing incentives of this form does not eliminate the risk and is only viable as a short term solution. Such methods may be suitable to allow wind power to compete in the early stages of technological development but in the long term it will disadvantage more efficient generation and hinder wind power from becoming an economically viable form of generation. Reducing the risk of curtailment will be a key factor in ensuring long term investments and competitiveness of wind power.

One of the main reasons that wind curtailment is preferred over adjusting conventional generator output is the requirement for must run units which need to be online to maintain system security and stability (de Magalhaes Carvalho et al. 2012). The uncertainty associated with the congestion induced curtailment increases the uncertainty and financial risk for wind power producers (Burke and O'Malley 2011; Yingzhong et al. 2011; Burke and O'Malley 2009; de Magalhaes Carvalho et al. 2012).

While network congestion induces significant wind curtailment, it is possible to minimise the effect of congestion by strategic system planning. To account for congestion in wind scheduling it is necessary to accurately assess the effect of congestion and thermal limits on wind curtailment. Burke and O'Malley (2011) examines some of the factors which affect wind power curtailment in a congested network and suggests that wind power curtailment risk is highly dependent on wind farm locations in the network. This implies a scope for reducing the curtailment risk by selecting optimal locations. Yingzhong et al. (2011), Burke and O'Malley (2009) also note that error in estimating wind power output leads to curtailment and can be reduced by effective prediction techniques. Reduced uncertainty in wind power forecasts leads to reduced uncertainty of congestion induced wind curtailment.

While studies such as the aforementioned can improve the wind integration under congestion by strategic planning, they do not address the mitigation of network congestion. The techniques for maximising wind integration should be used to complement congestion management techniques for overall efficient network operation.

Short term congestion management techniques involve market based measures (Luo et al. 2014; Androcec and Wangensteen 2006; Muneender and Kumar 2009;

Vergnol et al. 2009) such as redispatch or counter trading, network based measures such as transmission switching (Khanabadi and Ghasemi 2011; Khanabadi et al. 2013) or the use of FACTS devices (Xiao-Ping and Liangzhong 2008; Jianhua et al. 2011; Zhang et al. 2007), and as a last resort generation curtailment (Kamga et al. 2009).

The use of FACTS devices is also an important network based method for congestion management. Xiao-Ping and Liangzhong (2008) additionally suggest that FACTS devices together with high voltage DC (HVDC) technologies and wide area measurement system (WAMS) may be more cost effective for managing the network congestion while ensuring the electricity network flexibility. The main requirement for congestion management by network based methods is that there must be existing capacity in some parts of the network which can be diverted to congested areas. Alternative means of congestion management such as generation curtailment will be required if there is a limited capacity in the overall system.

Instead of focusing on a single strategy, Kamga et al. (2009) combines all three techniques namely market based measures, network based measures and generation management, in an optimised combination for the most efficient congestion management. This study considers large scale analysis of wind energy and uses a genetic algorithm to assess requirements such as network security constraints or short circuit calculations. The optimisation demonstrates that while it is possible to reduce some of the wind farm curtailment, there is still a significant amount of curtailment. In an optimised mix of congestion management methods generation management plays the most significant role compared to other methods.

Thus, the challenge of congestion management is becoming more significant as the grid evolves and moves towards a decentralised structure. It is evident that conventional congestion management methods are unable to keep the pace with the scale of the problem and will have to be replaced by dynamic and intelligent grid methods which can be deployed in real time. While existing congestion management techniques are somewhat effective, most of them lead to a significant level of wind curtailment and associated uncertainty for wind producers. Given the advent of smart grid technologies more research could be directed at finding new techniques for short term congestion management that would focus on increasing wind penetration without adversely affecting the system security or the reliability.

7 Grid Code on Renewable Generation Connection

The UK Grid Code covers renewable generation under general distributed generation connection guidelines. Guides outlining the connection process for distributed generation including renewable generation are covered in EREC G59 (Energy Networks Association 2014c; Energy Networks Association 2014b) and EREC G83 (Energy Networks Association 2014a). Large power stations (usually greater than 100 MW in the National Grid Network) have additional responsibilities. Large power stations require generation licenses while those between 50 and 100 MW may be exempted.

Large power stations also need to enter into an agreement with the National Grid Electricity Transmission (NGET). This could be in the form of a Bilateral Embedded Generation Agreement (BEGA) or a Bilateral Embedded License Exemptible Large Power Station Agreement (BELLA) (applicable only in Scotland).

Renewable generators are subject to standard feed in tariff structures as detailed in Chap. 3. However, there are additional mechanisms in place to incentivise renewable energy generators. Renewable energy generators over 50 kW capacity may be eligible for Renewable Obligations Certificate (ROC) (Energy Networks Association 2014b). Smaller generators are supported through standard feed in tariffs. An ROC places an obligation on UK electricity suppliers to generate an increasing proportion of energy from renewable sources.

ROCs are issued by Ofgem (Office of Gas and Electricity Markets) to operators of renewable energy generators. The number of ROCs depends on the type of renewable energy technology. This process is called ROC banding and the band is fixed for the eligible period of 20 years lifetime. The certificates can be traded and their price may fluctuate based on supply and demand. Suppliers of renewable energy purchase energy from generators along with ROCs which they must present to Ofgem. If the supplier does not produce sufficient energy they must pay a penalty. If they present insufficient ROCs, the difference in value must be paid into a buyout fund which is distributed back to the suppliers in proportion to the number of ROCs they originally produced.

Under electricity market reforms ROCs are being phased out. They will not be issued beyond 2017 but existing ROCs will be honoured. ROCs will be replaced by contracts for difference in addition to standard feed in tariffs (FITs).

A Contract for Difference (CFD) is administered by the low carbon contracts company (LCCC) which is owned by the UK government. A renewable energy generator enters into a CFD with the LCCC to gain greater stability of their revenue while being partially protected from the volatility of wholesale electricity prices. It also protects consumers from paying for high support costs when electricity prices are high. Generators who are party to a CFD get paid the difference between the strike price and reference price. The strike price reflects the cost of investing in a specific low carbon technology and the reference price is a measure of the average market price for electricity. CFDs were brought into effect in 2014. Renewable generators commissioned in the transition period between 2014 and 2017 can choose between ROCs or a CFD (DECC n.d.).

8 Key Enabling Technologies for Grid Connection of Renewables

The feasibility of grid connection of large quantities of renewables is largely dependent on the economics of enabling technologies. As such there are significant efforts to utilise more efficient and lower cost technologies. It is also important to

optimise the management of these technologies so that they are not used more than necessary. This section describes the state of the art of some key technologies which will influence the grid integration of renewables.

8.1 Storage Technologies

The fundamental problem of integrating a large amount of renewable generation into the grid is the fact that it is intermittent and it does not provide the same level of inertia that conventional rotating machines provide. Long term capacity planning challenges are also a result of the intermittency. Large scale availability of storage is a possible solution for addressing these key challenges. However, the cost of traditional storage technologies has limited the viability of large scale renewable integration. There are numerous efforts to discover new and more cost effective storage technologies as well as ensuring that existing technologies are operated in an optimum configuration to minimise their cost.

Existing storage technologies can be of many types (Vazquez et al. 2010; Styczynski et al. 2009)

- Flywheels—use a rotating mass to store kinetic energy which is ideal for short term applications. Traditionally, they have been used to stabilise output from synchronous generators. They have the advantage of being fairly robust and being able to store or deliver large amounts of energy within a very short period of time. The number of charge/discharge cycles is almost infinite. Recent advances in power electronic interfaces have made it possible to use flywheel based storage for renewable energy integration and power quality applications.
- Natural and pumped hydro—Pumped hydro is arguably the best form of storing large scale energy. It is based on a large body of water stored at some elevation which is then used to drive a turbine. When the energy is not required, electricity from the grid used to pump the water back into the storage. The biggest challenge with pumped hydro is finding the required land area with suitable topography. It is quite a mature technology and can provide the balancing energy needed for large scale grid integration of PV or wind. The discharge time is controllable and new technologies are used at subterranean pumped hydros.
- Compressed Air Energy storage (CAES)—CAES uses excess energy during off peak to compress air which is used to run a gas turbine in times of high demand. This is also a form of large scale energy storage. It uses about a third of fuel of a conventional natural gas turbine.
- Hydrogen—Hydrogen based storage is centred on fuel cells which use hydrogen and oxygen to produce water and electricity. Hydrogen has the advantage of being storable, efficient, transportable and clean. The hydrogen could be stored as a liquid or compressed gas, metal hydrides or carbon nanotubes.
- Supercapacitors—Supercapacitors are also called electrochemical double layer capacitors (EDLCs). EDLCs store energy by charge separation like conventional

capacitors and do not rely on chemical processes as in the case of batteries. Compared to conventional capacitors, EDLCs have extremely high capacitance ratings (350–2700 F). They achieve this by using a high permittivity membrane and porous carbon electrodes to maximise surface area. While they may not be able to store a high amount of energy like batteries, they can charge and discharge very quickly making them ideal for voltage regulation. EDLCs require minimum maintenance and have a high number of charge/discharge cycles.

- Battery based storage—The storage of electrical power in batteries in electrochemical form is well known. Batteries produce direct current electricity and thus require a power electronic inverter to interface with the grid. Battery life is measured as the number of charge/discharge cycles and the discharge rate is limited by the type of battery. Different types of batteries exist. Lead acid batteries are still common for low cost applications as they are rugged as long as low energy density and cycle life are not an issue. Lithium-ion batteries have the advantage of high energy density, no memory effect, and low self-discharge. However, Li-ion batteries are quite expensive for large scale applications. They are the most promising technology for use in electric vehicles and plug in hybrid vehicles. Sodium Sulfur batteries are also a promising technology due to their high power and energy density and ease of mass production. They are also cheaper than Li-ion batteries. Flow batteries are a promising technology that work similar to fuel cells and decouples the power output from the amount of storage.
- Superconducting magnetic energy storage (SMES)—SMES uses a coil of superconducting wire to store electrical energy in a magnetic field. SMES can release high amounts of energy in a fraction of a cycle and have high efficiency. SMES has a high cost due to the requirements for refrigeration as well as superconducting wires. Thus, they are mainly used for short term storage e.g. power quality applications
- Vehicle to grid (V2G) storage—Vehicle to grid storage relies on using batteries in parked electric vehicles as storage. This is dependent on development of battery technology and adequate grid reinforcement, coordination and control are also required to supplement V2G schemes.

A number of applications which require storage cannot be satisfied by a single technology. In this instance hybrid storage systems are commonly used. These can include (Vazquez et al. 2010)

- Battery and EDLC
- Fuel cell and battery/EDLC
- CAES and battery/EDLC
- Battery and flywheel
- Battery and SMES.

Using multiple sources necessitates additional coordination requirements to ensure that multiple sources can operate as a single source. Often this requires power electronic converters. The multiple sources may be connected directly if their

voltages are synchronised. Alternatively, they may be separated by a power electronic converter to provide more flexibility. A third option is to let each source have its own power electronic converter which allows for the highest degree of flexibility.

Power electronic converters/inverters are essential for connecting storage to the grid as they must often interface between different DC voltage levels or between DC and AC voltage. Power converters are required to be capable of managing bidirectional flows and having a high efficiency.

8.2 Demand Management

Demand management refers to the modification of consumer demand directly or indirectly. Direct demand management may be in the form of controllable loads which the utility may shed based on the supply. Indirect demand management achieves variation in consumer demand though financial incentives such as real time pricing structures. Consumers adjust their behaviour based on price and the price can be increased during peak periods. The aim of demand management is to shift the consumption away from peak periods. For renewable energy integration this has the advantage of being able to adjust consumption in response to renewable intermittency.

Another application of demand management is in the form of frequency responsive loads and dynamic demand control (Short et al. 2007). These loads monitor the system frequency and adjust their power consumption based on the variation in frequency. The cumulative effect of a large number of frequency responsive loads significantly improves the frequency stability of a system. This will significantly aid renewable energy integrated systems where frequency stability is a major challenge.

8.3 Dynamic Ratings

Dynamic line rating (DLR) or dynamic thermal rating (DTR) determines line ampacity based on real time weather conditions to allow transmission network expansion to be deferred or even avoided. Dynamic ratings can provide a significant increase in the normal and emergency operational flexibility of power transmission systems compared to the more traditional static rating. A review by Howington and Ramon (1987) concluded that dynamic thermal ratings can lead to momentary increases in line capacity by up to 300 % and average increase by up to 50 %.

While initial studies such as these showed promise, Howington and Ramon (1987) identified a few major challenges which made it infeasible to use real time DTR on a system wide scale. One of the challenges was the accurate monitoring of all sections of a line. Since lines span long distances and have different weather

conditions throughout the line, the level of monitoring is vital and this was deemed to be cost ineffective. Secondly, the increased risk associated with operating assets above the rated capacity led to reliance on the accuracy of DTR algorithms and the level of monitoring, neither of which was reliable enough to make it economically feasible.

In the modern power system, increasing electrical demand and an increase in the amount of renewable generation has resulted in the existing transmission/distribution network becoming one of the critical limiting factors which may constrain generation during heavy loading and/or system contingency (Fu et al. 2011). A number of sources (Fu et al. 2011; Hosek et al. 2011; Kazerooni et al. 2011) agree that when a network congestion occurs frequently the only long term solution is network expansion which is prohibitively expensive and time consuming. As a result of the growth of the electrical network especially in regards to renewable energy penetration, researchers have shown renewed interest in dynamic line ratings.

The issues encountered due to lack of technology in monitoring status in early studies on DTR are addressed by a number of current smart grid technologies such as distributed power line sensor network (PLSN) for real time monitoring of overhead power lines (Yi et al. 2009), and using line sag as a means of improving measurement of the thermal dynamics of the line (Hosek et al. 2011).

Another issue with DLR is the inherent uncertainty which is addressed to some extent in (Shaker et al. 2012) by using fuzzy theory. Models such as those in (Hosek et al. 2011) take extensive measurements to predict DLR in real time and are ideally suited for specific systems where large amount of data monitoring is available.

When implementing DLR, it is also important to ensure that the extent of monitoring in the network is optimised to ensure efficient usage of resources (Matus et al. 2012). It is also true that there is a correlation between wind speed and dynamic line rating due to the cooling of the line due to wind. However, the final thermal capacity of the line is determined by the section of line with the highest temperature and lowest capacity. Thus, regions with low wind speeds could potentially negate the effect of wind speed cooling in other sections of the line. Alternatively, targeted network reinforcement in those bottleneck regions could be used to maximise benefit of DLR.

It is expected that within the context of a smart grid, a sophisticated level of monitoring and communication will be readily available thus addressing one of the biggest impediments to implementing DLR. Despite the renewed interest in DLR, and the availability of smart grid infrastructure to support implementation of DLR, there is still reluctance by utilities to adopt modern dynamic line rating methods on a large scale. To account for real time variation in thermal line ratings most ISOs in North America use more than one rating to account for different weather conditions based on the relationship between temperature and ampacity outlined in IEEE Std 738-2012 (2013). There are separate ratings for hot and cold weather as well as normal and emergency situations. However, these are also fixed ratings and actual ampacity may be significantly different from these ratings. While this method takes

into account the temperature dependence of line ampacity to a limited extent, it may not necessarily reflect the true operating conditions of the line and hence under-utilise the network capacity. In modern power systems which consist of multiple competing entities and fast changing power flows due to presence of intermittent renewable generation, congestion and inefficient allocation of available network capacity can result in unfair advantages to some participants over others. DLR can exploit the advanced real time monitoring and control capabilities of smart grids to potentially alleviate network congestion by dynamically releasing latent capacity, and ensuring a more equitable allocation of costs between market entities.

8.4 Smart Grid

Smart grid and micro grids have been universally proposed as the future vehicle to facilitate grid integration of renewable energy. The advantage of smart grids is that they provide a framework for advanced monitoring and control of the electricity grid at a micro level. This reduces a number of barriers (especially economic) to implementing enabling technologies and ancillary services for renewable generation. Examples of this are as follows:

- Smart grids can aid demand management by coordinating loads on a home area network with pricing signals from the utility.
- Smart grid can coordinate storage technologies by determining appropriate times to store, import or export energy.
- Smart grids can utilise dynamic line ratings since sag and temperature sensors can be installed in strategic locations along transmission lines. The information from these devices can be used to calculate the line rating and communicated to smart protection devices to ensure that the line is overloaded.

Smart grids often go hand in hand with micro grids which are sections of the grid capable of operating autonomously as well as in grid connected mode. Successfully implementing a micro grid will require application of smart grid technologies to ensure that distributed generation, storage, load and distributed energy resources can be coordinated. Having an intelligent local grid will also facilitate renewable generation. Micro grids are discussed further in Chap. 3.

One of the key requirements for large scale implementation of smart grid technologies is clearly defined interoperability standards. This covers three basic aspects (Basso 2014)

- Electric power—how electricity moves and devices interconnected.
- Communications—how information is exchanged and devices communicated.
- Information—What data and information is exchanged and how it is organised.

The goal of interoperability standards is to ensure that two components in a smart grid (devices, networks, appliances etc.) can communicate and exchange information and data effectively.

The first version of IEEE Std. 2030 was released in 2011 and covered the Smart grid interoperability with Energy technology and information technology operation with the power system. IEEE Standard 2030.1 covered electrification of transport. IEEE Standard 2030.2 was released in 2015 and covered integration of energy storage systems with transmission and distribution infrastructure. The latest version of IEEE Standard 2030.3 includes testing procedures for grid integrated storage systems and infrastructure. Future releases are also expected as smart grid requirements and technologies evolve.

9 Case Studies

9.1 The London Array

The London Array is the world's largest offshore wind farm and Europe's largest wind farm as of 2015 and was completed at a cost of GBP 2 billion. It is located 20 km off the coast of Kent and has a capacity of 630 MW provided by 175 turbines. Each turbine has a diameter of 10 m and sweeps an area of 11,300 m^2 (Moskvitch 2015).

There were additional plans for a second phase to increase the capacity to 1 GW. However, known technical challenges with shallow water, longer cable routing, and threat to bird habitats resulted in plans for phase 2 to be terminated (London Array Limited n.d.).

The London Array project is driven by a consortium of renewable energy companies consisting of E.ON, DONG energy, and Masdar. Onshore works were completed between 2008 and 2012 while offshore works were completed between 2010 and 2013. The London Array is connected to the grid through a dedicated substation at Cleve Hill which is one kilometre from the North Kent coast. There are four transformers to step up the voltage from 150 to 400 kV before connecting to National Grid's network (London Array Limited n.d.).

The London Array is an example of one of many offshore wind power plants that can provide a large and steady power output to the transmission network. Existence of appropriate policies and tariff structures encourage growth of renewable generation projects such as the London Array. This leads to a sustainable growth in the grid penetration of renewables.

9.2 Australia's Rooftop PV

At the end of 2014, Australia was the global leader in rooftop PV installation per household by a wide margin. This consisted of approximately 1.4 million homes which started at 8000 homes in 2007 (Mountain and Szuster 2015). There are a

number of factors which contributed to the rapid growth of rooftop PV systems in Australia.

1. Household electricity prices increased by 90 % due to rising network costs over the period from 2007 to 2013. Household electricity prices in Australia are higher on average than the European Union, Japan, Canada and the United States.
2. During the same period a number of capital and production subsidies made the economics of distributed generation quite attractive. Capital subsidies were offered in the form of renewable certificates that could be traded between owners of PV systems and retailers. Production subsidies were provided in the form of jurisdictional feed in tariffs. In addition energy retailers offered payments to households for energy exported to the grid.
3. While the cost of household electricity was increasing, the cost of PV panels was decreasing. The price of rooftop PV decreased from $AUD 12/W in 2008 to less than $AUD 2/W in 2014. This rapid decrease in price can be attributed to global drop in price of PV panels as well as a rising Australian Dollar.

Households which installed PV experienced an average internal rate of return (IRR) of 8.9 % between 2010 and 2013. Household with PV experienced indirect benefits such as higher control over their electricity supply as well as no tax on income from selling electricity to the grid. The cost of production and capital subsidies have been recovered from consumers and thus households without PV had to bear the additional increase in network charges from the high penetration of PV systems.

Electricity distributors' have benefited from the increase in PV systems as it can lead to deferred network augmentation costs. One study (Mountain and Szuster 2015) estimates the value of the avoided network augmentation to be $AU 1.3 billion. However, this may not be strictly applicable for residential feeders where the peak occurs just after sunset. At the same time, income for electricity distributors from households with PV has decreased by about $AU 414 million as of 2014. Network service providers raise this revenue by increasing their prices under the Australian regulatory framework. Similar mechanism also affects the wholesale price of electricity in Australia.

The effect of the rapid increase in PV penetration has a number of effects:

- The centrally dispatched model faces a serious competitive threat. As demand for grid electricity drops, prices are raised and this leads to further decrease in demand. Regulatory policy, market structures and tariffs will have a major impact on the viability of the centrally dispatched model in future.
- Due to the rise of household PV there are increasing debates about tariff structures. Existing tariff structures lead to higher costs for non PV households as utilities increase network charges to raise the lost revenue.
- Australia's regulatory framework was developed at a time before distributed generation was widespread. This framework will need to evolve to accommodate a rapidly growing industry.

The Australia experience demonstrates the adverse impacts if effective renewable integration methods are not utilised. It demonstrates some of the adverse effects of renewable energy penetration when effective market structures are not in place. Due to tariff structures which were implemented prior to widespread use of renewables, there are adverse impacts on utilities as well as customers. This example also demonstrates the importance of regulatory framework in overall grid integration methodologies.

10 Conclusions

The grid integration of renewable energy systems faces significant challenges with the increased presence of intermittent renewable power generation in the power grid. It is of vital importance to have a favourable technical and regulatory framework that can effectively manage the short term and long term challenges of large scale renewable power penetration. The growths of renewables are limited in some parts of the world due to the short term problems that should be mitigated in order to achieve long term objectives of smart grids. There are grid codes and standards for integrating renewable power generation into a power grid. However, their maturity and periodic upgrade are important to plan and operate the future grid. Increased presence of intermittent renewable power generation also stresses the reserve margins of the power grid in order to limit the operational impacts. Thus, the integration of renewables into a power grid that is moving to be a smart grid is a multi-dimensional problem that needs robust and economic solutions for meeting long term objectives of smart operation of a power system.

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Technical Challenges, Security and Risk in Grid Integration of Renewable Energy

Duong Quoc Hung, Md Rakibuzzaman Shah and N. Mithulananthan

Abstract Renewable energy sources, especially wind and solar photovoltaic (PV) are well on the way to dominate power systems as their penetration levels are increasing at a staggering rate in many countries. Consequently, utilities around the world are discussing and conducting feasibility studies of "100 %" renewable energy based power systems. Even though a very high penetration level of renewable energy looks plausible, the technical challenges associated with them could be a hindrance to the seamless integration. This chapter focuses on technical challenges associated with the grid integration of renewable energy and they are classified as challenges in the distribution and transmission systems, respectively. Most of the PV integration is happening in the distribution system while wind integration can also be in the transmission system. This chapter also highlights security concerns and associated risks, which are categorized as technical and non-technical issues. Finally, the chapter summarizes the way forward for the renewable energy integration in power systems.

Keywords Grid integrated PV · Grid integrated wind · Intermittency · Offshore wind · Power quality · Stability issues

1 Renewable Energy Growth

Extracting energy from inexhaustible natural resources with no or minimum ecological impact would lead to a sustainable energy future. Two of the natural resources that have received worldwide attention in terms of popularity and investment growth are wind and solar. These two technologies have been experiencing a remarkable growth during the recent past. Figure 1 shows the global

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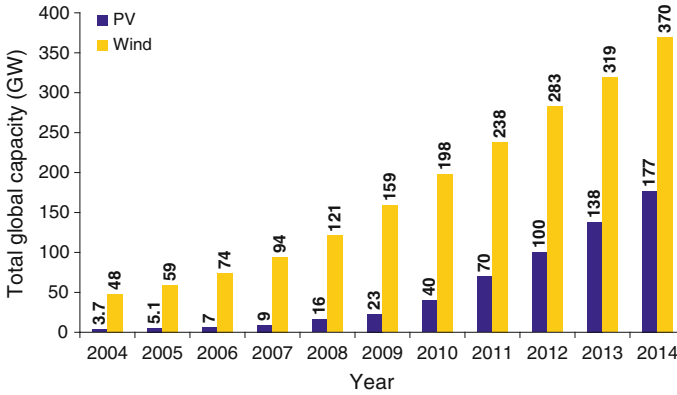
Fig. 1 Solar PV and wind global power capacity, 2004–2014 (Renewables global status report 2015)

installed capacities of solar photovoltaic (PV) and wind over the last 11 years. These figures were just over 370 and 177 GW, respectively at the end of 2014. Another observation is that the ratio of the wind to PV installed capacity has reduced from 13.7 in 2004 to around 2 in 2014, indicating that the grid-connected PV grew faster. Given this trend, it is expected that the amount of PV would exceed that of wind in coming years.

The fact is that not only are renewable sources helpful in mitigating global warming as well as green house gas emission, they are also readily available for an area affected by war, natural disaster and epidemic deceases. Though wind and solar resources would not lead to any disputes in claiming ownership among countries and available to all the countries, the technologies used to harness energy, especially electricity should be understood better. The technology referred to as renewable energy is completely different from the majority of conventional technology that is used to generate electrical energy from fossil fuels. One of such conventional technology called synchronous machines comes with so-called inertia, which is rather helpful in balancing energy by releasing or absorbing whenever there are changes in the energy consumptions from consumers. In contrast, for renewable energy the degree of uncertainties are generated from the supply as well as consumer sides. These uncertainties combined with the deficits in technology that have been used to harness energy make the grid integration of renewable energy resources more challenging. Some of the technical challenges would lead to fundamental changes in power system structures and business models, if there is an increasing amount of renewable energy resources integrated into power systems.

The recent success of several countries such as Norway, Denmark, Portugal, Italy, Spain and Germany, United Sates and Australia in accommodating large amounts of renewable energy have motivated power utilities to consider enabling higher renewable penetration levels in their power systems, possibly "100 %" of energy generation from renewables. It is noted that the penetration of renewable

energy depends heavily on technologies adopted. In Norway, renewable energy is predominately generated from hydro sources and only an insignificant amount comes from wind and solar. This would make the operation of the system relatively easy, as there are large amounts of inertia and spinning reserve. On the other hand, the greatest proportion of renewable energy is generated from wind in Denmark and Spain, and solar PV in Germany and Italy. In Australia, the grid-connected PV has been unprecedentedly growing in the last few years, and it reached a total installed capacity over 4.1 GW at the end of 2014. Although most PV installations are based on small-scale rooftop arrangements, utility-scale solar farms are being installed all over the world in the range of 200–500 MW. Wind farms are already in their large-scale with a single turbine capacity ranged from 10 to 15 MW. Figure 2a, b shows ten top countries with PV and wind energy integration until 2014. In most countries, as power systems accommodate high renewable penetration, a possibility
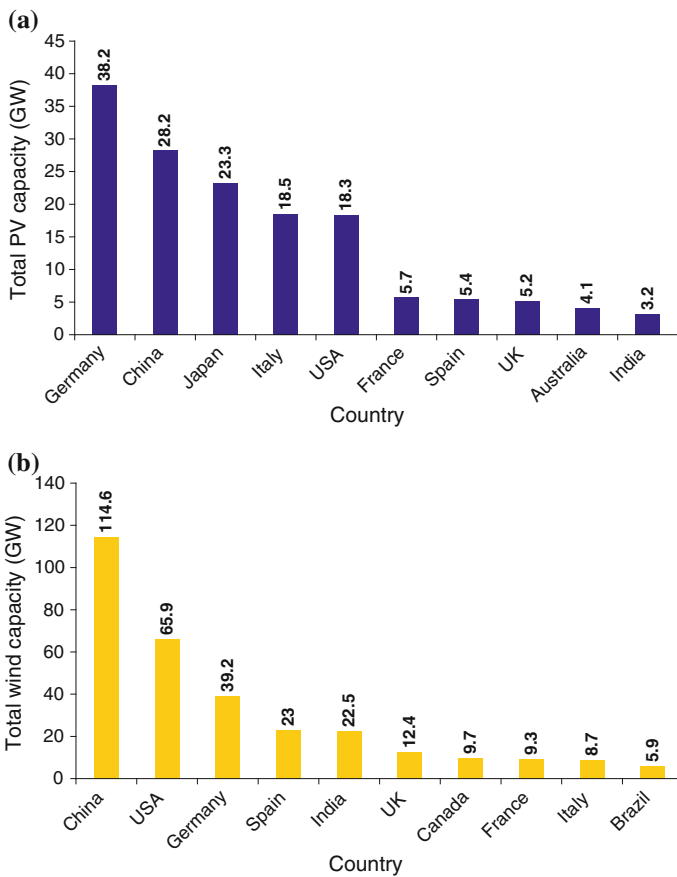

Fig. 2 Renewables capacity, top 10 countries until 2014: **a** solar PV and **b** wind (Renewables global status report 2015)

of technical challenges would occur. A typical example of such problems is that in South Australia wind technology has dominated the frequency control of the power system. The key question is that can a power system accommodate 100 % of energy generation from renewables? This chapter makes an attempt to identify a wide range of challenges, security and risk associated with renewable energy in a power system.

The rest of the chapter is organized as follows: Sect. 2 presents key technical challenges in the distribution systems that are demonstrated through some practical examples. Challenges in the grid integration of large-scale renewable energy plants in the transmission system are covered in Sect. 3, along with some case studies depicting the real threat that could be imposed on planning and operations. Overall security and risk associated with renewable energy integrated power systems are discussed in Sect. 4. Section 5 concludes the chapter by summarizing major blockades in increasing the penetration of renewable energy and the way forward.

2 Challenges in Distribution Systems

In the absence of distributed generation (DG) units, a distribution network is considered as passive one, which has a unidirectional power flow from the source to loads. In the presence of DG units such as biomass, wind and solar photovoltaic (PV) power plants, especially at high DG penetration, the passive network becomes an active one that has a bidirectional power flow, which happens between the load side and the substation. Figure 3 shows a typical example of the structures of
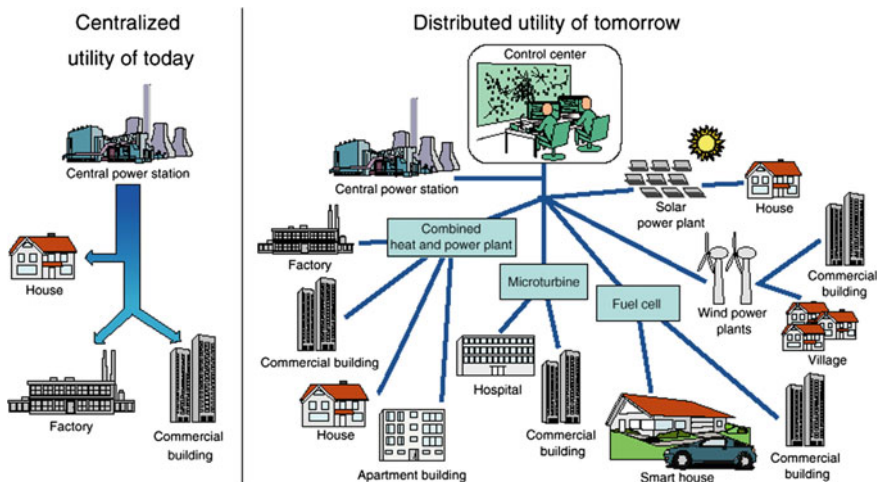
Fig. 3 Passive power system (*left*) versus active power system (*right*) (*Source* ABB 2002)

passive and active systems. In the former, the customers such as houses, factories and commercial buildings consume the energy from the central power station. On the other hand, in the latter, they import the energy either from the central power station or from DG units such as combined heat and power, wind power and solar power plants, which are located close to loads.

From the utility perspective, the benefits associated with the active network are that DG units, e.g., solar PV units located close to distribution system loads can lead to reliable power flow and loss reductions, voltage profile and loadability enhancement, network upgrade deferral, etc. However, the high penetration of renewable DG units together with their intermittency and variability has created a variety of challenges to the distribution system.

2.1 Change in Standard Load Patterns

The widespread adoption of domestic rooftop PV solar panels in the distribution system can lead to a characteristic change in the standard load curve. This change is most apparent during the middle of the day when the sun's radiance is at its highest and causes a significant load reduction. For instance, Fig. 4 shows PV impacts on a practical (Currimundi, Sunshine Coast, Queensland) feeder load profiles on the Energex network, where the drop in demand during the middle of the day has arisen from an increasing PV capacity on the feeder (Energex Limited 2013). The day load has dropped below the night-time trough; however, the night peak load requirement remains unchanged.
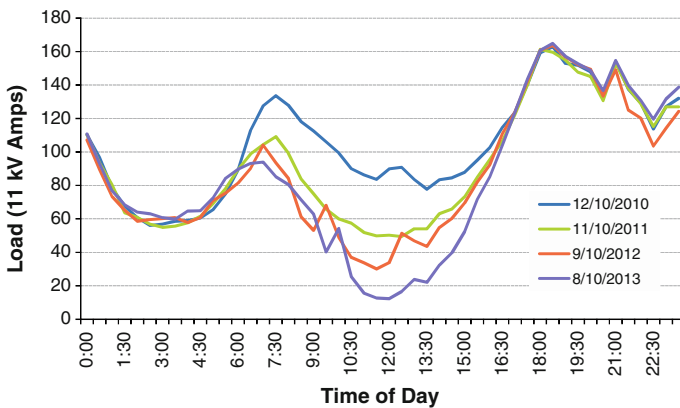

Fig. 4 PV impacts on a Currimundi feeder load profiles on the Energex network (Energex Limited 2013)

2.2 Intermittency of Generation

Although solar energy is redundant and inexhaustible, it is weather-dependent, intermittent and unavailable during the night. Figures 5 and 6 show the instantaneous power outputs of the PV solar system with a combined capacity over 1.2 MW at St Lucia Campus, Queensland, Australia, on November 4, of years 2011, 2012, 2013 and 2014. As shown in the figures, the intermittency of PV generation due to moving clouds frequently experienced, even within an extremely short time period during the day. It is also interesting to note that November 4 was a highly intermittent day for solar PV panels with instantaneous power varying quite significantly from 1.1 to 0.25 MW during the last 4 years. The changes were roughly 0.75 MW
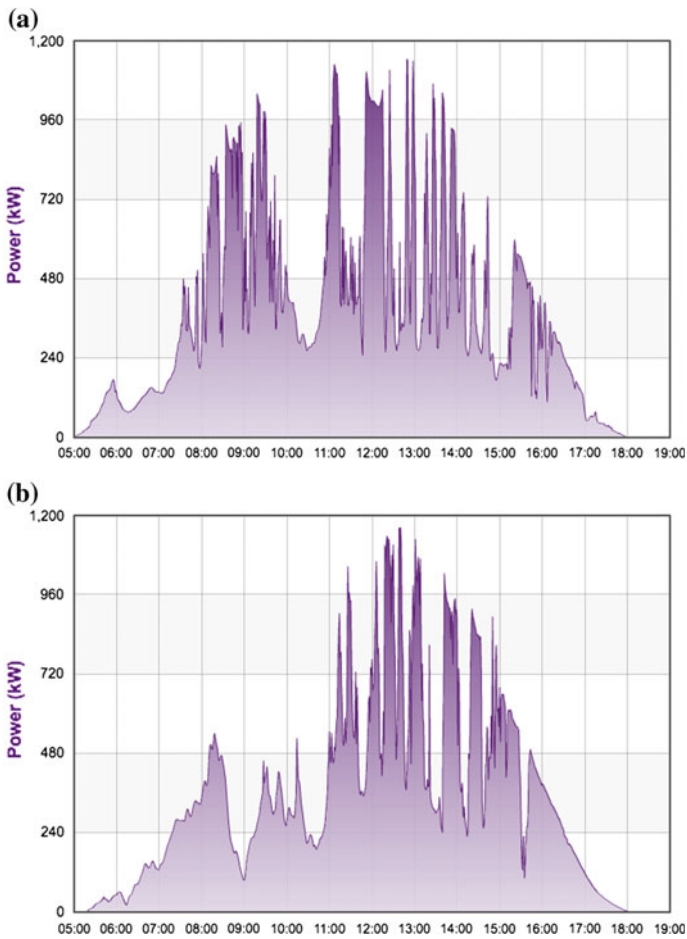
Fig. 5 The instantaneous power outputs from combined solar PV panels at St Lucia campus, the University of Queensland, Australia on November 4 of years: **a** 2011 and **b** 2012
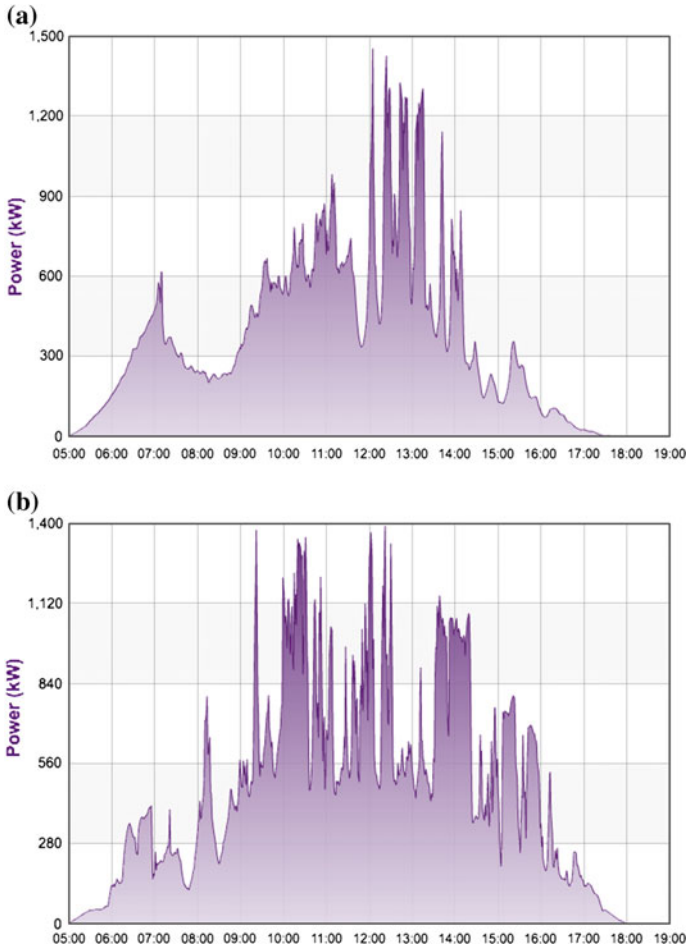
Fig. 6 The instantaneous power outputs from combined solar PV panels at St Lucia campus, the University of Queensland, Australia on November 4 of years: **a** 2013 and **b** 2014

within a minute interval. This could be severe for a rural system where a possibility of voltage control is limited. However, as the distribution system at St Lucia Campus was a suburban network with a total load of 25 MW, which was considerably larger than the PV system capacity, the intermittency did not lead to any noticeable voltage violations. If the total amount of loads is no larger than the PV capacity, the direction and magnitude of power flows on distribution feeders can fluctuate significantly. Such fluctuations might result in low system stability and poor power quality. Although used as a viable solution to eliminate PV intermittency, battery energy storage is limited in terms of high investment costs.

2.3   Reverse Power Flow

The power flow in the distribution system is traditionally unidirectional from the medium voltage (MV) to low voltage (LV) networks. However, when the total amount of PV generation is larger than that of load demand, reverse power flows occur on the feeders, flowing from the LV to MV sides. The reverse power flows may also lead to complexity in setting and operations of voltage control devices such as switched capacitors; automatic voltage regulators and on-load tap changers. In some circumstances, modifications of existing protection schemes together with a possibility of extra equipment may be required, as most of the distribution system components are normally not designed to coordinate with bidirectional power flows that are caused by a large amount of PV generation. Energex, a distribution power utility in Queensland, Australia has reported that the growing solar PV system installation on the Currimundi feeder has resulted in reverse power flows (Swanston 2014). No adverse effects on the protection systems at substations have been recorded. However, the increasing swing from the minimum to peak load and the inherently intermittent power supply of solar PV panels has caused unexpected issues associated with voltage regulation on power distribution feeders with high solar PV penetration.

2.4   Voltage Rise

Depending on the capacity, the generation of PV can reduce the stress on the distribution system and enhance its performances such as power losses and voltage profiles (Yeh et al. 2012; Hung et al. 2014). However, the high penetration of intermittent PV sources at the distribution system level has adverse impacts on power quality, especially the voltage rise which normally occurs due to reverse power flow when the generation of PV exceeds the local demand (Katiraei and Aguero 2011). This issue has been one of the major concerns at Australian distribution utilities. For example, Essential Energy and Endeavour Energy reported frequent occurrences of PV inverter tripping due to voltage rises in their residential systems (Noone 2013). Similarly, the voltage at PV connection points was regularly over the upper limit of 263 V in Ausgrid's residential systems (Noone 2013). Moreover, the problems associated with surplus PV generation may include feeder overloads and high power losses.

2.5   Reactive Power Support

Under the recommendation of the current standard IEEE 1547, most of the DG units are normally designed to operate at unity power factor (IEEE 1547 2003).

Consequently, the inadequacy of reactive power support for voltage regulation may exist in distribution networks, given a high DG penetration level. Conventional devices such as switchable capacitors, voltage regulators and tap changers are actually employed for automatic voltage regulation, but they are not fast enough to compensate for transient events (Yeh et al. 2012; Turitsyn et al. 2011). It is likely that the shortage of reactive power support may be an immediate concern at the distribution system level in the future. On the other hand, depending on time and weather variability, the simultaneous occurrence of excess intermittent renewable generation (i.e., wind and solar PV) and low demand would lead to loss of voltage regulation along with unexpected voltage-rise on distribution feeders due to reverse power flows (Thomson and Infield 2007).

2.6 Power Quality Concerns

Power quality issues, especially harmonic distortion in distribution networks are one of the major concerns of power utilities. Such distortion is a serious power quality problem that may occur due to the use of power inverters, which convert DC to AC currents. The produced harmonics can result in parallel and series resonances, overheating in capacitor banks and power transformers, and mis-operation of protection devices (Farhoodnea et al. 2012). The widespread usage of inverters to interface between solar PV panels and the power grid principally can produce harmonic currents, thus increasing the total harmonic distortion in the form of voltages and currents at the point of common coupling (ElNozahy and Salama 2013). The fact is that voltage harmonics are normally within limits if the network is stiff enough with low equivalent series impedance, whereas current harmonics are produced by high pulse power electronic inverters and usually appears at high orders with small magnitudes (Quezada et al. 2006; Katiraei and Dignard-Bailey 2009). The problem associated with higher-order current harmonics is that they may trigger resonance in the system at high frequencies. Another power quality issue is that the inter-harmonics appearing at low harmonic range below the 13th harmonic may interact with loads in the vicinity of the inverter (Infield et al. 2004). Even harmonics, especially the second harmonics can probably add to the unwanted negative sequence currents that affect three phase loads (Farret and Simoes 2006). In addition, variations in solar irradiation can cause power fluctuations and poor power quality. A study in Chidurala et al. (2013) has showed that a high penetration level of PV in a 4.16 kV distribution network has negative impacts on system operations, including unbalanced voltages, voltage rise, harmonics, flicker, sags, and swells. However, at a higher voltage level, such an issue may not be severe. For instance, the National Renewable Energy Laboratory has reported that all power quality issues, namely harmonics, flicker, sags, and swells have been maintained within the acceptable range with a minimal negative impact on distribution operations and utility customers, when a 12 kV distribution network was accommodating a PV penetration level of greater than 15 % (Bank et al. 2013).

2.7 Distribution System Stability

With the integration of renewable energy, especially based on inverters and other small scales with synchronous or asynchronous machines, distribution systems could be probably considered as small power systems with rich dynamics and complexities. The dynamics of the technologies combined with the intermittent nature of the output of generation could lead to a number of instability problems, including static and dynamic voltages and modal interactions that may lead to resonances. The primary reason for voltage instability in transmission systems is normally considered as lack of reactive power support. In a distribution system, voltage instability could be possibly affected by both real and reactive power imbalance, as its resistance to reactance ratio is quite high. A study in (Yaghoobi et al. 2014) has reported that static voltage stability in a distribution system, which is typically evaluated by loadability, can improve as a result of rooftop PV integration in the system. However, if PV units are unevenly distributed among phases, a more unbalanced three-phase condition in a distribution system may occur. This could lead to poor loadability and less static voltage stability margins.

Dynamic voltage stability, which is defined as the system's ability to maintain acceptable voltages following an event or a change in system conditions such as faults, could be severely affected by rooftop PV units. In a PV integrated distribution system, due to passing clouds or faults in the system and the consequent tripping of PV units, voltages can drop below a given lower limit. If there is no voltage control mechanism in the network, induction motors connected to it can stall. Moreover, a sudden absence of real power coupled with reactive power imbalance could lead to dynamic voltage collapse (Yaghoobi et al. 2015). Another stability issue that has attracted great attention in the recent past in distribution systems is called small signal stability. When a distribution system is purely a passive system, the issue of small signal stability may not be a concern. However, with the integration of renewable generation through power electronic interfaces and their associated controllers, the stability of the system operating point when subjected to small disturbances became a major concern. With an increase in a number of dynamical elements (including generating units and dynamical loads such as induction motors and air conditioners) in the close proximity oscillation of systems' state variables have been reported. If there is lack of damping on those weak modes, they could result in oscillatory unstable situations in distribution systems, thus leading to partial blackouts or brownouts (Dahal et al. 2012). It was reported that when the unbalanced condition in a distribution system increases, the small signal stability in the system could be severely impacted (Nasr-Azadani et al. 2014).

2.8 Other Concerns

Integrating renewable energy in three-phase distribution systems can also develop acute phase imbalance as a majority of PV sources are connected in the form of a single-phase units. The phase imbalance could lead to unbalanced voltage profiles among phases and shift the neutral point voltage to an unacceptable and unsafe value. A severe phase imbalance due to PV integration, exceeding 6 % was reported in Freiburg, Germany while the utility standard is to keep the unbalanced condition within 2.5 %. An unbalanced three-phase condition could also influence various instability problems as discussed in Sect. 2.7 and lead to higher network losses. This loss, in general, is a concern in distribution systems with high penetration of renewable energy—even the systems are operated in balanced conditions. As the penetration of PV increases, reverse power flows from the load side to the sub-station may occur, thus resulting in a higher network energy loss. Such a loss may become very high when compared to those in distribution systems without any renewable energy generation. Another concern is that the electromagnetic interference of high switching frequency of PV inverters with other circuit elements such as converters, DC links, protecting devices and capacitor banks may lead to malfunctions of those devices.

3 Challenges in Transmission Systems

A large number of large-scale renewable projects are under construction around the world (Adeuyi et al. 2013) for a possible connection to the transmission system. Current transmission level Renewable Power Plants (RPPs) are mainly located onshore and connected at 132 kV voltage level of the transmission grid (WECC 2010). Due to the large potential of offshore wind resources around the world, a further development of offshore wind can be seen in the next 10 years, especially in continental Europe and North Sea countries. The huge potential of wind resources will be connected to the transmission network by high voltage DC (HVDC) due to the constraints involved in high voltage AC (HVAC) transmission. The increment of renewable resources in a power grid will eventually displaced the conventional generator in the system which may lead to the new paradigm of operation for transmission grids. Some of the challenges in terms of transmission system security of operation with high penetration of RPPs are briefly discussed in this chapter.

3.1 Voltage Stability

It is believed that due to the distinct characteristics of RPPs (the controllers involved) and current grid regulation, the voltage stability of the system can be

significantly affected by high RPPs penetration. The effect of high RPPs penetration on the voltage magnitude and stability of the transmission and sub-transmission systems has been studied in the literature by using both deterministic and time series analyses (Shah et al. 2012; Vittal et al. 2010). The impact of RPPs on voltage stability of real power systems such as Irish system has been analysed (Vittal et al. 2010) using real wind data to find out the possible adverse effect and the solution of the voltage instability problem that may be incurred. Due to the displacement of conventional generators and the limited reactive power capability of some of the RPPs, a reduction of voltage stability margins of both long and short-terms is anticipated in the system. Operating RPPs in extended reactive power limit or siting dynamic STATCOM on the RPP site is recommended to solve his problem (WECC 2010).

3.2 Rotor Angle Stability

A number of researches have devoted to revealing the impact of RPPs (i.e., large-scale wind and solar on power plants) on power system large-disturbance rotor angle stability. Many of the works reveal the reduction of system inertia due to the displacement of conventional generators by RPPs is the main reason for reduction of system rotor angle stability margins. The authors of Vittal et al. (2012) have analyzed the impact of reactive power control methodology on converter based RPPs and revealed that the reactive power control employed in converter control of RPPs can directly influence the large-disturbance rotor angle stability of the system.

Recently, there is an increasing interest to analyse the impact of large-scale RPPs on power system small-disturbance rotor angle stability. Although the mechanical dynamics of some RPPs (i.e., full converter wind, PV, DFIG) are completely decoupled from the power grid, however, there are primarily four mechanisms by which they can affect the critical modes of the system:

M 1. Impacting the major path flow, thereby affecting the electromagnetic torque of the system.
M 2. Re-dispatching synchronous machine with and without PSS.
M 3. Dispatching the synchronous generator with PSS.
M 4. Controller interacting with the damping torque.

The detailed studies on inverter based generation impacts on small-disturbance rotor angle stability have been presented in Quintero et al. (2014). This work has emphasized to explore the forth mechanism by which PV and other converter control generators affect the small-disturbance rotor angle stability of the system. Three test cases for the years of 2010, 2020, and 2022 of Western Electrical Coordinating Council (WECC) were used for this analysis. It has been identified from the simulation that there is relatively low interaction between converter control generators and synchronous generators in inter-area modes. Generally,

Fig. 7 Matrix of grid operating condition (Mithulananthan et al. 2014)
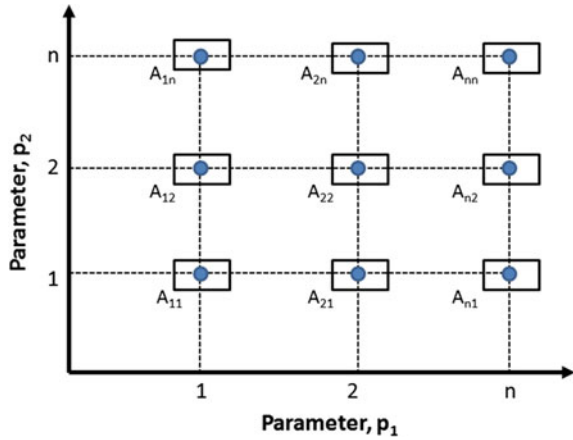
reactive power control gain and voltage control integral gain are participating in the interaction. This research has also identified two new types of low-frequency modes associated with converter control generators and some of which have very poor damping. Between two newly emerging modes, one is exclusively dominated by converter-controlled generators and the other is originated due to the interaction between synchronous generators and converter-controlled generators in the system. A number of methods have been proposed by both power industry and academia to evaluate this issue such as designing active and reactive power modulation based on power system damping controllers, similar to Flexible Alternative Current Transmission (FACT) controllers. Moreover, system operational planning adjustment (switching reactive power control) has also been proposed by some researchers to address the issue (Vittal et al. 2012; Mithulananthan et al. 2014). The underlying idea of reactive power management proposed in Mithulananthan et al. (2014) is based on the theoretical view of structured singular value (SSV). The fundamental idea behind this approach is to control the robustness measure (μ) by a varying reactive power control scheme of each renewable generation cluster with underlying uncertainties in the system. System loads (ρ_1) and renewable generation variations (ρ_2) are considered as the underlying uncertainties for the process as shown in Fig. 7.

3.3 Frequency Stability

With the high penetration of RPPs, a significant number of synchronous generators in the system would be replaced by RPPs and resulting in the reduction system inertia. The high penetration of zero inertia generators such as PV and full converter

wind turbines, the conventional generators that co-existing with these generators will be forced to provide torque and inertia to mitigate any instability events, which could lead to the frequency instability problem. The incident in Electricity Reliability Council of Texas (ERCOT) system on Feb. 26, 2008 is an excellent example of such a situation (Ela and Kirby 2008), where the unexpected loss of some synchronous generators with wind generator ramp down and load ramp-up led to a decline in system frequency. It is believed that high penetration of zero inertia generators such as PV with a higher ramp rate could adversely affect the frequency stability of the system. Similar findings have been obtained in Yan et al. (2015), where the impact of high penetration of solar and wind on the frequency stability of the South Australian power system was assessed. The analysis in Yan et al. (2015) shows that the low inertia and secondary voltage tripping of solar PV can create a serious frequency stability issue in a power system in a area like the South Australian power system with high penetration of RPPs. A number of studies have proposed artificial inertia emulation to mimic the RPPs same as conventional generators. Moreover, coordinated controls of battery energy storage with RPPs have also been proposed to solve this issue.

3.4 Critical Ancillary Service Planning

The power system relies on primary, secondary and tertiary responses to regulate the imbalance between generation and loads when sudden contingencies occur in the system. Traditionally, synchronous generators associated controls are used to provide such regulation. Over the years synchronous generator inertial response has been used to limit the rate of change of frequency. However, RPPs have very limited inertial regulation capability. Moreover, RPPs that are operating at their maximum available power do not participate in frequency regulation. Due to current grid practice in Europe, most of the wind turbine manufacturers have added frequency response capabilities in their designed systems (Junyent-Ferre et al. 2015), which make the wind turbine to operate below their maximum loading level. However, the recent offshore grid development (wind turbines are mostly connected by HVDC links) makes the frequency response planning more difficult. HVDC systems make the wind power plants completely decoupled from the rest of the onshore AC system. Hence, offshore wind power plants are unaware of the frequency deviations in the main grid. A number of inertia emulation methods both communication and communication free has been proposed. Additionally, the communication-based method has a short coming in terms of signal latency and loss of communication. Therefore, alternative methods using HVDC link DC voltage and frequency modulation are illustrated in Nanou et al. (2015) to make the offshore wind turbine actively participate in frequency responses.
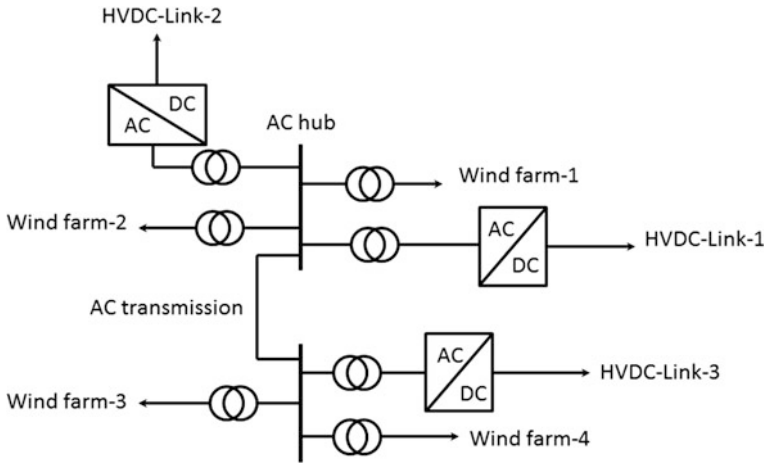
Fig. 8 Proposed offshore AC grid model (Stevens and Rogers 2013)

3.5 Offshore Grid Operation

With the increment of offshore wind there is a possibility of having an offshore AC grid with grid forming VSC-HVDC only as depicted in Fig. 8. Controlling such a grid without physical inertia would be a challenge for system operators. Control and power sharing among the grid forming converters may lead to the AC-DC dynamic interaction into the system. A number of power management schemes both communications based and communication free have been proposed to manage this issue. Moreover, issues such as fault-ride-through (FRT) for an offshore grid with wind power need to be assessed. Currently, there is no such a grid code for offshore grid FRT responses for wind power plants. Furthermore, previous research has proposed low frequency or variable frequency operation of offshore grids. However, currently most of the electrical devices used in offshore were built for standard constant frequency operation (50 or 60 Hz). Therefore, new standardized operational procedure needs to be assessed.

4 Security and Risk

Grid integration of renewable resources can significantly improve energy security of power systems as primary sources are diversified and renewable energy resources are available locally. However, a very high penetration level of renewable energy in power grids can bring operational security concerns and risks. Moreover, a very high penetration level is only possible for large-scale plants (wind and solar farms in the range of hundreds of megawatts), which are going to be located far away

from potential load centers. This can bring additional security concerns in the form of reliable transmission and distribution systems. As discussed in Sects. 2 and 3, there are a number of technical challenges associated with grid integration of renewable energy in both distribution and transmission systems. These challenges are primarily associated with the intermittent nature and the technologies used for harnessing energy from renewable sources. The challenges can lead to a variety of instability and operational security problems, covering voltages, angles and frequency, due to lack of reactive and real power (inertia) support.

The risk related to system security with wind and PV technologies has been assessed in a number of studies (Preece and Milanovic 2015; Shah et al. 2015). To prepare for the high penetration of RPPs in both transmission and distribution systems, power system operators should thoroughly explore the subsequent risk associated with power system static and dynamic operations. Power system operators should regularly perform security analyses to ensure that the network does not operate beyond the acceptable limits of operation. These limits could comprise of a wide variety of facets such as line overloads, voltage limit excursions, voltage stability, etc. (Preece and Milanovic 2015; Shah et al. 2015). However, it is equally important to evaluate the mid and long-term security of a power system before commissioning variable generators such as wind and solar PV to the system. Risk assessments are recognized as a complementary power system planning criterion (Shah et al. 2015). However, the most prevailing risk assessment techniques considered for choosing the planning substitutes are related to system reliability analyses. These analyses do not comprise the mid or long-term static and dynamic security risk of a system. With this in consideration, Preece and Milanovic (2015), Shah et al. (2015) have proposed a risk-based static and dynamic security assessment criterion for the transmission and distribution systems. Moreover, Shah et al. (2015) has proposed a time series-based risk assessment method for efficiently preserving the temporal information associated with renewable generation and loads of the system. The methodology proposed in Shah et al. (2015) is the extended form of time series analysis method. A clustering based scenario reduction technique is used to utilise the data efficiently by preserving the temporal information. The proposed risk assessment procedure can be summarised as

(a) Establish the multiple operating conditions of the system.
(b) Simulate a large number of operating scenarios and perform deterministic studies on these samples to evaluate the performance indices.
(c) Determine the PDF of the performance indices using Kernel density estimation.
(d) Select the severity measures and use this to quantify the corresponding risk indices.

A number of composite risk indices as depicted in Fig. 9 have been used to address the static and dynamic security of the system. The threshold values for the performance indices are given in Table 1.

In terms of other types of non-technical risks, early stages of renewable energy integration projects could face financial risks (Managing the risk in renewable
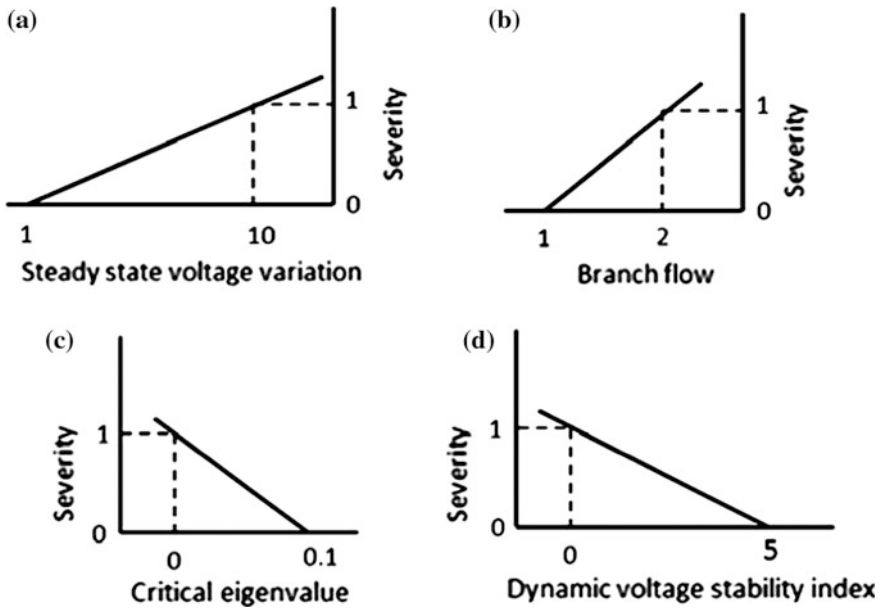
Fig. 9 Continuous severity functions for risk assessment (Shah et al. 2015). **a** Steady-state voltage. **b** Line flow. **c** Static voltage stability. **d** Dynamic voltage stability

Table 1 Threshold values of different severity functions (Shah et al. 2015)

Severity function	Lower threshold	Upper threshold
Steady state voltage variation index	1	10
Branch flow index	1	2
Static voltage stability index	0.1	0
Dynamic voltage stability index	5	0

energy 2011). As a number of companies have expanded their investment portfolio on renewable energy integration projects, securing funds could be a major challenge. A diminishing macroeconomic climate and doubts over national commitments to address climate change and global warming could be the major factors affecting the financial risks. Other types of nontechnical risks identified in renewable energy projects are the risk associated with building and testing large-scale renewable energy projects, strategic or business risks, political or regulatory risks, market risks, environmental risks and weather-related risks. Building and testing risks are the risk to damage the property and facility or a third party liability situation during building and testing the renewable energy projects. Environmental risks are the risk of damaging environment as a result of large-scale renewable energy projects, which often demand huge land space given the low energy density (kWh/km^2), when compared to the conventional fossil fuel based power plants.

Risks associated with changes in public policies such as feed-in-tariff and subsidy affecting the profitability of renewable energy business is categorized as a political or regulatory risk.

5 Summary

Renewable energy is growing fast in many parts of the world. The recent successes in many countries in the seamless integration of wind and solar PV have motivated researchers and engineers to think towards "100 %" renewable power systems. To achieve such an ambitious target, the challenges associated with the grid integration of renewable technologies should be fully understood and technically and economically feasible smart solutions should be prepared. One of the major concerns about renewable energy technologies is the uncertainty and the seasonal variation of output power. The variation and uncertainty of the supply side combined with variations that already exist in the demand side could be quite challenging for operational planning of power systems. At this stage of renewable energy development, the problems of variability and uncertainties are tackled using innovative demand side response programs and small-scale energy storage options. However, when the penetration grows higher, large-scale energy storage options would become inevitable.

Another key concern about renewable energy is the technologies used to harness the energy from the nature and appropriate transmission technologies to bring the bulk renewable energy to load centers. Solar PV has been integrated with power electronics inverters while some technologies for wind energy have developed in the form of doubly fed and permanent magnet synchronous machines. The deficits in the majority of renewable energy technologies are the inability to provide reactive power support and no possibility of immediate energy balance due to lack of inertia. However, this problem can be rectified by utilizing a technology as a combination of asynchronous and synchronous machines and inverters, along with other technologies such as FACTS devices with innovative controls. A number of operational security concerns and associated risks can also be minimized by using suitable technologies and control strategies. Other non-technical risks, however, can be handled by various entities involved in renewable energy business as they have tools to mitigate and transfer the risks. A strong collaboration among various entities working in renewable energy integration is suggested to deal with these risks by sharing knowledge and tools.

Overall, having appropriate technologies, proper control solutions, and strong interconnections among neighboring grids would be the key to achieving a renewable energy-based power system for sustainable energy future.

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Dynamic Modelling, Simulation and Control of a Commercial Building Microgrid

Lasantha Meegahapola and Duane Robinson

Abstract Microgrids are becoming popular in commercial buildings due to the recent drive to achieve net-zero energy targets and improve energy efficiency and reliability in building installations. The commercial building microgrids depict unique characteristics due to generation mix and various types of loads connected to the commercial building installations. Therefore, the commercial building microgrids require special consideration during the operation and control stages. Dynamic models of a microgrid enable researchers to investigate their operational performance and control techniques before the control schemes are actually being implemented in the microgrid system. It is essential to develop more accurate dynamic simulation models of a microgrid in order to verify the fidelity and the effectiveness of control schemes. This chapter presents a dynamic modelling of a commercial building microgrid system and conducts a stability analysis of the microgrid under various operating conditions.

Keywords Commercial building microgrid · Dynamic modelling · Dynamic real-time simulation · Energy storage system · Load modelling solar-PV

1 Introduction

Microgrids are considered as one of the cornerstone components of Smart Grids. The microgrid is defined as an independent entity which can sustain its load demand by its own generation without depending on the external grid imports.

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119

In addition, microgrids can function autonomously while managing its generation and load demand. Microgrid systems are designed for various purposes, such as powering remote communities (typically known as remote area power supply systems (RAPS), distribution network loads and commercial buildings, universities etc.). In the last few years, commercial building sector became very much interested in microgrids due to the recent drive to achieve net-zero energy targets and improve energy efficiency and reliability in building installations. The commercial building microgrids are unique in terms of their generation portfolios and connected loads (Meegahapola et al. 2014; Marnay et al. 2008). Therefore, special emphasis must be placed on modelling, simulation and control of commercial building microgrid systems.

A number of research studies are conducted on commercial building microgrid design, control and operation. In Meegahapola et al. (2014), authors have investigated strategies for mode transfer for a commercial building microgrid from the grid-connected to the islanded mode. In addition, authors have presented a strategy to determine the size of the energy storage system and the reactive power compensation devices. In Marnay et al. (2008) authors have presented a model to optimise the equipment required for a commercial building microgrid considering operation and maintenance cost, load profiles and other techno-economic aspects. A number of studies are also conducted on optimising commercial building microgrids to improve the energy efficiency and reduce the impact on environment (Bozchalui and Sharma 2012). In addition, researchers have investigated the impact and control strategies for commercial building microgrids from electric vehicles (EVs) (Nian et al. 2015; Beer et al. 2012).

The dynamic modelling of a commercial building microgrid is of paramount importance, to determine the dynamic performance of various control strategies prior to the implementation. In particular, in order to investigate the performance of mode transition strategies, it is essential to develop accurate dynamic model of a microgrid (Meegahapola et al. 2014). In the published literature only a few studies are presented on dynamic modelling of commercial building microgrids (Meegahapola et al. 2014; Katiraei et al. 2005). Therefore, it is essential to place special emphasis on dynamic modelling of microgrid components for stability simulations and analysis.

This chapter focuses on dynamic modelling of a commercial building microgrid system for stability studies. Typically stability studies are conducted using root mean-square (RMS) simulations which have the capability to accurately capture electro-mechanical transients in a power network. This chapter outlines how each generating source and loads are modelled for dynamic simulations and finally performance of a microgrid system was analysed under various fault scenarios.

2 Commercial Building Micro Grid System Layout

The microgrid system presented in this study is derived from the microgrid system designed for the Sustainable Buildings Research Centre (SBRC) at the University of Wollongong, Australia (Meegahapola et al. 2014). The SBRC microgrid is specifically meant to contribute to the net zero energy target of the SBRC and improve practical understanding of microgrid operation, especially for commercial building installations (Collin et al. 2014).

A schematic of the SBRC microgrid model is shown in Fig. 1. The generation capacity of the SBRC microgrid is summarised in Table 1. In addition to the
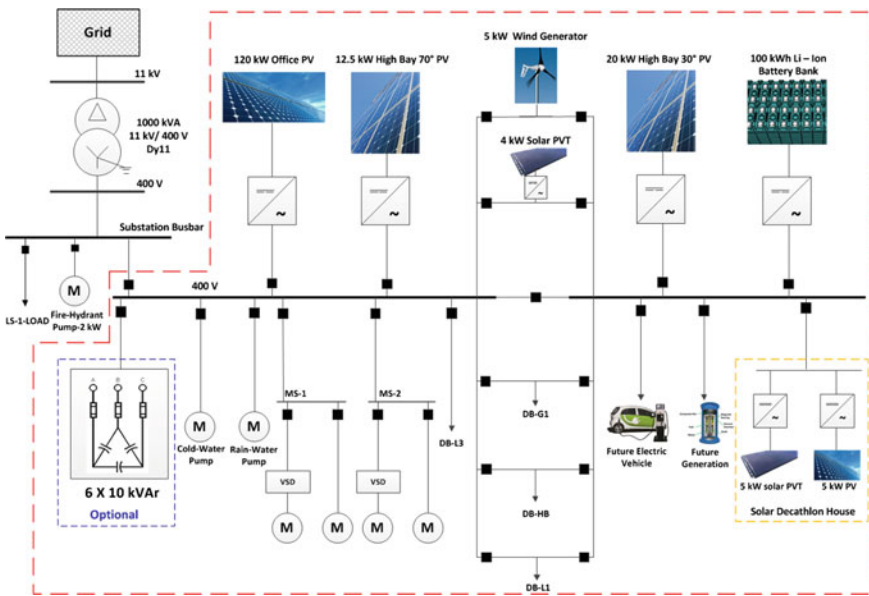
Fig. 1 Schematic of the SBRC microgrid

Table 1 Generation and storage capability of the SBRC microgrid

Generation source	Installed capacity
Office solar-PV system	120 kW
High bay 30° solar-PV system	20 kW
High bay 70° solar-PV system	12.5 kW
Office solar-PVT	4 kW
Wind generator (PMSG)	5 kW
Battery energy storage (Li-ion)	50 kW Inverter (100 kWh)
Solar-house PV system	5 kW
Solar-house PVT	5 kW
Total	**221.5 kW**

Table 2 Installed SBRC load capacities

Sub-distribution board	Installed capacity (kW)
MS-1	3.59
MS-2	65.3
DB-L1	49.1
DB-FL3	26.9
DB-HB	17.4
DB-G1	8.2
Main board (pump loads)	17.6
Total	**188.09**

installed generating sources, the existing SBRC installation has some provisions for the future generation sources and loads such as fly-wheel energy storage system and electric car. The SBRC installation has six-sub distribution boards (MS-1, MS-2, DB-L1, DB-FL-3, DB-HB, DB-G1) for the loads, in addition to the main distribution board. Two distribution boards (MS-1, MS-2) are dedicated for supplying the motor loads in the microgrid.

Approximately 50 % of the installed loads are dynamic loads such as motors; hence it is a significantly challenging task to maintain the microgrid stability under the mode transition from the grid connected to the islanded mode and during the faults. The installed load capacity at each distribution board is given in Table 2.

The installed variable-speed drive (VSD) and direct online (DOL) based motor load capacities are given in the Appendix-A. The complex load model given in DIgSILENT power factory has been employed to represent the other loads in the SBRC microgrid. The load parameters given in Collin et al. (2014) have been adopted for each load type to represent their dynamic behaviour. It must be noted that the final installed generation and load capacity of the SBRC microgrid is different from the assumed capacity at the planning stage capacities given in Meegahapola et al. (2014). Sizing of the microgrid Energy Storage System and Capacitor Bank is presented in Sect. 3. In addition, modelling description with regard to each generation source and loads are given in Sect. 4.

3 Sizing of Micro Grid Components

This section presents the sizing methodology associated with the energy storage system, and the capacitor bank of the SBRC microgrid. To assist in the design process, field measurements of voltage, current, and active and reactive power were obtained from another commercial building located at the University of Wollongong, which contained similarly configured electrical loads and load types. The measured data has been scaled to match the design details associated with the SBRC facility; however ramp rates related to equipment operation, power factor, etc. remain unchanged. In addition, characteristics of the other dynamic loads are also considered during the modelling study.

The design philosophy of the SBRC microgrid system is primarily based on the net zero energy target of the SBRC building as part of the facility's certification requirements (McLennan 2012). The net zero energy target is achieved through appropriate sizing of the microgrid's main generation unit, which is made up of several solar-PV systems. It must be noted that the load and solar-PV generation from Solar Decathlon house was not considered for the sizing study.

3.1 Active and Reactive Power Characteristics

The load profile of the SBRC is proposed to closely match that of a similar building for which a measurement campaign was undertaken. Figure 2 illustrates the projected real and reactive power demand of the SBRC facility and microgrid when the SBRC facility is fully operational with its full capacity.

3.2 Sizing of Energy Storage System (Li-Ion Battery Bank)

Several strategies can be considered when sizing energy storage; peak demand reduction, energy harvesting to reduce export, mitigating intermittent grid outages, and standalone operation of the microgrid. Each strategy has differing demand on energy storage sizing and economic constraints. For the SBRC microgrid, standalone operation is desired for demonstration and research purposes (while still utilising the grid for reliability). Sizing energy storage for prolonged intentional islanding is not required for the SBRC, and in order to minimise the energy storage requirement (due to financial constraints), intentional islanded operation is limited to single day demonstration. During the intentional islanded period, it is expected to have load shedding procedures in place. Li-Ion batteries are the selected energy storage technology due to their high performance and material considerations associated with the building certification (Collin et al. 2014).

The expected demand profile of the SBRC is plotted against the solar-PV localized generation (inverter output) to assist in establishing energy storage requirements, as shown in Fig. 3. The localised generation is based on solar-PV design and weather data from the previous 5-years, with the minimum monthly average insolation data utilised to provide margin in energy storage requirements. The reactive power requirement is also allowed for battery sizing. From Fig. 3, it is estimated that the energy requirement from the batteries will vary from 60 to 300 kWh depending on available generation. It is anticipated that appropriate capacity will lie somewhere between these figures.

For preliminary design 100 kWh is selected as the capacity, with intentional transition to the islanded mode dependent on state-of-charge (SOC), available generation (weather forecast) and load shedding. Extending islanded mode
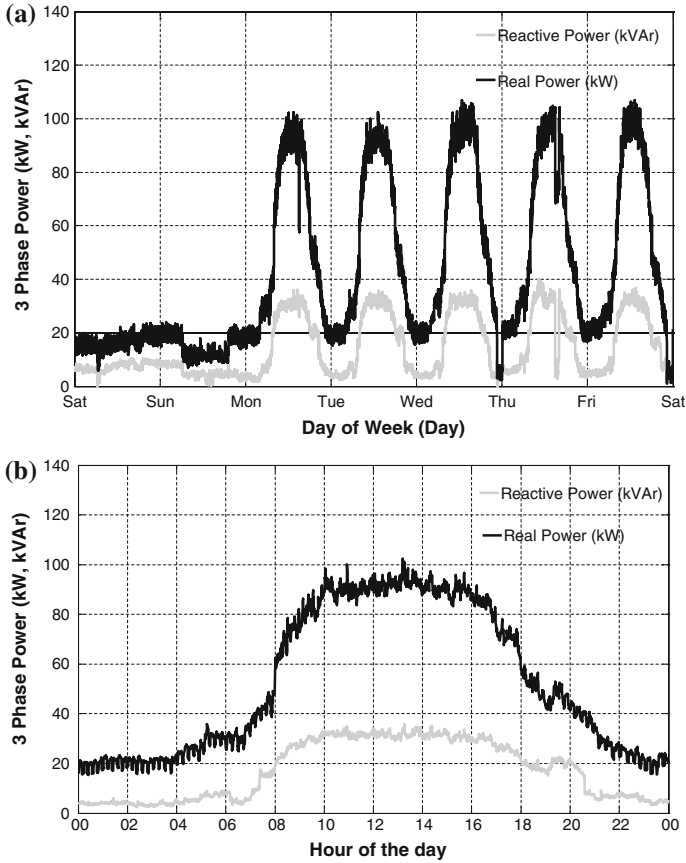
Fig. 2 Projected active and reactive power for SBRC; **a** weekly profile, **b** typical weekday profile

operation may, be made possible in the future by increasing energy storage or localised generation.

3.3 Sizing of the Capacitor Bank

To meet utility connection requirements, the reactive power demand of the SRBC facility is compensated using dynamically switched banks of power factor correction (PFC) capacitors. In order to determine the size of the PFC capacitor bank, field measurements from the example building have been utilised.

Six segmented PFC stages are selected to match typical installations at most of the commercial building locations within the university. The peak reactive power demand of the sample building is able to be delivered by the first four segments of
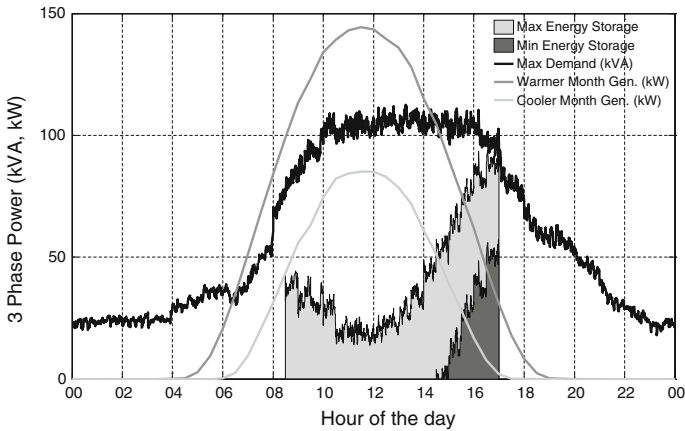
Fig. 3 Commercial building demand profile and estimated localized generation based on minimum monthly average insolation

PFC capacitors, i.e. 40 kVAr. Additional segments (i.e. 20 kVAr) are provided to deliver margin for motor start requirements of experimental equipment proposed for the SBRC (but not included in demand calculations summarized in Table 2). Figure 4 illustrates the proposed PFC switching operations and reactive power demand for a nominal day using example building data. It is proposed that the PFC capacitor control remains unaltered for both grid-connected and islanded modes. However, during islanded mode, it is necessary to provide additional reactive power demand from energy storage and/or localized generation. This requirement is included in sizing of energy storage. It must be noted that the final capacity of the PFC capacitor bank is determined when the SBRC has reached its full occupancy, and the value determined here will only be used for analytical purposes.
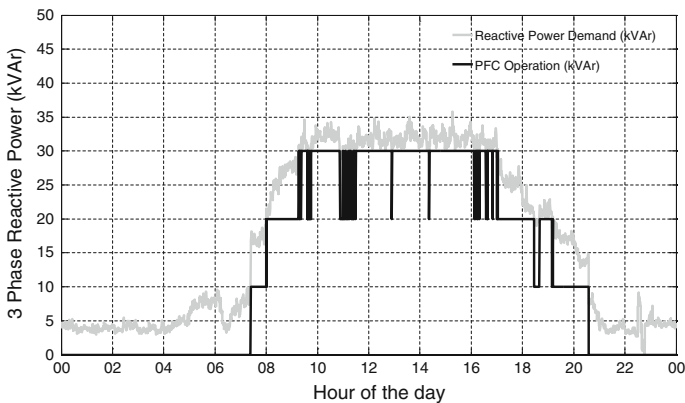
Fig. 4 Reactive power demand and PFC capacitor switching operation

4 SBRC Dynamic Simulation Model

A dynamic simulation model was developed in DIgSILENT Power Factory considering the dynamic characteristics associated with the various generators and loads connected to the SBRC microgrid. The dynamic models of various generators and loads are described in subsequent sections.

4.1 *Modelling of Solar-PV Systems*

Each solar-PV system in the SBRC microgrid is modelled as an aggregated model irrespective of number of parallel inverters connected to each system. The schematic of the dynamic simulation model of the solar-PV system is shown in Fig. 5.

The dynamic simulation model of the solar-PV system is comprised of the solar-PV array, maximum power-point tracking (MPPT) system, the DC-DC converter, three-phase voltage source inverter (VSI) and a LCL filter. The solar-PV array is represented by appropriate number of series and parallel solar-PV modules and also it has the capability to respond to the solar-irradiation and ambient temperature conditions. The solar-PV module characteristics are based on the actual solar module used at the SBRC (Datasheet 2012). The MPPT system is designed based on the incremental conductance algorithm (Hussein and Mota 1995). The LCL filter parameters (L_g, C_d, L_f) are selected based on the method outlined in Liserre et al. (2005). The DC link capacitor (C_d), input filter capacitor (C_{pv}) and DC coupling inductor (L_c) sizes were determined based on (Feng et al. 2009). The main solar-PV system was designed with the capability to control both voltage and frequency of the microgrid and its control architecture is shown in Fig. 6. The VSI was represented by an average converter model.

The active and reactive power generation from the solar PV system is calculated at the *Power Calculation* block and they are determine using real and imaginary axis voltage (u_r, u_i) and current (i_r, i_i) components as follows:

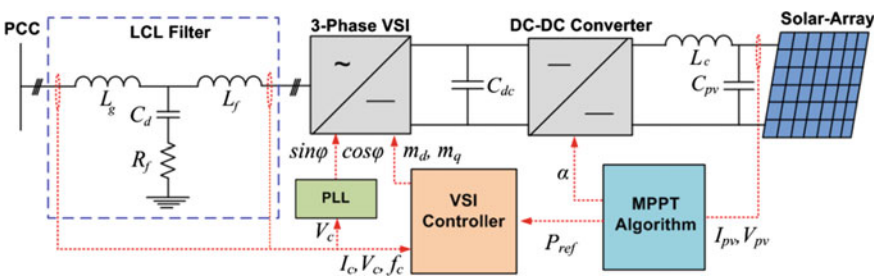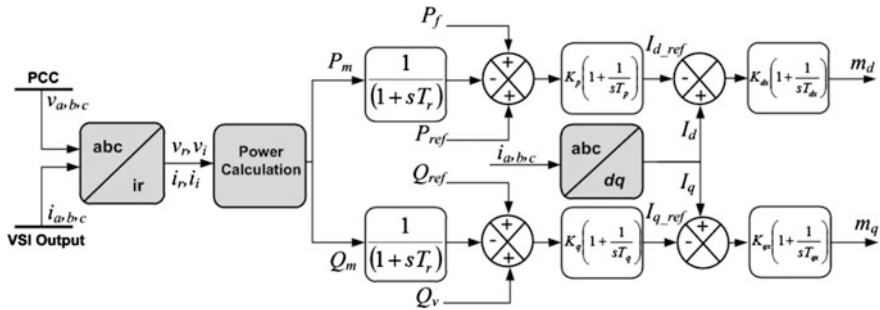**Fig. 5** Schematic diagram of the dynamic simulation model of solar-PV

Fig. 6 The solar-PV model active and reactive power control scheme

$$P_m = u_r i_r + u_i i_i; \quad Q_m = u_r i_i + u_i i_r$$

Then calculated P_m and Q_m is filtered through a low-pass filter to remove any transients. The active power reference (P_{ref}) is determined based on the available solar-PV power capacity at the MP P. In addition, the office solar-PV system (120 kW) is designed to control the microgrid frequency during the islanded operation; hence P_f is calculated based on the frequency deviation in the microgrid during the islanded operation. However, in order to use this frequency regulation functionality, the solar-PV system is operated in sub-optimal MPPT operating mode (Tan et al. 2014). The frequency regulation functionality was disabled during grid connected operation. In addition, the solar-PV system designed to control the microgrid voltage (both during the grid connected and the islanded operation), hence Q_v was calculated based on the voltage deviation at the microgrid main busbar while the Q_{ref} was made zero unless there is a specific reactive power requirement in the microgrid. Once the active and reactive power error is determined that will be processed through a PI controller to determine the *d*- and *q-axis* current references. The *d-axis* and *q-axis* current error is then processed through a PI controller in order to determine the *d*- and *q-axis* modulation indices (m_d, m_q).

The solar PVT system (4 kW) and solar house PV systems (10 kW) are also modelled similar to the models shown in Figs. 5 and 6; however they were not modelled with frequency and voltage control capability.

4.2 Modelling of Wind Generation System

A 5 kW permanent magnet synchronous generator (PMSG) based wind generator was modelled as a three-mass model (wind turbine, gearbox and shaft system and PMSG). The back to back converter system (i.e. machine-side converter (MSC) and grid-side converter (GSC)) is rated at generator capacity (i.e. 5.5 kVA) and they were represented by an average converter model. The PMSGs don't have the
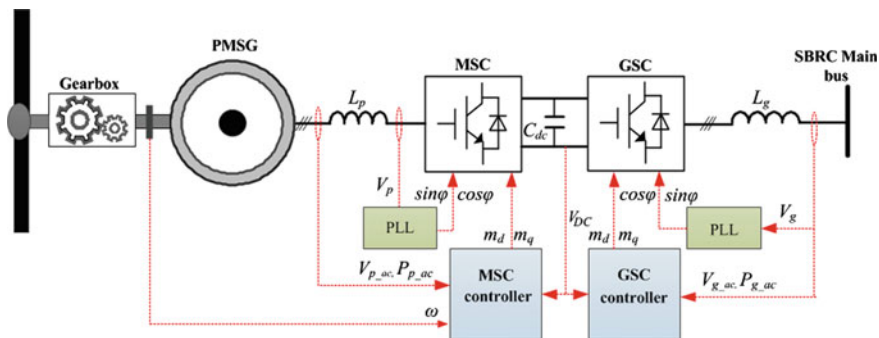
Fig. 7 Schematic diagram of the dynamic simulation model of the wind generator

capability to control both voltage and frequency and operates at unity power factor while providing maximum power to the SBRC microgrid. A schematic of the dynamic simulation model of the solar-PV system is shown in Fig. 7.

The machine-side controller (MSC) carryout the maximum power point tracking (MPPT), while the grid-side controller (GSC) facilitates the power transfer between the PMSG and grid while maintaining the DC link voltage constant. The dynamic simulation model was designed based on the modelling methodology outlined in Achilles and Pöller (2003).

4.3 Modelling of Battery Storage System

A Li-Ion battery bank was modelled with a battery model and a converter model rated at 50 kW while it has a capacity of 100 kWh. The battery energy storage system is comprised of two parallel strings, each string having 68 series connected batteries. Each battery has a capacity of 50 Ah with a full charge voltage of 14.6 V and values are based on the specification[1]. The charging characteristics are incorporated to the battery model while the active and the reactive power control capabilities are incorporated to the converter model. The three-phase VSI was represented by an average converter model. It must be noted that battery storage system is capable of controlling the microgrid voltage and frequency based on the references provided by the microgrid energy management system (see Fig. 11). A schematic of the dynamic simulation model of the battery energy storage system is shown in Fig. 8.

The charge controller determines the state-of-charge (SOC) of the Li-Ion battery bank and based on the requirements dictated by the microgrid energy management

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[1]Smart Battery: 12V 50AH Lithium ion battery data sheet. http://www.lithiumion-batteries.com.
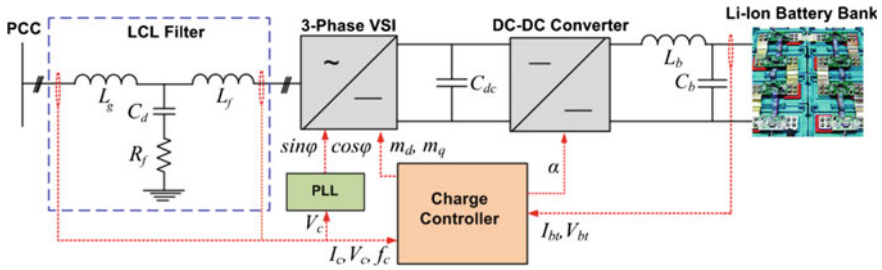
Fig. 8 Battery energy storage system

system charge controller will either charge or discharge the battery. In addition, it will maintain the DC link voltage constant by controlling the duty cycle (α) of the DC-DC boost converter. The battery energy storage system has the capability to control both voltage and frequency. The voltage control system activates when microgrid main busbar voltage decreases below 0.95 pu while the frequency control mechanism activates when the frequency decreases below 49.5 Hz. The parameters associated with the LCL filer (L_g, C_d, L_f), DC link capacitor (C_{dc}) and input filter (L_b, C_b) are determined based on the methods outlined in Sect. 4.1.

4.4 Modelling of the Capacitor Bank

A 60 kVAr switched capacitor bank provides steady-state reactive power requirement for the microgrid which is comprised of six-steps with each step has a reactive power capacity of 10 kVAr. Capacitors are switched based on the voltage error between the microgrid busbar actual voltage (V_m) and reference voltage (V_{ref}). A schematic of the PFC capacitor bank and its controller are shown in Fig. 9.
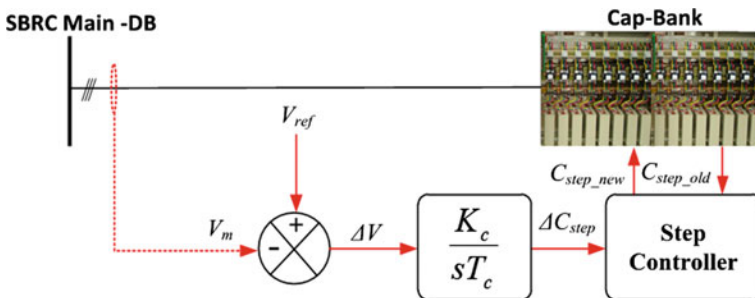
Fig. 9 Capacitor bank and controller model

4.5 Modelling of VSD Motor Loads

The two types of motor loads (i.e. VSD and DOL) were modelled separately in order to accurately represent their characteristics in dynamic simulations. The composition of VSD driven and DOL motor loads are given in Table 5. The VSD driven motors are model with a VSD and respective load characteristics. The VSD was modelled with a front-end controlled rectifier with inbuilt transformer, and an inverter system, while their load dynamics were represented by respective load characteristics (i.e. fan and pump models). A schematic of the dynamic simulation model of VSD driven motor is shown in Fig. 10.

The front-end controlled rectifier will maintain the DC link voltage constant by varying the Thyristor firing angle (α) based on the AC voltage (V_{ac}) at the Main Distribution Board. Also VSD controller has the capability for start and the drive speed can also be set constant by changing the speed reference (ω_{ref}).

4.6 Modelling of DOL Motor Loads

The direct-on-line (DOL) induction motor load is the most dominant load component in the microgrid, as the heat pump unit is comprised of two scroll compressors, each rated at 43 kW. These motor loads were modelled with an induction motor model and incorporated the respective load characteristics (i.e. fan and pump models) in order to replicate the actual load behaviour. In addition, soft-starter has also modelled at the front end of the induction motor for the motors larger than 1 kW to reduce the starting transients.

Fig. 10 The dynamic simulation model of the VSD driven motor load

4.7 Modelling of General Loads

General loads connected to the SBRC microgrid can be divided into four categories, such as computer loads, lighting loads, loads connected to socket outlets and building management system (BMS) loads. The installed load capacity of e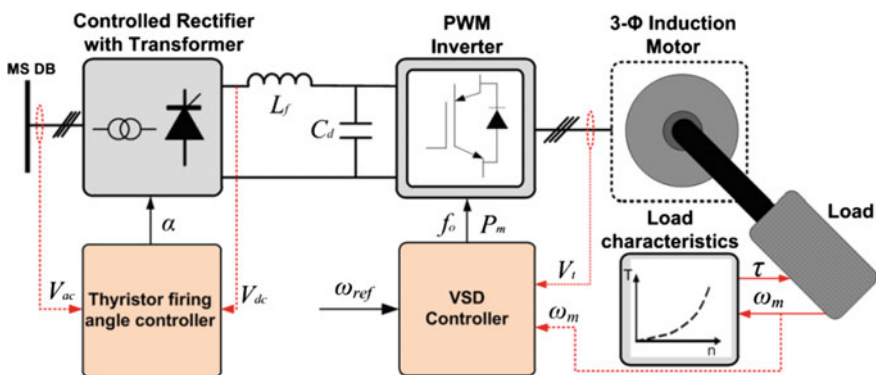ach load type at each distribution board is given in Table 6. The polynomial load model was used to represent characteristics of various load types.

$$P = P_o \left[Z_p \cdot \left(\frac{v}{v_o} \right)^2 + I_P \cdot \left(\frac{v}{v_o} \right)^1 + P_p \cdot \left(\frac{v}{v_o} \right)^0 \right]$$

$$Q = Q_o \left[Z_q \cdot \left(\frac{v}{v_o} \right)^2 + I_q \cdot \left(\frac{v}{v_o} \right)^1 + P_q \cdot \left(\frac{v}{v_o} \right)^0 \right]$$

where P_o and Q_o represent the initial active power and reactive power consumption of the load. Z_p, I_p and P_p are the constant impedance, constant current and constant power coefficients for active power, while Z_q, I_q and P_q are the constant impedance, constant current and constant power coefficients for reactive power. The polynomial load model enables represent any load using a mix of three different characteristics. Therefore, by specifying the proportion of each load component (e.g. Z_p and Z_q) multiple characteristics can be represented using the polynomial load model. The polynomial load model parameters used for each load type are given in Table 3.

The polynomial load parameters are selected based on the information provided in Collin et al. (2014). All the computer loads are represented by the characteristics of the passive power factor correction (p-PFC) based switched-mode power supply (SMPS). The lighting load was represented by the characteristics of the compact fluorescent lamp (CFL). In terms of the socket outlets it is assumed that modern power electronic based loads are connected, hence load characteristics of active power factor correction (a-PFC) based switched-mode power supply (SMPS) was used to represent the loads connected to socket outlets. Same assumption was made for the BMS loads.

Table 3 Polynomial load model parameters

Load Type	PFC	Z_p	I_p	P_p	Z_q	I_q	P_q
Computer Loads	0.97	0	0	1	0.45	−1.44	1.99
Lighting Loads	0.91	−0.01	0.96	0.05	0.1	−0.73	−0.37
Socket Outlets	1	0	0	1	–	–	–
BMS Loads	1	0	0	1	–	–	–

5   Microgrid Energy Management System

The SBRC microgrid control scheme presented here is designed to optimise the grid-connected operation of microgrid. Therefore, the energy management system will monitor generation and load demand of the microgrid and control the charging/discharging modes of the battery energy storage system. The main solar-PV system (office-PV-120 kW) and battery energy storage system are designed to control both the voltage and frequency of the microgrid. Therefore, based on the voltage and the frequency at the Microgrid Main Distribution Board, energy management system provides appropriate control signals to the office-PV and Battery energy storage system. In addition, High-Bay solar-PV systems and capacitor banks operate at local voltage control mode. The other generating sources such as 4 kW solar-PVT systems, 5 kW wind turbine and the solar-PV systems at the solar-decathlon house purely act as active power sources, hence don't provide any ancillary services to the microgrid. The overall SBRC microgrid control system is shown in Fig. 11.
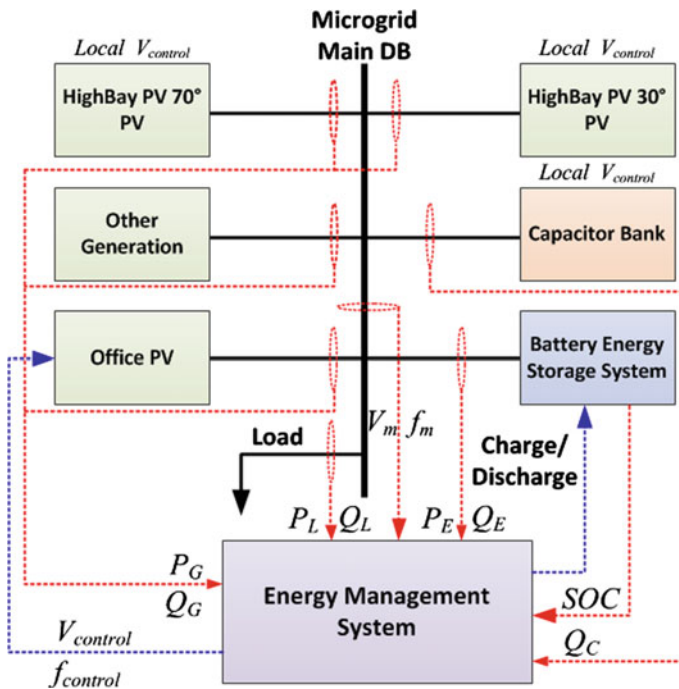

Fig. 11 Microgrid energy management system

6 Dynamic Response of the Microgrid

This section investigates the dynamic response of the microgrid during external and internal faults during grid connected mode of operation under various different operating scenarios for the microgrid. The load and generation for the three operating scenarios are illustrated in Table 4. The operating scenarios were developed considering a typical sunny day and a weekly load pattern of the SBRC.

It should be noted that some of the non SBRC loads are disconnected (fire-pump, LS-1-LOAD) during the simulation as they are not frequently operated loads.

6.1 Morning Scenario

A 150 ms three-phase short-circuit fault has simulated at $t = 1$ s both at the external network and in the microgrid and investigated the dynamic performance of the generation and loads connected to the microgrid. Figure 12 illustartes the microgrid dynamic peroformamce following the three-phase short-circuit fault for both external and internal fault scenarios.

When the three-phase short circuit fault occurs at the microgrid both the local power generation and load demand instantaneously decrease to zero, however recovers to pre-fault conditions after clearance of the fault. However, the VSD based motors are disconnected due to the commutation failure at the front-end rectifier as both voltage magnitude and angle significantly deviate during the fault. The DOL motor loads will absorb significant level of reactive power during the post-fault period and subsequently recover their nominal speed.

When the three-phase short-circuit fault occurs at the external grid, microgrid has a much lower voltage drop (≈ 0.4 V) in comparison to the short-circuit fault within the microgrid. The office solar-PV system provides reactive power support in order to improve the voltage recovery of the microgrid (see Fig. 13).

In both fault scenarios DOL connected motor load indicates the same speed decrease; however for the external fault case DOL motor load requires a considerable time to recover its speed. This is due to the fact that when the fault clears the acceleration torque is less for the external fault scenario in comparison to the internal fault scenario.

Table 4 Operating scenarios for SBRC microgrid

Operating scenario	Generation (kW)	Load (kW)	Battery storage (kW)
Morning 8.30 AM	46.13	53.65	7.52
Mid-day 12 Noon	151.02	114.00	−37.02
Afternoon 5.30 PM	25.11	75.11	50.00

Fig. 12 Dynamic response during short-circuit faults for the morning scenario

6.2 Mid-Day Scenario

A 150 ms three-phase short-circuit fault has simulated at $t = 1$ s both at the external network and in the microgrid. Figure 14 illustartes the microgrid dynamic peroformamce following the three-phase short-circuit fault for both external and internal fault scenarios.
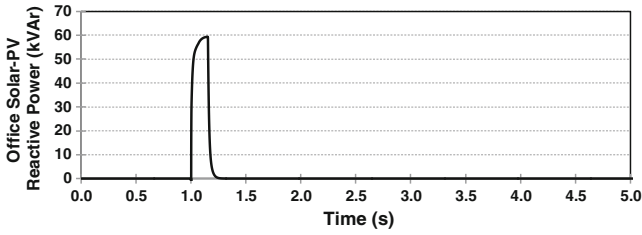
Fig. 13 Reactive power support of the office solar-PV system
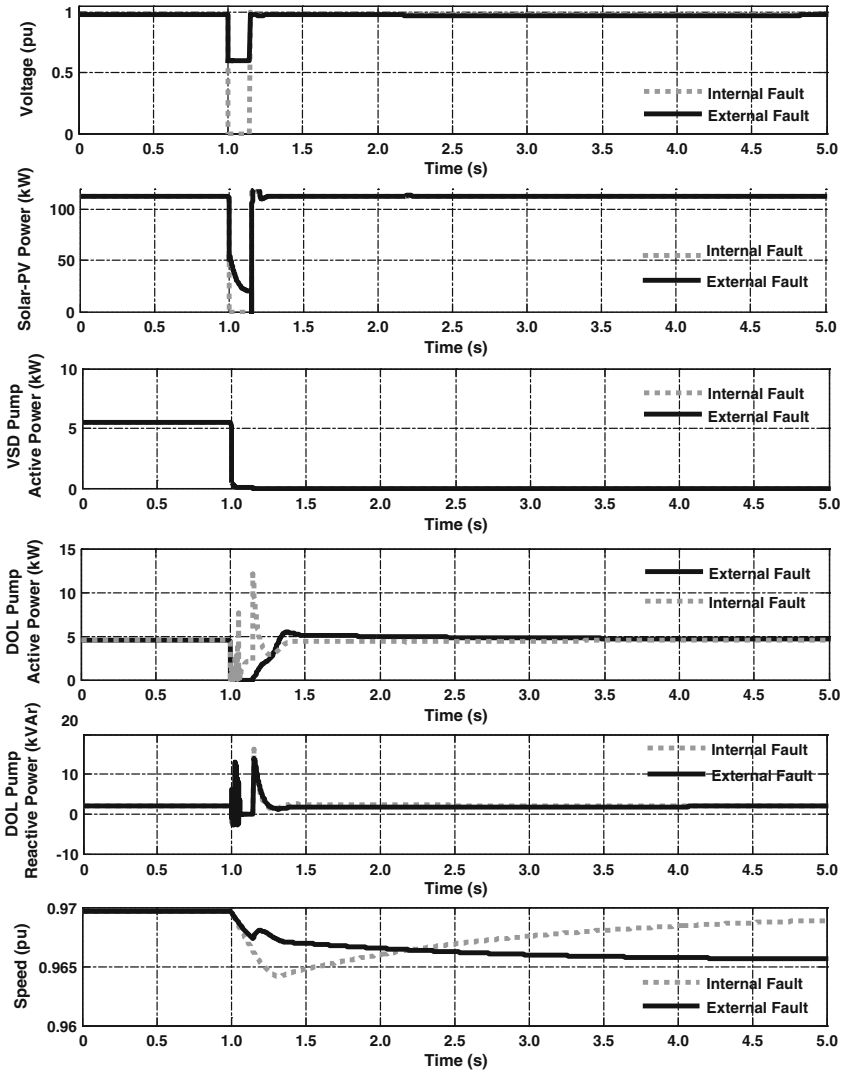
Fig. 14 Dynamic response during short-circuit faults for the day-peak

Similar observations can be made when faults occur during the day-peak; however severity of the fault is much greater in comparison to the morning fault scenarios as the microgrid experiences much higher generation loss when fault occurs during the day-peak. Therefore, speed of the DOL connected motor loads decreases to much lower values in comparison to the morning scenario. The VSD motor loads also trip due to the commutation failure at the front-end rectifier.
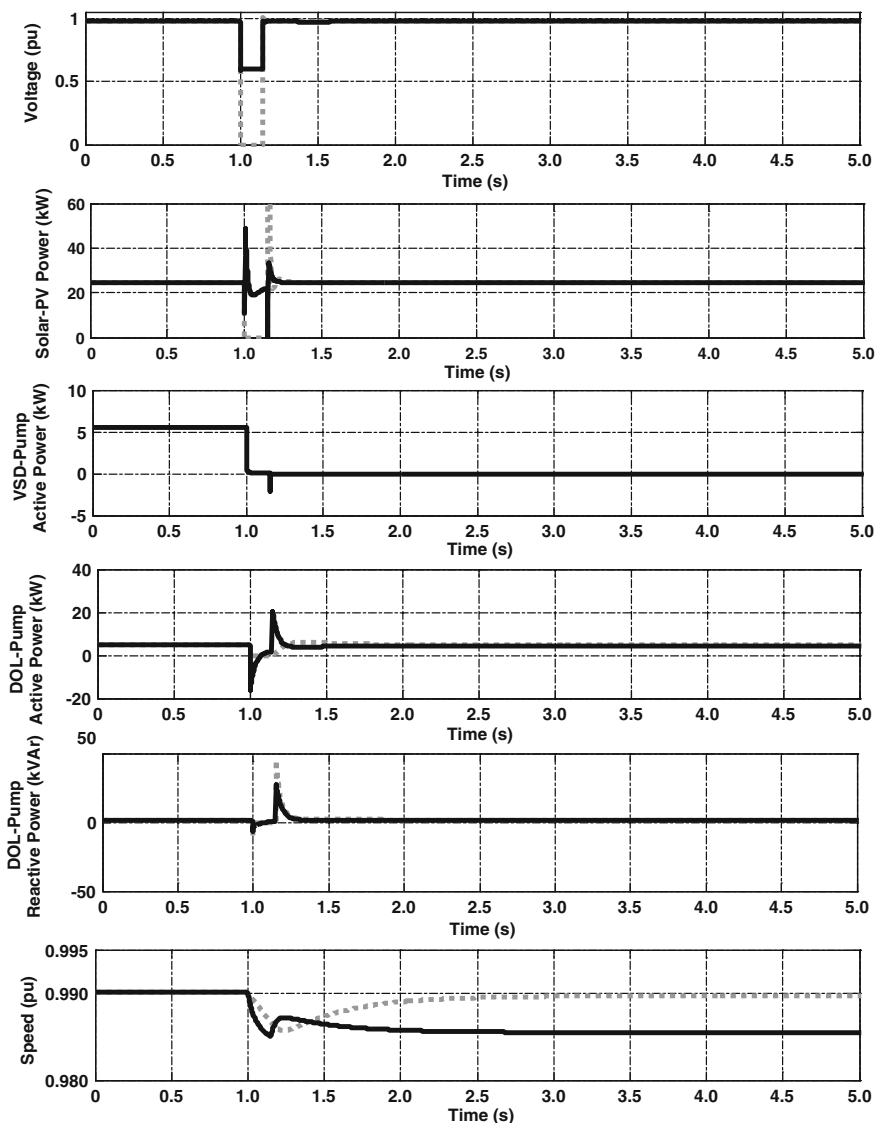
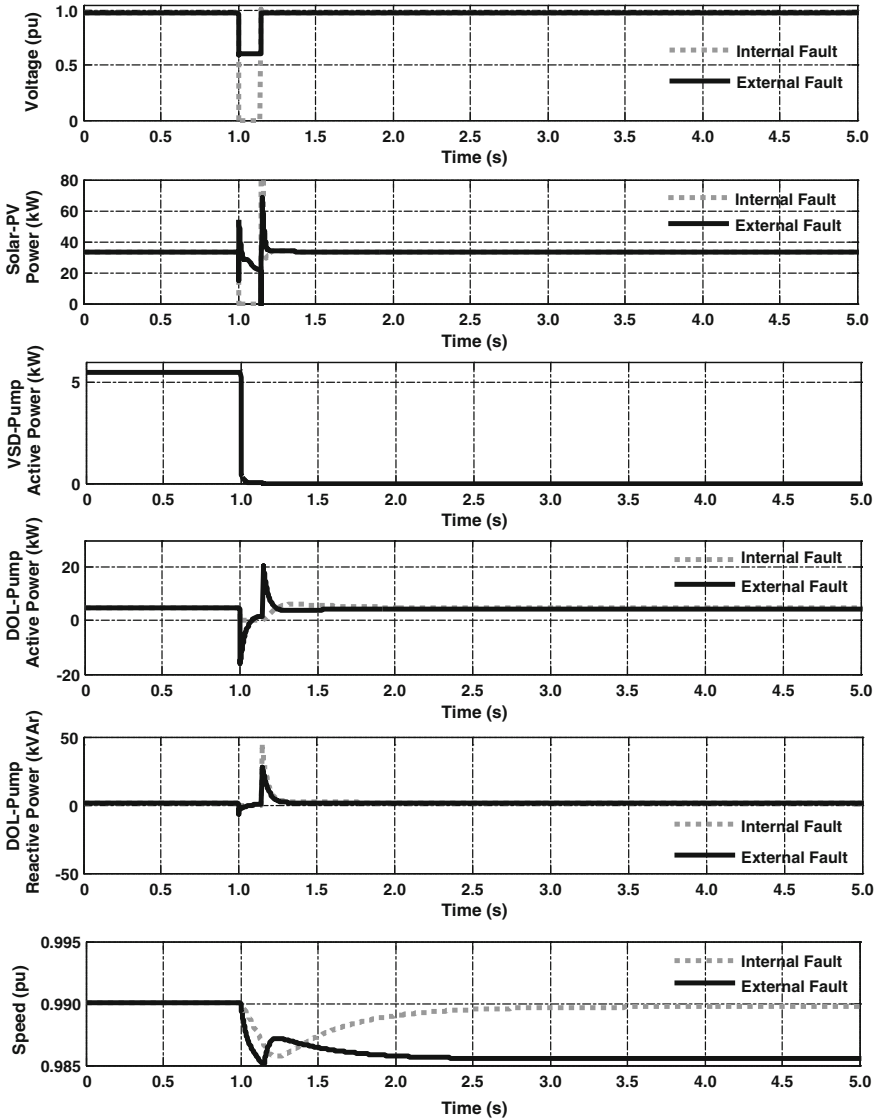**Fig. 15** Dynamic response during short-circuit faults for afternoon

6.3 Afternoon Scenario

A 150 ms three-phase short-circuit fault has simulated at $t = 1$ s both at the external network and in the microgrid and investigated the dynamic performance of the generation and loads connected to the microgrid. Figure 15 illustartes the microgrid dynamic peroformamce following the three-phase short-circuit fault for both external and internal fault scenarios. A similar dynamic trend can be observed for the afternoon scenario and severity of the impact is less in comparison to the other two scenarios.

7 Discussion and Conclusions

This chapter presented a detailed dynamic modelling of a commercial building microgrid for stability simulations. Commercial building microgrids are unique in terms of their load dynamics and generation portfolio; hence require careful attention when developing accurate dynamic models. The generation sources were modelled using an average model of the power electronic converter. In addition, the control schemes associated with each generation source was also discussed in detail. Furthermore, the microgrid loads were also modelled with more details; hence DOL and VSD motor loads were modelled separately with appropriate load dynamics. The other loads of the microgrid are also modelled using the polynomial load model. Microgrid energy management system was designed to optimise the grid connected operation of the microgrid; hence it will determine the charging and discharging modes for the battery energy storage system at a given time of the day.

The dynamic simulations were conducted considering three scenarios for the microgrid. It is observed that the VSD motor loads trip for both external and internal faults due to commutation failure at the front-end rectifier. The DOL motor loads absorb considerable amount of reactive power during the post fault period, however the Solar-PV system and battery energy storage system provide dynamic reactive power support to the microgrid voltage profile. Therefore, this work has indicated the importance of detailed modelling of microgrid components for stability simulations. In particular, the motor loads must be modelled accurately with much detail to accurately characterise the dynamic behaviour of a microgrid during grid faults.

Appendix A SBRC Microgrid Load Distribution Data

Installed VSD and DOL motor load capacities are shown in Table 5.

One of the major motor load is the Heat Pump (43.6 kW) which is supplied through the MS-2 distribution board. In addition, two DOL pumps (i.e. Rain Water (8.8 kW) and Cold Water (8.8 kW) pumps) are connected to the Main Distribution Board. The other distribution board supplies lighting load, computer load, power outlets and building services. It is also assumed that solar-decathlon house has a load of 5 kW. The portion of each type is given in Table 6.

Appendix B: SBRC Microgrid Cable Impedance Data

The substation transformer (11/433 kV) has an internal impedance of 0.0496 + j0.0011. The impedance associated with each circuit of the microgrid is given in Table 7.

Table 5 Installed capacities of VSD and DOL motor loads

	MS-1 (kW)	MS-2 (kW)
DOL motor loads	1.39	52.2
VSD motor loads	2.2	13

Table 6 Load distribution by sub distribution boards

	DB-L1 (kW)	DB-FL3 (kW)	DB-HB (kW)	DB-G1 (kW)
Lighting Load	11.3	1	6.3	0
Computer load	31.1	6.1	0	1
Power sockets	6.4	19.5	10.5	6.4
Building services	1	1	1	1

Table 7 Cable impedance of the SBRC microgrid

Circuit	Impedance (Ω/km)	Length (m)
Substation to SBRC	0.0785 + j0.0818	400
Office PV	0.1939 + j 0.0868	100
High bay PV 70°	0.3879 + j0.0924	50
High bay PV 30°	0.3879 + j0.0924	25
Solar decathlon house	0.3879 + j0.0924	250
Solar PVT	0.2686 + j0.0893	20

(continued)

Table 7 (continued)

Circuit	Impedance (Ω/km)	Length (m)
Wind generator	0.2686 + j0.0893	100
Battery energy storage system	0.2686 + j0.0893	25
Cold water/rain water pumps	1.8302 + j0.084	30
MS-1	0.2686 + j0.0893	30
MS-2	0.2686 + j0.0893	20
DB-G1	0.2686 + j0.0893	20
DB-HB	0.0785 + j0.0818	20
DB-L1	0.1939 + j0.0868	20
DB-FL3	0.1939 + j0.0868	20
Cap bank	0.2686 + j0.0893	30

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Probabilistic Methods Applied in Power and Smart Grids

Yingliang Li and Dilan Jayaweera

Abstract System level assessments in a smart grid require a probabilistic approach in order to better reflect the likelihood of uncertainties and their impacts. Applications of probabilistic approaches are not new to the traditional power grid however their need and advances are increased in smart grids with the involvement of smart elements in the physical layer of the smart grid and the cyber network interaction. This chapter presents a detailed investigation on the probabilistic methods applied in a traditional power grid and their intended extensions in a smart grid. The chapter explores wider avenues of probabilistic researches ranging from steady state to the dynamic state.

Keywords Dynamic assessments · Monte Carlo simulation · Reliability assessments · Security assessments · Steady state assessments · Stochastic assessments

1 Introduction

The power systems are stochastic in nature, and the levels of uncertainties have increased greatly with the developments in smart grids with growing participants. The traditionally used deterministic-based approaches cannot adequately take account of the uncertainties in smart grids or incorporate varying probability considerations, which can potentially result in reduced power system reliability and power outages. On the other hand, probabilistic approaches have shown growing

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importance in the management of uncertainties and the prediction of performances of smart grids. In this chapter, the probabilistic methods applied in power and smart grids are presented in the context of steady-state analyses, dynamic analyses, and system planning and reliability assessments. The chapter ends with the exploration of the need for new tools and techniques in smart grid to realise objectives.

2 The Importance of Probabilistic Methods

The power system and its disturbances are stochastic in nature, and can be affected by a large variety of factors (EPRI 2003, 2004; Li and Wolfs 2013; Kovacevic et al. 2013). With the emerging changes in smart grids, such as deregulation, increased interconnections and renewable energy integration, the level of random and other uncertainties in the power system has increased considerably (EPRI 2003; Buygi et al. 2004d, 2006; Jayaweera and Islam 2009; Zhao et al. 2009). The uncertainties associated with generation, such as new generation facilities, capacity and timing, and uncertainties associated with demand and regulatory rules have added to the complexity in system analysis. There are also vague data in the network that has added difficulties in the system characterisations (Buygi et al. 2004b, c). Besides, in this increasingly energy-conscience world, detailed and more accurate characterisations of power systems become important and they are aimed at promoting the conservation, efficiency, and new technologies. The traditional deterministic based approaches employing deterministic analyses, which ignore the stochastic nature of power systems, appear unable to incorporate the above considerations that may be seen in a smart power grid. The probabilistic based analyses have become ever more important, especially in the aspects of system stability, reliability, security, forecasting, and optimisation. The deterministic approaches are beyond the scope of this chapter, and the reviews on the comparison of deterministic and probabilistic approaches can be read in (EPRI 2003; Dong et al. 2010; Zhang et al. 2004).

Probabilistic methods (Buygi et al. 2004a, d, 2006), decision analysis (De la Torre et al. 1999; Fang and Hill 2003; Linares 2002), and fuzzy decision making (Buygi et al. 2004b, c) are the common approaches in considering random uncertainties, nonrandom uncertainties, and data vagueness, respectively, and a combination of the three approaches can be applied as well (Buygi et al. 2004d, 2006), with probabilistic methods being applied dominantly (Anders and Vaccaro 2011).

3 Probabilistic Methods Applied in a Power System

Probabilistic assessments incorporate analyses tools and techniques involved in the steady-state analyses, dynamic analyses, system planning and reliability assessments. These tools and techniques span over power system planning to operating horizons, and they are discussed in detail in the following sections.

3.1 Probabilistic Steady-State Analyses

Probabilistic steady-state studies generally include probabilistic load flow, probabilistic voltage stability and probabilistic small signal stability analyses (EPRI 2003).

3.1.1 Probabilistic Load Flow Analysis

Probabilistic load flow analysis is the most widely used tool in the probabilistic steady-state studies, and it provides information on the steady state of the power system for a specified set of generation, loads, line parameters and grid conditions. The early probabilistic load flow studies, being proposed in the early 1970s, took into consideration of the stochastic nature of load and introduced a simplified probabilistic load flow model (Booth 1972; Borkowska 1974; Allan et al. 1974). There are two ways of adopting probabilistic approach to load flow analyses—probabilistic load flow (PLF) (Allan et al. 1981; Meliopoulos et al. 1990; Wang and Alvarado 1992; Dimitrovski and Tomsovic 2004; Su 2005; Verbič and Cañizares 2006; Zhang and Lee 2004; Schellenberg et al. 2005; Hu and Wang 2006; Morales and Perez-Ruiz 2007; Chen et al. 2008) and stochastic load flow (SLF) (Dopazo et al. 1975; Sobierajski 1979; Sirisena and Brown 1983). The PLF approach has been used more widely because of its extensive mathematical background, and it can be performed numerically using Monte Carlo simulation (MCS) (Conti and Raiti 2007), analytically (Allan et al. 1976) or a combination of them (Silva and Arienti 1990). As opposed to the deterministic load flow approach that uses expected average or peak data values to give a set of deterministic values, the PLF approach studies generally follow probability distribution function(s) (PDF) and propose the possible ranges of load flow, which give power engineers more confidence in decision making involved in system operation, planning and investments.

3.1.2 Probabilistic Voltage Stability Analyses

Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition (Kundur et al. 2004). Voltage instability can be considered a steady-state or a dynamic process, each requires relevant analysis methods. The dynamic stability analyses will be discussed in the next section.

When considering the stochastic nature of a power system subjected to voltage stability issues, apart from the parameter of voltage levels, probabilistic voltage stability indices can reflect not only the event severity, but also its probability and frequency of occurrence. There are two categories of voltage stability indices—bus oriented (Kessel and Glavitsch 1986) and system/area oriented indices (Tamura et al. 1983; Tiranuchit and Thomas 1988). Bus oriented indices are based on local

information associated with each bus, whereas system/area oriented indices give a scalar criterion for the entire system (Kundur 1994; Momoh et al. 1999). For example, Aboreshaid and Billinton (1999) quantified the probabilistic voltage stability in two sets of indices for each bus and for the overall system using a contingency enumeration approach. The two sets of voltage stability indices complement each other to produce an overall appreciation of system voltage performance as well as localized performance of certain areas in the system. Liu et al. (2013) took account of the uncertainties of wind power and load into probabilistic voltage evaluation by using two-point estimate method and continuous power flow method.

3.1.3 Probabilistic Small Signal Stability Analyses

In the small signal stability (SSS) analyses, the disturbances need to be small enough that linearsation of system equations is permissible for the purposes of analysis. The probabilistic analyses can be analytical (Burchett and Heydt 1978; Pang et al. 2005; Bu et al. 2011), numerical (Chung et al. 2003; Xu et al. 2005, 2006), or using ad hoc strategies such as structured singular value theory (Castellanos et al. 2005, 2008).

Eigenvalue sensitivity analysis has been widely used in probabilistic small signal stability (PSSS). The probabilistic analysis was firstly introduced into SSS studies by Burchett and Heydt (1978), and the probabilistic property of the eigenvalues in a two-machine system was obtained from the known statistical attributes of variations of system parameters, such as the rotor angle and mechanical damping. In the probabilistic eigenvalue sensitivity analysis, the probabilistic distributions of critical eigenvalues can be determined, and the probabilistic stability properties of the power system can be obtained (Wang et al. 2000; Chung et al. 2003). Multivariate normal PDF can be used to analyse the joint probability of the system eigenvalues, which allows the probability of the system eigenvalues under stochastic parameter perturbations to be studied (Pang et al. 2005). MCS can be used in PSSS analysis (Xu et al. 2005) based on eigenvalue analysis to provide high-accuracy outcomes although computational intensive and time-consuming.

There are other methods available for PSSS that are less time-consuming than MCS. A grid computing approach can be incorporated in PSSS analysis with enhanced performances in computing capacity, speed, accuracy and stability (Xu et al. 2006). The two-point estimation method can assess the statistical characteristics of random variables with less calculation requirement than MCS while keeping enough calculating precision (Yi et al. 2007; Soleimanpour and Mohammadi 2012). The analytical cumulant-based method can directly calculate PDF of critical eigenvalues and determined the probabilistic small-signal stability of a large-scale power system as affected by multiple source of wind generation (Bu et al. 2011).

3.2 Probabilistic Dynamic Analyses

Transient stability analysis is concerned with the power system performance being subjected to a sudden disturbance, and aims at finding out whether the synchronous machines will regain or lose synchronism in the new steady-state equilibrium (Dong et al. 2010). The conditional probability approach (Billinton and Kuruganty 1978, 1981; Kuruganty and Billinton 1981; Hsu and Chang 1988) and Monte Carlo based approach (Timko et al. 1983; Vaahedi et al. 2000; Goel 2000) are the two groups of methods commonly used for probabilistic transient stability analysis.

The initial studies on probabilistic transient stability analysis were carried out in the seventies (Patton 1970; Light 1977). Then Billinton and Kuruganty (1978, 1981), Kuruganty and Billinton (1981) developed a stability index based upon the probabilistic nature of the primary-system elements and demonstrated its response to the changes in selected system parameters. Hsu and Chang (1988) carried out stochastic stability analysis based on the outage statistics, evaluated stability index, and investigated the causes of system instability using the Bayes' theorem. Timko et al. (1983) carried out the Monte Carlo based stability analysis to provide a probabilistic measure of the transient stability of a power system, which can be directly compared with a reliability index.

There have been some other methods dealing with different aspects of probabilistic reliability, such as health analysis (Billinton and Fotuhi-Firuzabad 1994), bisection method (Aboreshaid et al. 1996), collocation method (Hockenberry and Lesieutre 2004), Bayes classifier (Kim and Singh 2005), cascading failure analysis (Baldick et al. 2008), copula theory (Papaefthymiou and Kurowicka 2009), cross-entropy methods (Leite da Silva et al. 2010) and grid computing techniques (Ali et al. 2007).

3.3 Probabilistic System Planning

The power system planning aims primarily to supply the future load at minimum cost and maximum reliability. The four main steps in probabilistic system planning include (Buygi et al. 2006; Li and Choudhury 2007, 2008): firstly select the planning alternatives based on the candidate pool formulated with the practical and management experiences; then conduct probabilistic reliability evaluation and unreliability cost evaluation for the selected alternatives over a planning time frame; and next calculate the cash flows and present values of investment, operation and unreliability costs for the alternatives in the planning time period; finally select an appropriate criterion (Manso and Da Silva 2004) and conduct an overall probabilistic economic analysis.

There have been various techniques applied in recent probabilistic system planning. Buygi et al. presented a market-based approach for network expansion planning in unbundled power systems (Buygi et al. 2006). The approach is a

combination of probabilistic optimal power flow, scenario technique, and fuzzy decision making to tackle the issues with random uncertainties, nonrandom uncertainties and vagueness. A fuzzy appropriateness index was used as a measurement of the goodness of expansion plans, planning criteria were determined using analytic hierarchy process, and fuzzy risk assessment was performed to select the final plan. In achieving a low-carbon power industry in Australia, the system planning process by Qiu et al. (2015) took into consideration of the gas and electricity system simultaneously and modeled as a mixed integer nonlinear optimisation problem. The plan with the highest cost/benefit ratio was selected to be the best augmentation option. Decision analysis was used to tackle market uncertainties by identifying several scenarios based on statistical analysis and expert knowledge. To accommodate renewables in the US, a two-stage stochastic network-planning model (Munoz et al. 2012) were proposed taking into account Kirchhoff's laws, uncertainties, generators' response and recourse investment decisions. For flexible transmission planning schemes, genetic algorithm (Hui et al. 2012) was used to obtain candidate planning schemes, and planning schemes were then selected by MCS based sensitivity method. Finally, reliability evaluations were made for each transmission planning scheme. The most flexible planning scheme was defined as the one which needs the least investment on extra control devices.

3.4 Probabilistic Reliability Assessment

Reliability of a bulk system is a measure of the ability to deliver electricity to all points of utilization within accepted standards and in the amount desired (Ringlee et al. 1994). The two fundamental approaches used in reliability index calculation are direct analytical evaluation and MCS. Analytical techniques evaluate the system reliability indices using mathematical solutions, whereas MCS provides reliability indices by simulating the actual process and the random behavior of the system (Billinton and Allan 1996).

Begen et al. (2014) summarised the results of the North American Electric Reliability Corporation (NERC) wide probabilistic reliability assessment in 2012. The majority of the eleven evaluations in the assessment employed MCS techniques and two of them used analytical convolution methods. The assessment also provided probabilistic indexes such as the expected unserved energy (EUE) and loss of load expectation (LOLE).

EPRI's Probabilistic Reliability or Risk Assessment (PRA) technique (EPRI 2001) is a practical hybrid approach to reliability assessment that provides the capability for determining the probability or likelihood of an undesirable event on the transmission system and a measure of its severity. The PRA is a combination of probabilistic and deterministic approach, and combines a probabilistic measure of the likelihood of undesirable events with a measure of the consequence of the events into a single reliability index called Probabilistic Reliability Index (PRI).

The analyses included in PRA are interaction, critical situation, root cause, weak point and probabilistic margin analysis (Maruejouls et al. 2004; Zhang et al. 2004).

There have been some recent progresses on reliability assessments. Li et al. (2014) proposed a technique to assess the reliability of multiple substations with associated distribution networks, based on Markov modeling, clustering approach, linear programming algorithm and the state enumeration method. Samadi and Singh (2014) develops a methodology for quantitative reliability study of generation systems with solar power, and evaluated the indices of LOLE, EUE and frequency of capacity deficiency. Koh et al. (2014) analytically evaluated the reliability of Roy Billinton Test System (RBTS) generation model, load model, photovoltaic model and energy storage model to determine the impact on system adequacy indices of LOLE and loss of energy expectation (LOEE). Zhang et al. (2012) presented a reliability evaluation method for large-scale commercial and utility-level photovoltaic power systems using central inverter topology. Energy-oriented and time-oriented reliability indexes were defined taking account of power output-dependent failure rates of system components. Leite da Silva et al. (2014a) proposed an approach to assess reliability in composite generation/transmission systems with high penetration of renewable energy by combining cross entropy based optimisation and quasi-sequential MCS to minimize the variance of the reliability index estimators. In another paper, Leite da Silva et al. (2014b) presented a methodology for database calibration as assessing reliability indices. Chronological MCS was used to evaluate the probability density functions of sampling errors associated with the reliability performance indexes.

4   Probabilistic Methods Applied in a Smart Grid

Previous sections of this chapter explored the probabilistic methods applied in a power system with or without the presence of renewable and distributed power generation. In a complex probabilistic modelling, uncertainties can be framed through MCS platform in order to expand the distribution of probabilities of events and then to fit them into to the normal distribution in most cases. In a smart grid context, the number of active participants together with intelligent device control and coordination entities will play key roles in transforming the traditional power grids into a more secure, efficient, and economic power grid. However, the transformation may not only transform the power system into intelligent grids but also transform some of the risks and uncertainties seen in traditional power systems into new levels, creating significant challenges to manage and to limit the hidden impacts. One of those challenges can be seen as the cyber security and its interaction related risks and uncertainties in a smart grid. These new risk components may not necessarily let the existing tools and techniques to harmonize impacts and to drive the smart grid objectives without additional costs.

Thus, risk and uncertainty assessment tools in a smart grid must be capable of adopting the additional layers of cyber security into the physical layers of a power

grid. On top of that several other layers should also be devoted in order to capture and manage the uncertainties and risks associated with the combinatorial effects arising from big data from the smart grid devices, controls, and appliances. Thus, the existing probabilistic tools may not necessarily be capable for handing risks and uncertainties in a smart grid unless the tools and techniques are upgraded to an advanced to a level that can operate in a smart grid environment or new and innovative tools are invented to capture risk and uncertainties at multi-layer and multi-disciplinary levels. Therefore, there is a significant need of addressing these challenges in order to realise smart grids that can provide the benefits as anticipated through their definitions.

5 Summary

In a stochastic-natured and increasingly uncertain smart grid environment, probabilistic methods have been applied in a growing number of areas, and have shown their increasing importance in handling the uncertainties involved in system stability, reliability, forecasting and optimisation. There have been comprehensive work dedicated to these probabilistic based analyses, and will require further research efforts. In this chapter, probabilistic methods applied in these aspects of steady-state analyses, dynamic analyses, system planning and reliability assessments are discussed. The chapter also expanded to cover the need of tools and techniques to manage novel risks and uncertainties in smart grids. There is no unique definition for a smart grid. Similarly, there is potentially no unique approach for assessing and managing risks in a smart grid. However, the advanced probabilistic tools together with adaptive, intelligent, and real-time assessment tools and techniques will serve smart grids to mitigate hidden risks and impacts and potentially provide real benefits for energy customers and other stakeholders.

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Planning and Operational Challenges in a Smart Grid

Zafar Ali Khan and Dilan Jayaweera

Abstract The power system planning and operation have always been challenging. However, with the advent of the new technologies, the traditional power grids are moving towards smarter and as a result, the planning and operational challenges will potentially increase further with the future grid. With the deployment of smart grids, the planning and operational paradigms of traditional power systems are require to be reviewed from a new prospective with system uncertainties of emerging technologies and their interactions. The smart grid technologies bring in new elements into in the system planning and operation including renewable energy sources, demand side management, dynamic line rating etc. The flow of large amount of data in a smart grid needs data monitoring and management to mitigate planning and operational uncertainties. The new and predicted challenges are required to be identified well in advance in order to ensure a secure, reliable and economic future with an evolving power grid. This chapter investigates the planning and operational challenges in a smart grid environment and discusses pathways impacts.

Keywords Cyber-physical system · Data clustering · Demand side management · Load forecasting · Real-time load forecasting

List of Abbreviations

AGC	Automatic Generation Control
AI	Artificial Intelligence
AMI	Advanced Metering Infrastructure
ANN	Artificial Neural Network
DLR	Dynamic Line Rating
DSM	Demand Side Management

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EMS   Energy Management System
ESS   Energy Storage System
ICT   Information and Communication Technology
LOLP   Loss of Load Probability
LTLF   Long Term Load Forecasting
MAPE   Mean Absolute Percentage Error
MLP   Multi-Layer Perceptron
MTLF   Medium Term Load forecasting
PMU   Phasor Measurement Unit
RTLF   Real-Time Load Forecasting
RES   Renewable Energy Sources
SCADA   Supervisory Control and Data Acquisition
STLF   Short-Term Load Forecasting
SVM   Support Vector Machines
VSTLF   Very Short Term Load Forecasting
WSN   Wireless Sensor Network

1 Introduction

The primary aim of a traditional power system is to supply the demand securely. Traditional power systems were planned by considering a centralized and bulk power generation, transmission, and distribution system with distributed connection of loads. In a traditional power system, the power flow was expected to be unidirectional. The system operator had a little information about the individual consumer's load patterns. Thus, utilities were somewhat blind towards consumer's consumption patterns of electricity although they had some estimated/predicted/or surveyed information.

The evolving grid systems are known as Smart Grids, where the power is to be generated and supplied to consumers as efficient, secure, and economic. The power flow can be unidirectional or omnidirectional. The grid incorporates real-time monitoring and control for better facilitating the objectives. The objectives are also achieved with the supports from Advanced Metering Infrastructure (AMI) and information and communication technology (ICT) platform of which the integrated system of smart meters, a communication network, and a data management system enable the two way communication between utilities and consumers (ENERGY). Thus, it is apparent that the smart grid is not a destination but it is a journey towards achieving smarter objectives to meet global challenges. The paths for achieving goals may not necessarily be uniform and may also hit unexpected territories that are to be researched in the future. In a smart grid, bidirectional flow and information can be exchanged among the nodes. The AMI with the help of ICTs enables the

system operator to look into the real time details of the consumed load by active consumers.

Planning and operation of a smart grid require the inclusion of many advanced functions which were not necessarily included in a traditional power system. These functions include the Real time load forecasting (RTLF), dynamic demand side management (DSM), management of renewable energy sources (RES) and many others that contribute to smart grid objectives. It is also vital to ensure that the accuracy of the data is maintained by incorporating real time measurement monitoring and control in an intelligent manner through error prediction and correction routines.

The smart grid environment requires better communication, control, and infrastructures to implement the operational planning horizons which include economic load dispatch, RTLF, unit commitment, dynamic line rating (DLR), etc. This chapter explores how power systems were planned in the past, additional planning requirements in the context of smart grids, and anticipated challenges in the planning and operation of future power systems, and pathways impacts.

2   Planning and Operation of a Power System

Planning is the activity which ensures reliable functioning of a power system and which can enable integration of new technologies into the existing system. Therefore, planning is a key to enable the implementation of smart grids. With the rapid growth in the area of renewable energy technologies, many integration challenges are evident. Therefore, it is of utmost importance to ensure that planning is robust, flexible, and it can accommodate paradigm shifts allowing integration of new and emerging technologies and meet the carbon reduction targets and the energy sustainability.

The operation is the activity that ensures that the security standards are maintained and take necessary preventive and corrective actions as desired by the power system at emergencies. Operation in a traditional power system is subjected to the information on the forecasting of loads and other auxiliary events. Forecasted load can be used for the operational planning, which include load/frequency control, economic load dispatch, unit commitment, and scheduling the maintenance of power plants, substations and other auxiliary components of the power system. The smart grids have opened new avenues of operational planning and real time monitoring, AMI, smart appliance data, distribution automation, and self-healing network properties, etc. The load forecasting is discussed in detail in Sect. 3.

A traditional power system typically comprises of bulk generating stations and a power transmission and power distribution systems. Generating stations in a traditional power system ensure that power is generated as planned and reserves are maintained as needed by the system. The power transmission and distribution systems are related to power delivery infrastructure. The transmission system

connects different generating stations with power distribution systems which feed load demand. The efficacy of a power transmission system enables reliable and economical operation of the power system by enabling electricity supply from most economical source at the time of need. Interfaces of the power transmission and distribution systems are the distribution substations. In a traditional power system, these substations are designed for unidirectional power flow, i.e. the power flows from the transmission system to distribution substations and not vice versa. The distribution system consists of distribution substations and the entire infrastructure between substation and load which includes feeders, distribution transformers, laterals, service wires and meters, which are installed at consumer's premises etc. The system planning is also divided into three categories. They are generation planning, power transmission system planning, and power distribution system planning.

2.1 Generation Planning

Generation Planning is carried out considering the future requirements of the power system. This planning includes expansion of existing generation facilities and addition of new generation to meet the future load demand to meet reliability and security standards within a realistic minimum cost. Generation of power at any time is a part of operational planning which concerned with the current and future development scenario of power generation. Bebic (2008) is of the view that generation planning is primarily based on load forecasting. Once the load is forecasted, the reliability is assessed to determine if any additional generation is required and if required then when it will be? Depending on the reliability evaluation, the optimal expansion capacity is planned with socio-economic considerations.

On a short horizon, the load forecasting can be more accurate but when it comes to a longer duration of weeks to months and then years, the accuracy of the load forecasting can be affected. The very short term load forecasting (VSTLF) or short term load forecasting (STLF) can be utilized for every day operational purposes such as generation scheduling, unit commitment, and economic load dispatch, etc. However, for the system expansion planning it is required a longer span of time for load forecasting. Details of load forecasting and VSTLF with a particular emphasis into smart grid scenarios are described in Sect. 3 of the chapter.

Generating stations require scheduling maintenance activities which requires plants to take off from the bar. The resulting outages are termed as scheduled outage. However, in some extraordinary circumstances, some of the stations can face forced outages due to system faults, equipment failure, or any other external factor/disturbance. The forced outages which are unplanned and can have a significant impact on a power system and system stability can be significantly affected by such events. If a large generation capacity faces a forced outage, then the system should be able to sustain the loss of generation until the reserve generation kicks

into the system. The generation planning should be carried out with such system events and the bulk generating stations should be able to maintain the inertia till the reserve plants start feeding the power to the system. This is to ensure that the security of the system is maintained within standards. Thus, the generation planning also needs to consider the reserve capacity to cover any forced outages. The required reserve generation capacity is commonly determined by using probabilistic approaches which determine the probabilities of simultaneous outages of generating units and then compares the resulting remaining capacity with the system peak load. Thus, to measure the generation system reliability, generation capacity shortage can be determined for a number of days per year and this measure, in reliability terms, is known as Loss of Load Probability (LOLP) index (Stoll and Garver 1989). LOLP is a consistent and sensitive measure of the power generation reliability (Stoll and Garver 1989).

While determining LOLP index, both scheduled and forced outages are evaluated. As scheduled outages are known, they are scheduled deterministically and forced outages are determined probabilistically. LOLP index is computed with large number of probabilistic experiments. LOLP index calculations are commonly performed for the entire interconnected system (Bebic 2008). The planners require considering the generation units for expansion of the system so that the capacity meets the required LOLP index. In a traditional power system, this scenario seems a quite straightforward with the LOLP index calculation, however in a smart grid environment; the anticipated complications are far more severe than that of a traditional power system. One of the anticipated complications may arise from intermittency of power generations and their interactions. The increasing accommodation of intermittent RES are affected by many factors including sun light, wind speed, variations in asset dynamics, new and sensitive technologies, etc. Thus, estimation of a sensitive LOLP index may become more complicated and can be more challenging.

The final step in generation planning is to plan the type of generation technologies that are needed to be installed (hydroelectric, thermal, nuclear, wind, solar, etc.). This part of the planning requires the plant to be cost effective, both in installation and operation. After determination of stability factor, the cost benefit analysis of the plant will be carried out to finalize the plant type and size. Stoll and Garver (1989) presented a model to determine plant type which is given in Fig. 1. With the help of such a model, the planners can hypothesize different types of power plants by checking their reliability and cost/benefit analysis.

A vast level of research is being carried out to compensate the intermittency of the RES. One of the proposed solutions, which can also be considered to enhance system reserve capacity, is the grid tied battery backup although there is a case of cost effectiveness beyond certain capacities of this solution. The energy storage system (ESS) can support the system during peak loads and be charged during low load times. More and more research is devoted into ESS with the aim of sharing the supports for a smart grid environment and to meet its objectives.
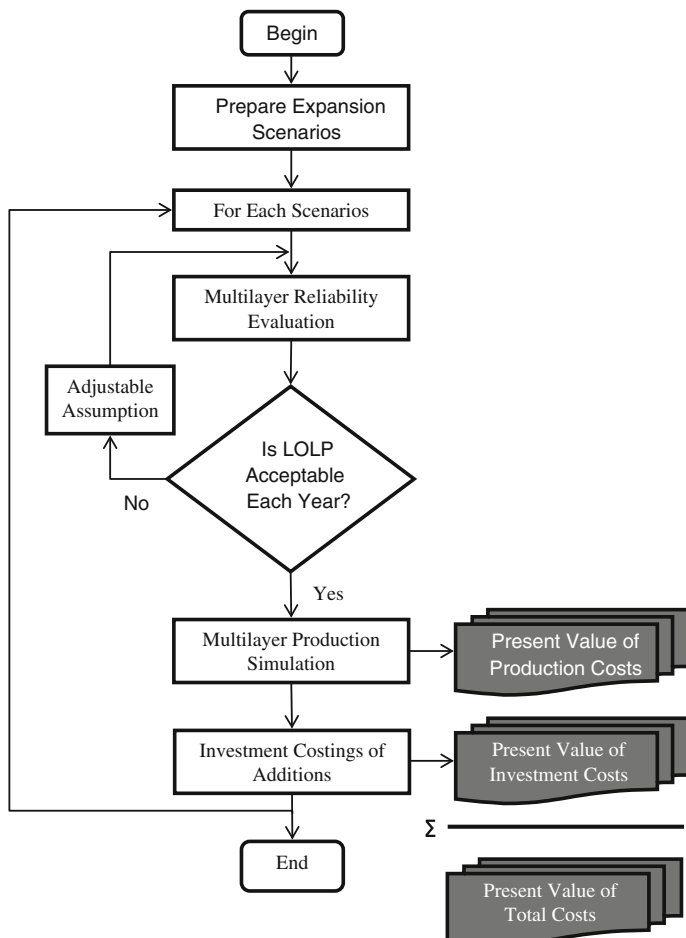
Fig. 1 Least-cost generation planning model (Stoll and Garver 1989)

2.2 Power Transmission Planning

Power transmission planning is carried out for optimal usage of generation portfolio, i.e., to make it possible to transmit power from most economical generating source with an adequate level of reliability. Transmission planning ensures that transmission infrastructure is capable of carrying out the power within the operating limits, both in normal and contingency conditions. According to Gonen (1988) "the purpose of transmission system planning is to determine the timing and type of new transmission facilities required in order to provide adequate transmission network capability to cope with the future generation capacity additions and load-flow requirements." This indicates that the transmission planning and generation

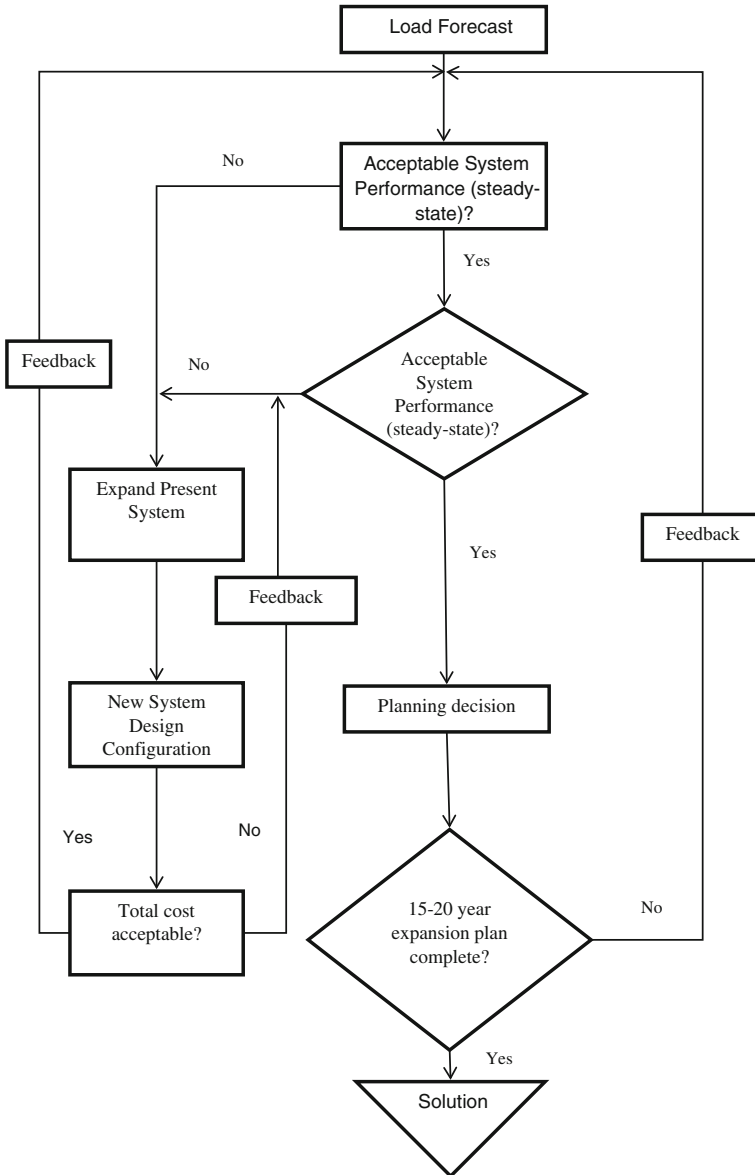**Fig. 2** Typical transmission system planning process (Gonen 1988)

planning are interrelated. Wherever power is generated, it requires to be transmitted to the load centres through distribution networks. A simple transmission system planning process presented by Gonen (1988) is given in Fig. 2. In that, there are a number of functionalities used to ensure the stability of power plants which are also

dependent on the transmission system reliability. According to Grigsby (2012) the dynamic behaviour of generator, governor system, excitation system, and network elements (transmission lines and transformers) take part in the assessment of power system stability.

Transformation of a traditional grid to a smarter grid requires a facility expansion to accommodate RES. Apart from expanding a transmission network to accommodate RES; the power system should also be able to provide a real time data through an advanced communication network and smart sensors. The accuracy of monitored data can play an important role in planning the transmission system. Conventionally, power rating or current carrying capacity of a transmission line is considered as static which is calculated initially for specific weather conditions and is considered to be fixed throughout a season. In a smart grid environment, with the help of sensors and communication devices, the DLR can be measured. The DLR depends on many factors including the ambient temperature, level of current passing through the line, wind speed and direction, age of the assets, etc.

In a traditional power system, the power transmitted through a line is often much lower than it's ampacity, however, in some cases it could be overestimated which can be dangerous for equipment and system stability (Albizu et al. 2015). Ampacity is the measure of current carrying capacity of a conductor. DLR can play an important role in transmission planning in a smart grid environment as it can help in utilizing the spare capacities of an existing transmission infrastructure rather than installing new transmission lines for small time frame events. According to Warren Wang (2014), the DLR can improve the efficiency of a transmission network and help mitigating the congestion in a power transmission system.

DLR can be implemented using dynamic data of transmission lines extracted through monitoring equipment and then feeding them to an appropriate algorithm for the calculation of ampacity. The data will also consist of other parameters of a line including line sag, conductor temperature, etc., and may also carry the information of weather condition parameters including ambient air temperature, humidity, wind speed, direction, solar radiation, etc. A simplified model for DLR assessment is given by Balango et al. (2015) which is reproduced in Fig. 3. Line sensors and weather sensors can be used to measure some of those parameters. Although the existing weather stations can be used to obtain some of the data, their reference heights may not necessarily fit into transmission line scenarios, thus they may result in inaccuracies in the data used in the DLR assessment. Therefore, for a DLR assessment, the transmission lines should have their own weather monitoring system to improve the data accuracy. The line data can be obtained by optical or by on-line monitoring techniques and technologies. The former uses a camera system to check the sag and measure the temperature, while later measures the span of vibration frequencies. Data about the weather and from the sensors then can be used for DLR assessment (Balango et al. 2015). Considering the information of load forecasting, the DLR can also be forecasted. DLR forecast can help the operator to plan the system operations and decide if any action such as DSM is needed to be implemented. The DLR forecast has got a great deal of attention by the researchers
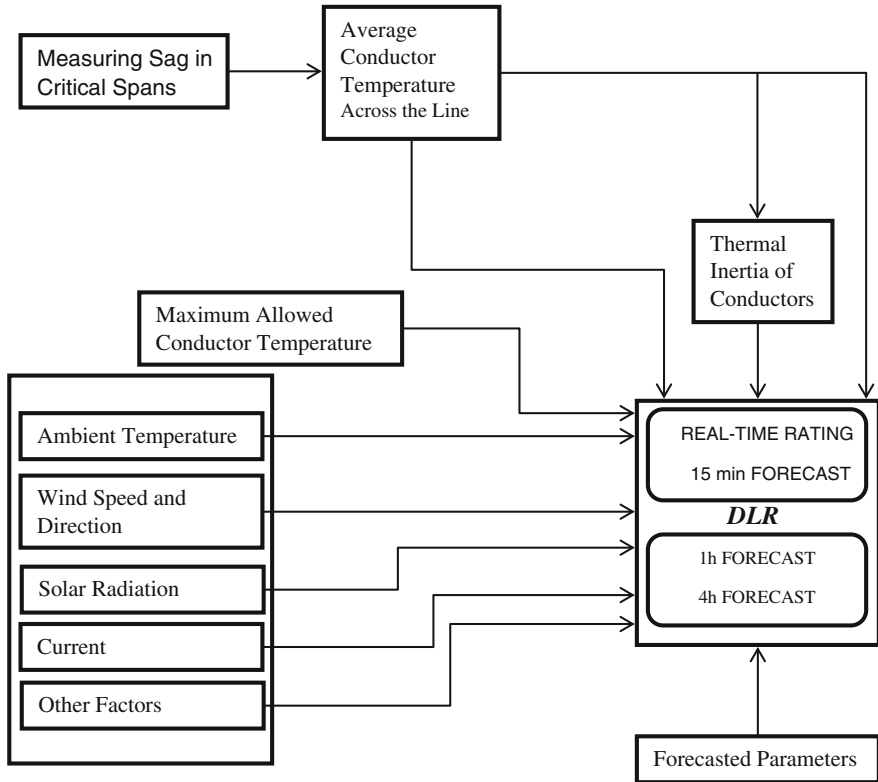
Fig. 3 Simplified model of DLR (Balango et al. 2015)

around the world and can play a key role in the future for the smart transmission system planning.

2.3 Power Distribution Planning

In a traditional power system, the role of a distribution system is to deliver the power received from the bulk generating stations through transmission lines to the consumer loads. A power distribution system consists of assets to deliver the power including distribution substations, distribution lines, poles, distribution transformers, capacitor banks, etc. Distribution system planning includes engineering design of distribution system and load forecasting (Bebic 2008). Load forecasting for generation planning and for distribution planning is somewhat similar. The distribution system engineering is mainly focused on design of a power distribution system. The design process includes site selection and sizing of substations and field equipment sizing and selection, infrastructure asset sizing and selection

including distribution lines. Robustness of the design calculations depend on accuracy of load forecasting.

In a smart grid environment, the distribution system planning will become complex and challenging due to the facts including the significant uncertainties presence in the system is to be taken into account for the design calculations. Integration of RES into a power distribution system has changed the dynamics of the traditional distribution system design. The distribution systems are no more a supplier of power to consumer but it also receives power from the prosumers. The load forecasting alone is not sufficient due to the involvement of the new and renewable generators and their sources may also need a forecast (e.g., wind speed, solar insolation, etc.). Deployment of AMI and intelligently operated transformers are expected to help in managing emerging challenges to some extent however, the grid management is needed to be done in a more proactive manner with the incorporation of advanced forecasting techniques to efficiently supply the energy to customers. Further use of energy storage systems and DSM techniques can contribute to enhance the reliability of the power distribution system with the help of AMI and ICTs however, in such context; their specific roles are yet to be identified.

3 Load Forecasting

Monitoring the system load at all times is the key to operate a power system adequately. To ensure that the system operation is economic, secure, reliable and the control actions are effective, the information about the loads are required in very short span of time of minute to a long span of years as possible. For the duration of seconds, the load variation is very small and can be controlled by the Automatic Generation Control (AGC) actions. However, for the duration of minutes, the load variation can be larger and economic load dispatch has to take necessary measures to alleviate impacts. Similarly, the duration of hours to days has even larger load variations and to operate the system in this context, the operator has to consider economic load dispatch as start-up or shutdown of power generating units, depending on the load variation. Thus, the load forecasting is very important to plan supply of fuel, allocate resources, schedule maintenance activities, expand generation commitments, and expand transmission and distribution system facilities as appropriate. Further, they will provide the utility to plan and operate the system in a reliable manner (Gross and Galiana 1987). In a smart grid environment, the changed dynamics of the system can make the load forecasting even more important with introduction of intermittent RES and ESS which can have significant effects on the load variation. Load forecasting in the presence of DSM is another major emerging research area which has been briefly described in Sect. 5 of the chapter.

3.1 Loads

In a smart grid environment, new types of loads will be added which were never faced by a traditional power system. These loads themselves can act as load or source of supply depend on their operating condition. For example, electric vehicles have changed the concept of conventional loads. They might be consuming power during the day and supplying the power during the night or vice versa. Concept of vehicles to grid is an emerging research topic (Chen et al. 2015) and this needs to be addressed with their interactions at system level as they can play an important in an smart grid environment. The smart homes and smart buildings are also being researched and they are materialized at an escalating pace to cope with the other emerging technologies (Young-Min et al. 2013). Martins et al. (2012) are of the view that these smart homes and buildings will contribute to the protection of the earth environment while reducing their operational costs. They will take into account not only technical issues but also the comfort of consumer. These new loads and technologies have changed the load patterns (frequency, magnitude, and duration) and hence traditional load forecasting techniques are required to be revisited and improved by incorporating the dynamic loads and associated technologies.

The energy market is another platform that determines the importance of load forecasting. Any power system is supported by a number of bulk generating stations which act together to maintain the frequency of the system. Some units of certain generating stations are made responsible for maintaining the system frequency. In the regulated energy market, the utilities are vertically integrated and they oversee the entire power delivery system, while in deregulated market the scenario is different (Mazer 2007). The utilities DTE energy and Consumers energy, in response to question regarding retail market structure in Michigan USA (Energy) differentiated between regulated and deregulated energy market models as "key difference between regulated and deregulated models is their ability to guarantee adequate generation capacity—a cornerstone of reliability. Fully regulated models provide assurance of generation reliability and stability while deregulated markets struggle to ensure that sufficient capacity is built". With these deregulated markets, complexities for the system stability have increased and to achieve the stability in such a system is challenging. Further to this, the feed in tariff has encouraged consumers to install renewable energy to sell energy to grid which can also cause a disturbance to the frequency of the power grid. In such circumstances, accurate load forecasting is vital for the system stability and achieving the ultimate objectives of a smart grid.

3.2 Load Forecasting, Types, and Techniques

According to the forecast horizons, load forecasting is broadly divided into four periods. They are VSTLF (very short term load forecasting) which accounts for the

time from minutes to several hours, STLF (short term load forecasting) which account for the time from hours to weeks, MTLF (medium term load forecasting) which account for the time from months to years and LTLF (long term load forecasting) which account for the time from a minimum of a year to a number of years (Hernandez et al. 2014; Loewenstern et al. 2015). According to Hernandez et al. (2014) VSTLF models are generally used for real time grid management, STLF models are used to adjust generation and demand, whereas MTLF and LTLF models are used to plan asset utilisation and expansions.

The load is usually forecasted using statistical and mathematical models or incorporating artificial intelligence (AI) techniques. The statistical models include regression, multiple linear regressions, stochastic time series, general exponential smoothing, and kalman filter. The AI based techniques include artificial neural network (ANN), fussy logic, expert system, grey system and many hybrids (Khan et al. 2016). The errors in the load forecasting is usually quantified using Mean Absolute Percentage Error (MAPE) (Loewenstern et al. 2015). Statistical methods are more of a traditional method whereas AI techniques are comparatively new. Most of the present research is focussed on AI based load forecasting. The advantages of the statistical methods over AI techniques are that they require less amount data to realise the objective. The AI based techniques require a large data and time to train the system for the improved results. Comparison of MAPE shows that accuracy of AI based load forecasting techniques often prove to be better than statistical techniques (Khan et al. 2016). Although the AI based techniques have a lesser prediction error in their forecasting they may also suffer from their own limitations. Lack of availability of large historical data is a major problem in the usage of AI based techniques (Daneshi and Daneshi 2008).

In statistical load forecasting, input to output is mapped using mathematical equations. This mathematical relationship is developed from different variables which are based on the data provided from the history and they are also dependent on the variables that user deems determinant for load forecasting (Khan et al. 2016). One of the simple statistical technique is the multiple linear regression model (Moghram and Rahman 1989). In this model, the load is calculated in terms of the explanatory variables such as temperature or non-temperature dependent variables that affect the load. This is mathematically presented by Moghram and Rahman (1989) in a form given in (1);

$$y(t) = a_0 + a_1 x_1 + \cdots + a_n x_n(t) + a(t) \tag{1}$$

where $y(t)$ is the load, $x_1(t), \ldots, x_n(t)$ are the variables correlated with $y(t)$, $a(t)$ is a random variable with zero mean and constant variance and $a_0, a_1, \ldots, a_n$ are the regression coefficients. The explanatory variables are defined on the basis of their correlation analysis with the load.

In the case of AI techniques, the models are trained offline to predict the future load and they also require the historical data to do so. In a smart grid, the data which is being taken through AMI and other grid technical data can be fed into the AI system to forecast the load. One of the AI techniques used in the practice is ANN
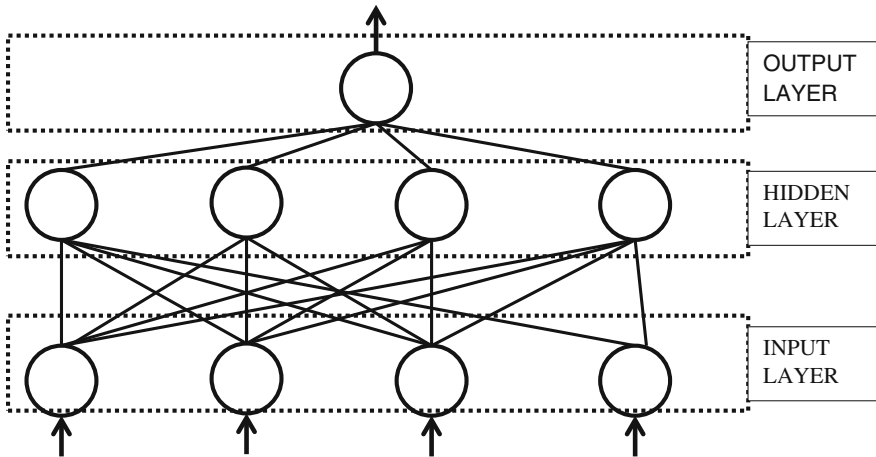
Fig. 4 A typical feed forward artificial neural network

(Artificial Neural Network) which is a computational model inspired by animal or human nervous system. It is the interconnection of neurons that can compute values from inputs feeding information through the network (Khan et al. 2016). With the deployment of AMI, the AI based techniques are more popular than others. A multi-layer perceptron (MLP) type ANN has three layers (Zhang et al. 1998). The first layer is known as input layer which receives the external information. The last layer is called output layer where the output of problem solution is received. The layer joining the input and output layer is called as the hidden layer. Commonly the nodes of two adjacent layers are connected from input layer towards output layer. Figure 4 shows a typical feedforward neural network.

3.3 Very Short-Term or Real Time Load Forecasting (RTLF)

VSTLF is also known as RTLF. A considerable work has been published on STLF, MTLF and LTLF. With the emerging smart grids and their technologies, the RTLF has gain the momentum and researchers have already begun exploring multiple avenues. Changes in load in a smart grid environment within minutes can be much greater than that in a traditional power system.

In regulated energy market, the electricity power network is vertically integrated. In such markets, only the utility controls the entire system including generation, transmission and distribution. However, deregulated or restructured markets are quite different from the regulated markets. It allows independent power producers to generate and supply the electricity to the consumers. Apart from bulk power generating companies, the renewable power generating stations in bulk power

quantities can participate in the electricity market in a smart grid environment. In an electricity market, the objective of the system operator is to maintain the balance between supply and the demand of electricity in an economical way while meeting the security standards. This balance is maintained using the energy management system (EMS) which plans the operations of the generation using AGC and other auxiliary controls and devices. The EMS plans the operations with the help of the load forecasting that it receives and in a smart grid environment, it needs RTLF to ensure that the economic and reliable operation of the system is attained. In a regulated energy market, as the system operator has control over entire generation units, some of the units are dedicated for load-frequency control and they act on the input from the AGC system to respond to any variation in load or any swing in the system. In case of a deregulated energy market, the independent power producers are free to decide if they want to participate in load-frequency control program or not depend on the set criteria. Therefore, the independent system operator can participate in the control of the load-frequency to maintain the power balance. In such cases, the AGC holds the key position to decide the generation levels to balance the market. DSM in a smart grid can also play an important role in the power balance which can be observed by the RTLF. The extent of energy production by the AGC will be determined by the RTLF. Therefore the accuracy of the RTLF is very important for economic and reliable operation of a power system. Daneshi and Daneshi (2008) states that "EMS requires load forecasts within real-time leads, from single to several minutes. These forecasts, integrated with the information about scheduled wheeling transactions, transmission availability, generation cost, spot market energy pricing and spinning reserve requirements imposed by an independent system operator are used to determine the best strategy for utility resources."

Daneshi and Daneshi (2008) developed a model of load forecasting using ANN. RTLF was done using this model and absolute performance error and MAPE were used to measure the accuracy of the load forecasting. A simplified data stream of ANN based RTLF model by Daneshi and Daneshi (2008) is given in Fig. 5.
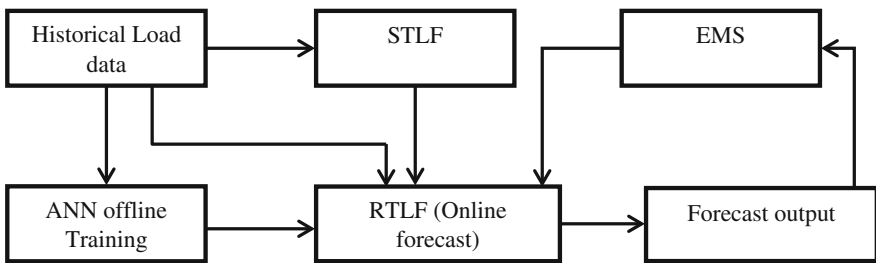

Fig. 5 RTLF model with ANN (Daneshi and Daneshi 2008)

4 Data in a Smart Grid

One of the main differences between a traditional power system and a smart grid is the bidirectional communication which means a large amount of data is to be exchanged. A large network of AMI and smart sensors generate a large amount of data which can be utilized for the optimal planning and operation.

In order to understand the voluminous amount of data that flows in a smart grid, consider the largely deployed phasor measurement units (PMU), which generate up to 50 or 60 measurements per second (Giri et al. 2009). Major portion of the data in a smart grid is the load data of each consumer and prosumer (a consumer with the capability of not only being consuming but also producing the electricity). For consumers, only the consumed power will be recorded while in case of prosumers the imports (electricity consumed from grid) and exports (electricity supplied to the grid) both will be recorded and transmitted to the smart grid for operational decisions. A large amount of data is also being produced by the SCADA (supervisory control and data acquisition) system and AMI which produce data in every 3–4 s and 15 min respectively (Fengji et al. 2015). This data can be very useful to understand the pattern of energy usage of each consumer or prosumer. In addition to the load data, there can be pricing signals, signals to the home energy managements systems, system commands including direct load control, etc. transmitted to the consumers and prosumers. The data collection, finding the information from the collected data, and extracting the knowledge from the information, and management play a key roles in planning the future grid (Chun-Wei et al. 2013).

A variety of data in a very large quantity is available in a smart grid environment. This data can help for forecasting the load in the future from seconds to years. However, this data is to be managed, processed or analysed, and stored for the effective usage. Issues of managing the data is discussed by different researchers including (Ortjohann et al. 2014) and it presents a basic approach by dividing databases of smart grid data into three categories; real time database, archival database, and configuration database. However, in a smart grid environment, the data provided by smart meters cannot be considered as real time data as they are not necessarily instantaneous data and may be received only after every 15 min typically. In such a case, it is more appropriate to have a fourth database which can be dedicated for smart meter load data. Figure 6 shows the architecture of a data management scheme.

The real time database will contain real time inputs such as inputs from PMU, generation data, etc. The metering database will contain data from the smart meters. Archival database will store the data that will be moved from other databases. The configuration database can have the system components data, calculations, and commands.

Data storage architecture of a smart grid is still evolving however the storage needs to be taken place in a manner that best suits the need of application. These applications include grid optimization, load forecasting, DSM, etc. According to Wu et al. (2011) China's smart grid information architecture consists of five
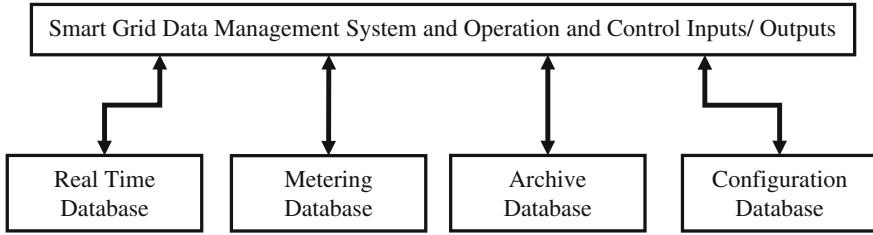
Fig. 6 Data management for smart grid data (reproduced from Ortjohann et al. 2014)
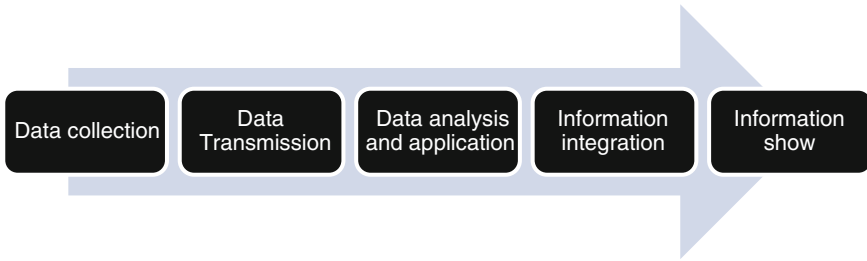

Fig. 7 China's smart grid information architecture (reproduced from Wu et al. 2011)

hierarchies which are shown in Fig. 7. This architecture stresses upon getting the knowledge from the information extracted from the data as explained by Chun-Wei et al. (2013).

To analyse the big data in a smart grid, there are different data mining and data clustering techniques. Different emerging technologies used in respect of big data analysis include quantum cryptography, cloud computing, secure multi-parties computation, MapReduce parallel processing framework, data-centric data storing and routing technologies, imprecise data querying, uncertain data mining and many more (Fengji et al. 2015). For data mining, the data samples are often considered to be having definite value but techniques which can bring out the uncertain features of the data are becoming more popular amongst researchers and data clustering is one of them (Tsang et al. 2011).

4.1 Data Clustering

Data clustering makes clusters of data with similarities and keeps dissimilar data into different clusters. Two clusters should have dissimilar data with respect to each other while similar data within themselves (Anderberg 1973). Data clustering can be used to classify the big data available from the smart meters of consumers and prosumers spread across a large area. The important factor in the data clustering is

Fig. 8 Clustering procedure (reproduced from Xu and Wunsch 2005)
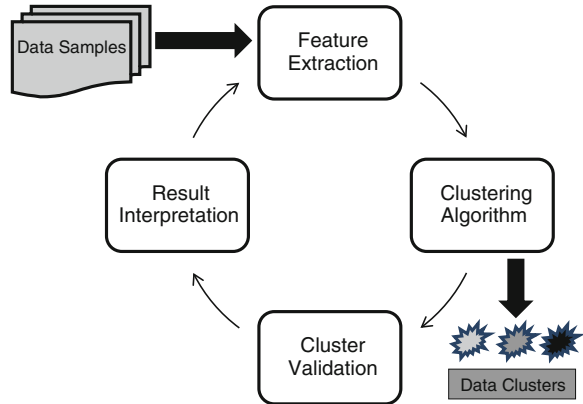
defining the clustering rules, i.e. the determinant factors which affect the accuracy of the clustering (Anderberg 1973).

Xu and Wunsch (2005) divide the data analysis procedure into four steps; feature selection or extraction, clustering algorithm design, cluster validation, and result interpretation. Figure 8 shows their clustering approach.

Hierarchical and K-means clustering can also be used in a smart grid environment for data clustering and there are some researches into further advancing the techniques.

4.1.1 Hierarchical Clustering

The hierarchical clustering is represented by a tree diagram called dendrogram. The dendrogram is a multilevel hierarchy in which one cluster is connected to another on a different level. The most important element for performing the hierarchical clustering is to find the similarity between the clusters. The process is iterative and clusters are merged into bigger clusters until a suitable or desired number of clusters are achieved. Determining the similarity between the clusters is dependent on the distance between the clusters (Prahastono et al. 2007). Young et al. (2011) described the processes of hierarchical clustering to generate load profile, which is shown Fig. 9.

4.1.2 K-Means Clustering

In K-Means clustering the data set x^m containing 'm' number of elements $(m = 1, \ldots, M)$ is divided into 'k' clusters $(k = 1, \ldots, K)$ by means of an iterative procedure. The initial 'k' is selected randomly for k cluster centres. The optimal number of clusters cannot be known beforehand and the quality of clustering is dependent on the number of clusters, i.e. 'k' (Chicco et al. 2003). K-means
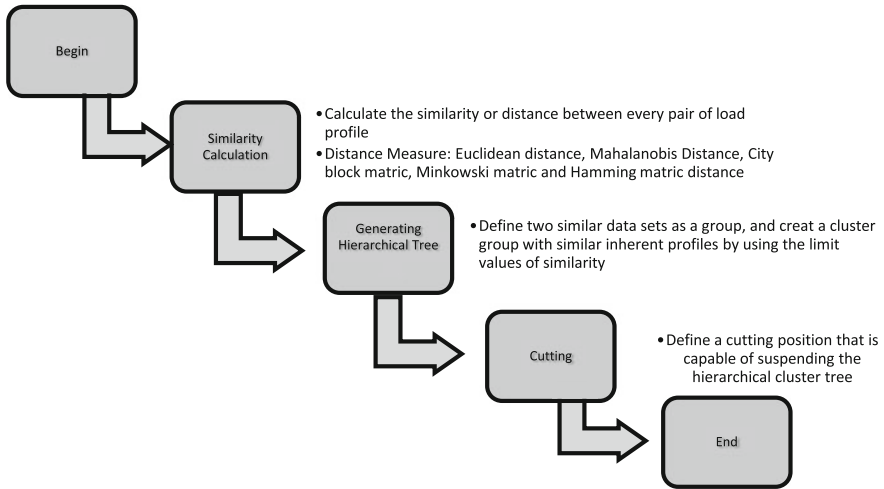
Fig. 9 Hierarchical clustering (reproduced from Young-Il et al. 2011)

clustering for classification of load profiles can be divided into parts and they are shown in Fig. 10 (Young-Il et al. 2011).

Quilumba et al. (2015) applied the K-means clustering technique for the AMI data from the individual consumers to generate VSTLF. One of the issues of the K-means clustering is to find the optimal number of number of clusters or in other words 'K'. To find the optimal 'k', the MAPE technique, which matches the output forecast with the real output and checks the variation between the both, is used. This process is carried out for different numbers of k and hence the optimal number was considered as the one which has the minimum variance.
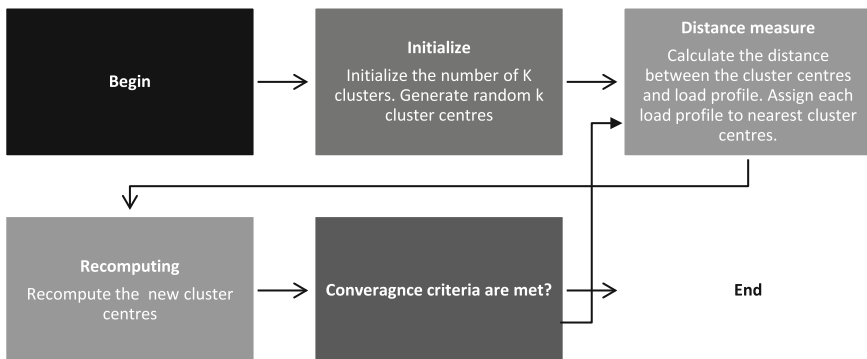
Fig. 10 K-Means clustering (reproduced from Young-Il et al. 2011)

5 Demand Side Management

Demand side management is another area which was not rigorously applied in a traditional power system. It is an extended dimension of research emanating for the smart grid environment with active customers. According to Peter and Dietrich (2011) DSM is the "Portfolio of measures to improve the energy systems at the consumption side". These measures can be taken into account by considering the desired output. The measures themselves can be in the shape of improving energy efficiency, dynamic pricing tariff, or smart scheduling, etc. Figure 11 shows an overview of the categories of the DSM.

One of the purposes of DSM is to optimise the energy such that the operation is feasible and network resources are wisely usable. Optimized demand in a smart grid can play an important role for improving the energy efficiency and to enhance the grid stability and the reliability. There are several ways of implementing DSM techniques including direct load control, load limiting, fuel management, home energy management, etc. The DSM can serve in many forms as peak clipping, valley filling, load shifting, load profile reshaping, cost and emission reduction, strategic conservation, strategic load management and flexible load shaping (Gelazanskas and Gamage 2014; Khan et al. 2015; Zhang; Gellings 2009). Using DSM techniques, the utilities can incentivise the consumers to reduce or increase the load as per the system and other needs. DSM also needs the information on the forecasted load. The real-time load forecasting is more desirable in a smart grid for achieving the DSM objectives.

As a result of DSM, there can be a change in the level of load at times and this may also affect the forecasted level of load. This is where the importance of RTLF comes in and STLF unable to manage such changes. Garulli et al. (2015) investigated this issue and they modelled such scenarios in detail. Their findings showed
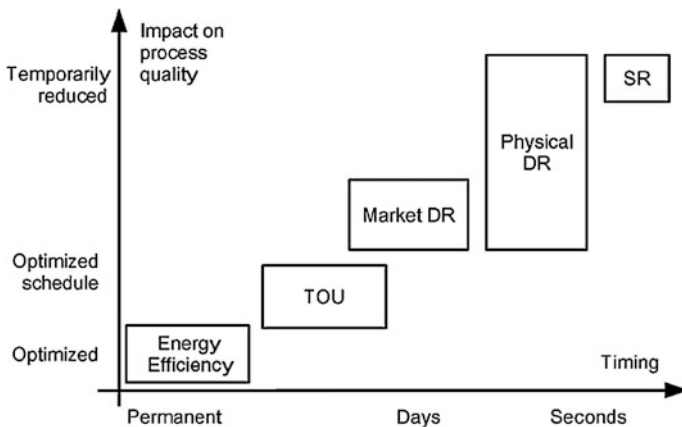

Fig. 11 Categories of DSM (Palensky and Dietrich 2011)

that the DSM can potentially introduce a non-negligible perturbation in the behaviour of the load. They incorporate black-box models and gray-box models in their scenario analysis. The black-box models do not require pre-processing of the raw load data time series and the gray-box models are applied after pre-processing of the load data. From the results of these models, it is clear that linear Transfer Function models provide more details, once the base-load component has been extracted from the raw load data. Otherwise if no low frequency component is extracted from the original data, nonlinear techniques such as Support Vector Machines (SVM) or ANN can be used for the purpose.

Apart from load forecasting, the DSM helps improving the efficiency of asset utilisation. It can also be considered as a potential source to mitigate the shortfall in the generation portfolio and to ensure economic load dispatch with optimized usage of RES.

6 Smart Grids, Infrastructure, Operation and Security Issues

A smart grid infrastructure can be composed of many innovative technologies, algorithms, and networks including AMI, ICT, PMU, wireless sensor network (WSN), distributed generation, smart controllers (remote terminal units), SCADA, monitoring and control algorithms, home energy management systems, and other smart components which in combination make the smart grid more efficient and reliable compared with the traditional grid. Major advantages of a smart grid include the increased efficiency, self-monitoring, real time monitoring, self-healing, automated control and operations. Table 1 presents a comparison of a smart grid over a traditional grid.

The AMI records the consumer load and transmits the data to the grid through the communication network. It can help in load forecasting, decision making, DSM, system operation and future planning. Monitoring infrastructure, WSN, and smart sensors take different types of measurements for monitoring the grid conditions and help maintaining the grid stability. PMU is one of the examples which measure the system voltage and current many times in every second to check the status/condition of the equipment/system. The home area network, wide area network and ICT including zigbee, wimax, etc., ensure that the reliable transmission of data flow to and from the grid. Power line carrier communication can also be used for communication. The control algorithms and control equipment including remote terminal units are playing a vital role in analysing and decision making for the grid operations. Infrastructure of a smart grid may have the advantages of integrated micro grids that can be operated in the grid connected and the islanded modes. Further functionalities including dynamic pricing, direct load control, and other DSM programmes help strengthen the reliability and the economy of system. Proliferation of ESSs in smart grids also enables the grid to work more efficiently

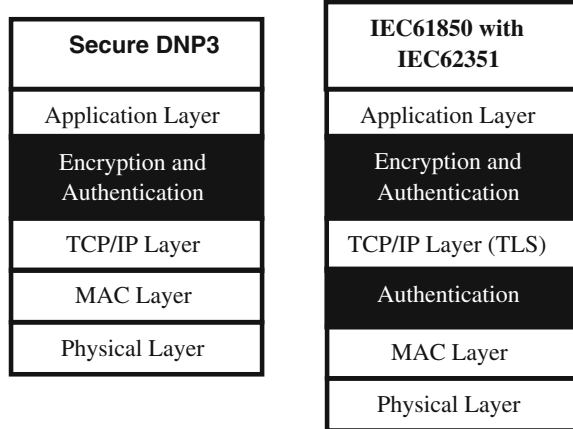**Table 1** Comparison of traditional and smart grids

Traditional power grids	Smart grids
Electromechanical	Smart technologies, cyber based operation
Uni-directional communication	Bi-directional communication
Uni-directional power flow	Bidirectional power flow
Centralized generation	Distributed generation
No real time monitoring	Real time monitoring of network
Few sensors	Sensors throughout
Manual monitoring	Auto/Self-monitoring
Manual restoration	Auto/Self-restoration
Failures and blackouts	Adaptive and islanding
Limited control	Higher control
No or very low energy storage	Grid tied energy storage
Consumers	Prosumers
No consumer involvement in grid stability	Consumer involvement opportunities
Conventional infrastructure	Smart infrastructure
No intelligent electronic devices present	Intelligent electronic devices present

and reliably. All of these components and features allow smart grids to optimise its operation dynamically and to open further planning and operational horizons and functionalities.

Although the highly digitalized or computerized grids are seen as more secure and reliable, they may also have vulnerabilities irrespective of how smart or how much investment is provided to be smarter. The smart grids are typically composed of a cyber-physical system which can be a corridor for cyber-attacks resulting adverse impacts on the physical power system. Sidhar et al. (2012) describes the cyber layer as cyber systems, consisting of electronic field devices, communication networks, substation automation, and control centers that are embedded throughout the physical grid for efficient and reliable generation, transmission, and distribution of power. The cyber-physical system is also prone to security risks at generation, transmission, and distribution levels. At the generation level, the automatic voltage regulation and AGC are vulnerable to cyber-attacks and in such incidents on former, the system frequency can be disturbed and system stability can potentially be threatened. False data injection can also be a problem for the power transmission system. AMI is also prone to cyber-attacks with the smart meter and other data reading (Sridhar et al. 2012). Cyber-physical attacks can be classified into three categories i.e. physical attacks informed by cyber, cyber-attacks enhancing physical attacks, and use of cyber system to cause physical harm (Committee 2013).

Smart Grid Cybersecurity Committee of "National Institute of Standards and Technology (NIST)" USA in its guidelines (Committee 2013) says that the basic objective of the cyber security is to ensure the reliability, integrity, and confidentiality of data protection in a smart grid. Communication system is the most vulnerable to the cyber-attacks and the communication protocols are of vital

Fig. 12 Secure DNP3 and
IEC 61580 with IEC62351
(Wang and Lu 2013)

Secure DNP3
Application Layer
Encryption and Authentication
TCP/IP Layer
MAC Layer
Physical Layer

IEC61850 with IEC62351
Application Layer
Encryption and Authentication
TCP/IP Layer (TLS)
Authentication
MAC Layer
Physical Layer

importance for the cyber-security. The two largely used protocols in power system
are the Distributed Network Protocol 3.0 (DNP3) and IEC 61850. DNP3 describes
the communication between client stations, RTUs and intelligent electronic devices
(Mohagheghi et al. 2009). IEC 61850 is a standard designed by international
electro-technical committee for substation automation and can be used for future
smart grids for communication outside the substation (Mohagheghi et al. 2009).
Wang and Lu (2013) proposed Secure DNP3 and IEC 61850 with IEC 62351 to
achieve end-to-end security for the power grid communication. Figure 12 shows the
multiple security mechanism in a smart grid environment (Wang and Lu 2013).

Smart grids need the deployment of new and innovative technologies which can
create new and complex challenges that may not be faced by traditional power grid.
New challenges create new research for the innovation of new tools and techniques
and the power system research will embark into a new paradigm of research. Smart
grids research will not only look its own area of research due to the highly cor-
relation of other industries including manufacturing and water resources with the
power sector and to meet the ultimate objectives. Thus, the future power system
will be embarking into interdisciplinary researches for the sustainability of energy
and other resources. Thus, one can also see the smart grid as a grand challenge.

7 Summary

Planning and operation of future power systems require a great detail of attention
with the deployment of intelligent control and coordination devices and associated
elements. With the growing concerns of the global warming issues, increased
uncertainties, and increased challenges, the smart grid is the foreseen solution for
the future of electricity grid. The transformation of the traditional power grid to a
smart power grid requires a considerable level of advanced planning in order to

mitigate the critical impacts and to achieve the anticipated smart grid objectives. Operation of a smart grid can further be challenged by the interaction of multiple layers from the physical level to the cyber system.

One of the most important parts of a power system planning is the load forecasting. In a smart grid context, the load forecasting uncertainties can further be increased with the reliance of many intelligent devices and their interactions. The accuracy of load forecasting can potentially be increased however, over reliance of smart elements in the grid may also pose a risk.

Although technologies of all components may be known to power system engineers in the future, combining them into a coherent manner such that they act coherently is a complicated task and further its integration with the present system while ensuring the interoperability of the components are even more challenging. Emerging smart grids seem very appealing however; the complexities involved in the deployments are more of a techno-economical battle to an extent. While technological advances exist, smartness of components, smart operations of the power grid, and the deployment of the smart grid objectives will also face many challenges and complexities. These challenges are being researched upon by some researchers. They can be identified at this stage as lack of trained manpower, unproven technologies, high risk with highly smart technologies, large volume of data to manage, data privacy, integration and interoperability of different systems and technologies, intermittency of renewable power generation, power quality issues, etc. Further to these challenges, the cost of deployment of a smart grid will potentially be very high however, if the technical challenges are overcome, the benefits will potentially surpass the investment barriers. Therefore despite the challenges, smart grids present a smart future for the sustainable electricity grid.

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Applied Research in Energy Storage

Andreas Helwig

Abstract The development and incorporation of energy storage into large electricity networks, micro-grids, and partially or fully islanded energy supplies have numerous applications as the sustainable energy generation uptake increases. The vagaries of sustainable energy supplies are driving the energy storage in two distinct directions. Firstly, there will be large scale energy storage such as pumped land or sea-based hydro-energy that can absorb excess renewable energy for the later discharge when there is a deficit in dispatchable energy available. As an alternative to large industrial scale units, there is a potential to develop smaller but numerous distributed smaller energy storage systems that are based on inertial or electro-chemical battery storage. These developments present huge opportunities to change the way sustainable energy uptake continues. Integrated energy storage into electrical supply networks has the ability to alter the way national, regional tied trade blocks and global energy linkage will occur in the future.

Keywords Artificial spinning reserve · Battery energy storage · Flywheel energy storage · Pumped-hydro · Energiewende

1 Introduction

In a traditional power generation/supply network, the spinning reserve of gas or steam driven turbine-generation units exceed the normal load steps to ensure that the power supply network frequency remains stable. System spinning reserve is normally defined as the difference between full load operational capabilities of the on-line generation units less the actual smaller operational load applied at any one time. If the spinning reserve is insufficient, then when there is a significant load step (or a major fault occurs), the frequency of the distribution network begins to drop.

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If the speed controllers of the generation units cannot respond sufficiently to compensate, then some network loads will have to be shed. If insufficient load is shed in time, and the frequency continues to drop, then under-frequency protection will act to disconnect generation units and results consequential significant black-outs. Therefore, the spinning reserve in electricity supply networks is critical, requires careful calculation and monitoring, and comes at a standby system cost. Integration of renewable energy sources into large electrical supply networks and also into micro-grids presents a number of challenges. The minute by minute, day by day and season by season variability of many sustainable energy generation sources can become problematic for any type of electricity supply network.

Increasing penetration of sustainable energy source generation into a distribution system network begins to manifest operational problems when its total generation capacity exceeds the other conventional steam or gas turbine generation sources' spinning reserve. Either system costs have to increase due to the need of bringing on line additional spinning reserve generation units, or alternative technology solutions have to be implemented. Potential ways to increase the spinning reserve of a system is by using energy storage systems (ESSs) which have different rates of response and maximum periods of operation. Energy storage systems discussed in this chapter are limited to[1]:

 (i) Pumped hydro-power energy storage systems (or PHESS);
 (ii) Large scale (i.e. 1–20 MWh or larger) battery energy storage system (or BESS);
(iii) Distributed industrial and domestic small scale BESS (i.e. typically 5–40 kWh units) that in part partially or fully match the daily excess energy output of local PV (Photo Voltaic) or sustainable energy source generation capacity;
(iv) Inertial flywheel energy storage systems (or FESS).

An added complication is typical national or even inter-country energy generation markets, where bidding and averaging times, and ancillary market services for

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[1]*Note* Flow batteries such as the zinc-bromide type are also potential technology solutions, but currently most require renewal of active cell exchange surface membrane at specified periods as detailed by ZBB Energy Corp (2011). Their online/offline availability criterion therefore has a crucial difference from the ESS technologies listed above. Similarly IEA-ETSAP and Irena (2012) also report on other energy storages such as compressed air energy storage (CAES), vanadium redox flow cell, super-conducting magnetic energy storage (SMES) and the NaS battery. However CAES has not achieved sufficient turn-around efficiency to challenge the other technologies discussed, and has limited opportunities for suitable storage sites that do not have or develop gas leakage. The vanadium redox battery pilot plants such as trialed for example by the Tasmanian Hydro KIREX Project (2003) have not been found to be robust in operation. SMES system superconducting materials remain expensive as does the coolant and protection systems; and the NaS battery requires high temperature operation of above 300 °C. Their potential future integration in significant numbers into the global power and generation industry depend on more theoretical research to pilot plant development, and are therefore not discussed here as applied research.

Table 1 Typical operational characteristics of ESS

ESS type	Rating range	Response time	Running time	Asset life
PHESS (Akhil et al. 2013; Helwig and Ahfock 2015)	100–1,000 MW	(i) From synchronous condenser mode to full power: 10–20 s (ii) Cold start: 5–15 m	0.5–10 h	>50 y
Large BESS (Akhil et al. 2013; Reihani et al. 2015)	0.5–20 MWh	4–10 ms	1 s–3 h	2,000–9,000 cycles#
Small distributed BESS (Helwig and Ahfock 2015)	5–50 kWh	4–10 ms	5 m–3 h	
FESS (National Energy Tech. Lab. 2013)	25–360 kWh	4 ms	10 s–15 m	125,000

\# Dependent on type battery electro-chemistry of the battery

security of the network will in the future define the roles and ratings of energy storage systems. Typical time periods in such energy markets vary from milli-seconds for ancillary service delivery for system security, to 10 min for generation capacity supply bidding, to 30 min average spot prices. Table 1 shows typical rating ranges of the ESS listed, with their typical response times and on-line time limits. (As a benchmark, steam powered turbine units, if already up to operational level, can respond from no-load to significant load take up in 15–20 min, while gas turbines if up to operational speed respond in seconds to a few minutes. Naturally cold start response of either of these is significantly longer.) In a large distribution network, the complex intermixing of variability of the prime sustainable energy source drivers (e.g. agricultural-waste energy, solar insolation and wave or wind), large conventional turbine generators, distribution network length and intricacy of the operation of various energy markets give opportunity for many areas of applied research into the energy storage technologies. Applied research is being driven by technical innovation, environmental policy, and reducing capital investment requirements/operational/life costs to keep energy costs as low as possible to the consumer, while being sufficiently profitable for the generators and distributors of energy.

2 ESS Research Emphasis

Research into each of the ESS technologies is traditionally driven solely on a narrow technology interest itself. However, energy security is beginning to interlink the prime requirement to achieve long-term sustainability, i.e. sufficient energy,

clean environment to support life for current and future generations, food security and fresh potable water security. These four key areas are beginning to directly mesh into much larger systematic and integrated research with energy storage and sustainable power generation. Similarly, integration and hybridization of electrical technology on larger scale integrated supply networks is also driving the research. Of course there is a continuing single technology based development, e.g. electro-chemical battery research to reduce costs or development of new battery types, inverter technology and super-capacitors. However, this is already well represented in scientific, engineering discipline, or technology based research literature.

2.1 Current System Integrated ESS Research

Applied research in integration of ESS into larger electrical energy networks serving national, or world regional trading partners and global development is a field that remains open to more detailed systematic investigation for improved technical efficiency and sustainability, large system dynamic response to load disturbances, and financial optimisation. Following are some examples of system integration research that has been undertaken, and continue to be researched.

2.1.1 PHESS Integration with Water Supply Grids and Close Coupled with PV Arrays

As an introduction to this, typically in Australia (as in many developed nations) debate continues between fossil fuel hydrocarbon based generators and the renewable energy sector. MacGill and Bruce (2015) suggest that the government energy agencies and electricity industry consider that the 4.2 GW now deployed in solar energy generation across Australia may be 'too successful'. As solar PV generation increases, solar sellback rates decrease typically. The PV feed-in tariff has been reduced in the last 2 years for new domestic solar arrays from $0.44/kWh on excess PV energy, to $0.06/kWh. Any domestic self-consumption of PV energy provides a cost offset to the consumer against a nominal average $0.24/kWh resulting in a $0.18/kWh incentive to better manage domestic self-consumption and reduce small domestic PV array energy export.

This is not all that different to the situation that is described in Germany by Stetz et al. (2015) where self-consumption for zero export is now encouraged by a €0.17 (~$0.25) margin per kWh. However, the German government has also introduced an incentive program to continue development of sustainable energy sources. This includes soft loans of €600 per kW for PV combined with a battery energy storage system (BESS), on the agreement of the domestic supplier to limit the grid feed-in energy to 60 % of the PV capacity. In 2015, Germany has 38 GW of solar energy generation capacity now installed and supplying 6.5 % of national electricity use,

with Government policy aiming for 52 GW capacity by 2020. Germany also has over 9 GW of pumped-hydro energy storage systems installed. Sustainable energy sources now account for 30 % of Germany's electricity consumption. It further intends to expand this to 40 % in 2025, to achieve the European Union's requirement by 2020 of 35 % from renewable sources. Karnitshnig (2014) reports that Germany also intends to increase this renewable energy share to 60 % by 2050 with a major infrastructure investment program initiative. From a German national grid perspective, when renewable energy sources reach 40 % of demand, then additional energy storage is required for system stability and spinning reserve.

As reported by ScienceDaily in 2013, Norway is proposing sea-based PHESS air-filled reservoirs on the seabed to tap the sea surface level to sea floor base hydrostatic potential. The Norwegian deep coastal fiords provide a number of potential sites for such pumped seabed hydro-storage systems. During the energy storage, seawater is pumped out of submerged reservoir to become an air void (i.e. to allow this, the above sea surface atmosphere is connected to the seabed reservoir by a snorkel tube). Energy generation would be then initiated by allowing seawater inrush into the sea floor cavity through the hydro-generator port, while the reservoir air vents back to atmosphere. For such technology hydraulic heads of over 400 m are quite possible to achieve, and in other global sites up to kilometer head could be achieved. The current limitation of this proposed ESS is development of the appropriate concrete or other tank materials for anchoring into the seabed and that can easily be formed and cure to sufficient strength to withstand the fill and empty cycle stresses at such ocean depths.

As reported by the American Wind Energy Association (2012), Wiser and Bolinger (2012) and the U.S. based Solar Foundation (2011), the USA based renewables industry has continued to rapidly expand both its wind and PV energy penetration; and while doing so creating many new job opportunities in manufacturing, installation and maintenance. Even though in 2010, there was 21 GW of PHESS available, the USA continues pursuing greenfield sites for the PHESS as sustainable energy penetration increases. The U.S. Department of Energy/Electric Power Research Institute (DOE/EPSI) Electricity Storage Handbook prepared by Akhil et al. (2013) provides daily operational present value Levelized Cost of Energy (LCOE) range for existing PHESS as being between US $0.15–0.20/kWh for a turn-around efficiency of up to 80 %, based on a 60 year asset life. For greenfield sites, the cost for new such energy storage schemes is estimated to be US $1,200 per kW of the proposed installation. By comparison, Australia's PHESS capacity is 1.5 GW, and has not increased in the past 30 years. Australia does have more potential for PHESS dam sites. As a typical example, recent investigation in Queensland (Australia) has revealed two existing water storage dams in Northern Queensland, two in central Queensland riverine dams with and additional site for one in its south-eastern region associated with a large local water storage dam. Private companies in both the USA and Australia are also looking closely at old open cut deep mine pits as potential locations. Typical parameters to make potential PHESS dam sites viable economically are:

- Greater than 200 m hydraulic head;
- Within 25 km or less of a HV feeder network;
- 3–6 G-litre storage easily achieved with less than 10 km of penstock tunnel or pipe;
- Suitable for 100, 250 or 500 MW hydro-generation capacity for minimum of 1 h to a maximum of 4 h capacity.

Helwig and Ahfock (2015) modelled a the south-east Queensland 100 MW PHESS with a 230 m hydraulic head for a potential 6 G-litre Jockey Creek dam added to the 82 G-litre Cressbrook Dam that is Toowoomba's largest water storage unit. The model was constructed using HOMER Pro © 2015 software. The model looked at a number of parameters based on use of local Queensland off-peak rates available at $0.05 per kW-hr cost, an option of a 50 MW close coupled local large PV array for water pumping, and a further option combination of a mix of off-peak and close-coupled PV arrays. The model was to investigate this system's $ LCOE break-even costs and compare them to the DOE/EPSI Akhil et al. (2013) reported costs. The initial model based on current Australian construction costs returned a best $ LCOE of $0.45 for the 50 MW solar close coupled PHESS option. For this model to achieve similar viable cost to those in the USA the following conditions would have to be met:

- Government infrastructure dollar investment for operator dollar borrowed investment capital, as is already the case for many Australian National and State Government infrastructure projects of national importance.
- Close-coupled large array PV gave the best results installed at $3.00 per kWh (i.e. these costs are already achievable) of PV capacity on a site nearby the PHESS.

If these conditions are met, then model results are summarised in Fig. 1. Here the cost of stored electrical energy ($ LCOE Y-axis) is plotted against the sale of energy price during peak periods as recorded for a series of incremental different HOMER ENERGY optimising models. The breakeven points of costs are indicated by the vertical lines for each major case scenario of PHESS storage.

Further investigation into the Australian electricity market revealed some issues that may be problematic to the further PHESS development. Here has an under-developed switchable baseload market which would be based on a spot price of up to $1,000/MWh credit for loads (AEMC 2012) that can absorb energy during troughs in the baseload demand. In Queensland, the single 500 MW PHESS at the Wivenhoe/Splityard Creek dams in SE Queensland is treated more as a generation entity or ancillary service synchronous capacitor, which limits its potential use of this facility for a switchable base-load levelling storage in the Australian national electricity market. However, in the U.S. it is a different outcome. In the more deregulated open-market many generator entities own their own PHESS, which they use in tandem with base-load generation plants to maintain off-peak baseload at optimal costs by storing energy during low baseload demand periods, as well as providing reserve energy storage capacity for excess renewable energy when available.
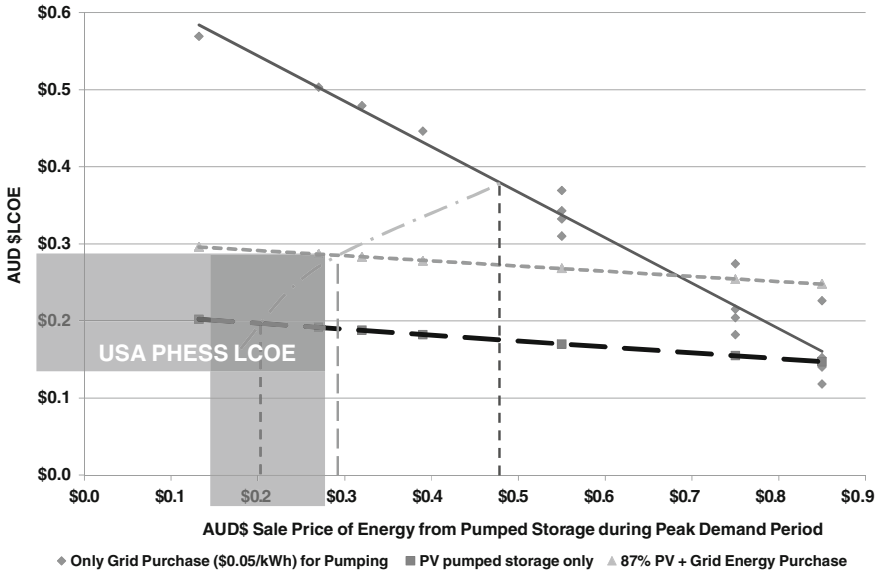
Fig. 1 PHESS modeling for break-even points of $ LCOE cost Y-axis for Queensland (Australia) versus break-even peak period sale cost of electricity for off-peak power costs, PV and off-peak power costs and PV stand-alone pumping

Sustainable energy generation expansion with its variability requires increasing energy storage capacity to act as artificial spinning reserve, as Germany has already realized as reported by Stetz et al. (2015). Thus, there are geographical opportunities and energy market regulatory issues that may need investigation to encourage PHESS development to become more easily embedded in national or international energy grids. These include:

- Global survey of potential PHESS dam site with beneficial head of greater than 200 m, and geographical location close to major HV network backbones. Careful consideration is also needed to minimise environmental impact for such sites to have long term sustainability advantages.
- Site availability for close-coupling with large PV arrays or Windfarms to absorb energy is an advantage to further improve sustainable energy and reduce energy storage costs (i.e., due to reduced transmission losses).
- An electricity market model that investigates energy storage as a means to an end to increase sustainable energy generation penetration. This would include a workable switchable baseload market segment for energy absorption by PHESS.
- Applied research dynamic modeling that combines 3-phase power inverters, some BESS with large PHESS permanent magnet generators/pump motors to investigate their abilities to change from energy storage mode, synchronous capacitor mode to energy generation mode in milliseconds.

PHESS can also play a potential role in fresh water supply networks. In the model for the south-east Queensland (Toowoomba) example, it was found that the Jockey Creek PHESS could reduce the costs of reticulated potable water to Toowoomba from Cressbrook dam. As compensation for resource rental of 8 G-litre capacity from the regional council owned Cressbrook dam for a PHESS, only a small 0.02–0.03 G-litre/week water bleed-off would be required from such a Jockey Creek upper PHESS pondage storage. This would drastically reduce by more than half the cost of the water pumping to overcome the hydraulic lift from the local Cressbrook dam storage (which is over 350 m below the elevation of the gravity supply point to the town of Toowoomba). Extension of this throughout Queensland using PHESS not only to act as a sustainable energy storage, but also to potentially transfer fresh water North or South between the four major east flowing riverine basin that all empty into the Pacific Ocean, warrants further investigation, especially as Queensland is prone to severe periodic droughts. These are similar major potential studies that are likewise required in Asia as water resources are being more heavily used for hydro-power generation putting pressure on agriculture and water supplies to settlements below new dams.

Hence combined applied research models for energy storage, water supply security and associated financial models remains a priority for land based PHESS. There are also new models to develop for close to shore and offshore potential sea-based PHESS systems.

2.1.2 ESS for Large PV Array Short Autonomy Periods

At present, planning and implementation globally for very large array PV sustainable energy generation is rapidly on the uptake. Australia as noted by McGill and Bruce (2015) has already greater than another 2 GW of solar potential under design and potential development in New South Wales and Queensland alone. These PV arrays will vary in size from 80 MW to 600 MW output ratings. Eskom in South Africa is also developing planned implementation of 2–50 MW PV arrays, while in California USA, development of both very large flat-panel based and high efficiency solar concentrators already is under implementation. This U.S. development is based on the opportunity via the national grid to export peak solar from the south-west across to the east coast of USA during the late afternoon for shoulder loads leading up to, and including, the start of the evening peak demand.

On the other hand, SE Queensland with its current 750 MW PV capacity, already experiences periodic problems with afternoon weather events suddenly reducing this region's solar output by more than 400 MW due to fast moving weather fronts. Where local spinning reserve cannot take up the load fast enough, then power has to be imported via Australia's national energy market. There have been a few recent events where power import rose for average bidding periods above $1000/MWh and on one occasion where it rose above $10,000/MWh. This resulted from poor forecasting of solar generation capacity interacting with predicted forward bidding capacity required from the spinning reserve from

conventional thermal power stations in Queensland. This is particularly problematic if this brings the afternoon shoulder load forward in time. Concentrated high domestic PV penetration or very large solar PV arrays can present a problem in electricity markets like in Australia. Here in 20–30 min cycles with 10 min bidding periods, then loss of a very large PV power generation source rapidly due to a major cloud weather event, if not forecast correctly, put result in unscheduled huge import costs on network distributors. Similarly transient cloud movements across a large array can diminish PV output by 5–20 % with fast fluctuations in output to the grid.

Very large PV arrays provide opportunity to incorporate ESS with autonomy periods of 20 min at short high rates of discharge. This would then allow a large scale PV or wind generator to guarantee supply for an electricity market bid that had been forward accepted. A close coupled ESS provides 'artificial inertia' as a local spinning reserve associated with such very large arrays. Provision of such energy storage 'artificial inertia' would also allow regulation of output supply to guarantee delivery of accepted electricity market bids for short autonomy periods in the event of major weather events. Provision of close-coupled ESS reduces both frequency and local bus voltage fluctuations in electricity supply networks that can result from the rapidly variable output nature of many sustainable generation sources.

Potential BESS systems hybridized with super-capacitors are possible solutions to improving performance and life for remote area power supplies as reported by Helwig and Ahfock (2009). These may also form a basis for high performance close-couple energy storage systems for large PV arrays or large windfarms. The Ultra-battery lead acid variant developed and reported by Furukawa et al. (2005), Lam and Louey (2006) and Akasaka et al. (2006) for use with electric vehicles continues development for wind energy. In the Ultra-battery, special very high surface area carbon foam had been added as an asymmetric half dipole ionic capacitor to the positive plate structure of the lead acid battery. Research into this battery now for wind power applications has shown that the ultra-battery has 1.5 times the life of conventional valve-regulated wet lead acid battery. This extension in life is achieved as a result of the rapid charge capability of the super-capacitor to absorb energy from a wind generator experiencing a gust of wind, preventing short duration over-potential spikes during charge that split the water in the electrolyte into the elemental gaseous state. The reduction of free oxygen particularly reduces the overall rate of corrosion in the battery. Similarly, on rapid discharge during a sudden lull in the wind, the ultra-capacitor is used to supply the initial high spike in energy required for such a load step. As a result, this reduces depletion layers forming in the lead acid cell, where localised pH boundary layers near to the value of 7 (or water) can form close to the battery plates. Preventing such random, but numerous depletion layer events reduces corrosion fatigue build up.

An alternative example of a rapid charge and discharge battery to smooth variability of sustainable energy generation output, but of a completely different type is the Beacon flywheel energy storage system (FESS). This Beacon FESS type is very high speed inertial energy storage, as reported by the National Energy Technology Laboratory (2013). It has been implemented in the United States

California region using a 20 MW Beacon Flywheel high speed inertial battery with an autonomy period at full output of 15 min. The Beacon flywheel inertial batteries have short time rated battery duty cycles for very high rates of discharge with long cycle lives (estimated to be 250,000 cycles) that remain a challenge for many electro-chemical batteries. The flywheel batteries, are generally composed of carbon fibre composites, do require specific safety design requirements. The Californian 20 MW unit is modulised in 200 kW rated units, and the flywheel is placed in a pit so that any failure of the high speed rotating inertial mass is fully contained. This has proved wise, with a two failures of these inertial batteries already occurring. These needed safety requirements do increase capital costs of such inertial flywheel batteries.

Another example of grid tied energy storage systems is being undertaken by AusGrid in Australia where currently it is implementing a trial 1–2 MWh BESS placed in a specific network bus line location for peak load shaving to defer capital development of a major feeder for growing local peak loads.

In terms of micro-grids, Tasmanian Hydro in Australia has also implemented a unique sustainable energy generation unit close coupled with ESS for the isolated King Island community. Here, a large BESS, plus a large low speed flywheel provide the ability to damp the windfarm output due to wind gusts from the very strong 'Roaring Forties' eastward airflow that circulates around Antarctica. Alternatively it can supply energy needed during sudden lulls, or when weather cold cloud fronts sweep over this island until other generation sources come on line. King Island is a good example of a SMART micro-grid where continuous opti-misation occurs for an integrated power system comprising 2.1 MW sustainable energy sources with a conventional 6 MW diesel generation plant, and a 1.6 MWh at a 3 MW peak output BESS. There are also auto-controlled large switchable dissipating resistors and remote controlled community switchable loads to absorb energy peaks. This system has significantly reduced reliance by 45 % on hydro-carbon energy diesel engine generation plant that traditionally supplied the island. The entire system provides a reliable uninterruptable remote micro-grid power network for a community of 2,000 residents.

Development of ESS research models for integration into the design and oper-ation of very large PV or wind farms or larger isolated micro-grid supplies is an area of expanding applied research.

2.1.3   Distributed Small BESS

Distributed small scale domestic and industrial BESS systems are becoming more common. Early high PV buy-back prices to increase solar penetration did not encourage the development of small BESS systems, i.e. there was more profit in exporting energy than self-using it. Similarly the cost of battery storage remains a problem for small systems, unless supplied under large contract order by an elec-trical utility or company that has large buying power abilities. Large production

runs of batteries costs would make small distributed systems economically viable. Likely types of battery for use (as reported by Bayles and Jackowitz 2002) are the:

- Advanced glass mat (AGM) lead acid batteries with gas recombinant to water abilities that can be discharged to 60 % of capacity. These have a nominal 3,000–4,000 deep discharge cycle life capability.
- SMART lithium-ion batteries which have a system health monitor built in for each cell. Cycle life of these for between 30–65 % of the full discharge capacity is nominally 1,500–3,000 cycles. The additional cost for the battery safety health check monitoring of each cell will add to the price of lithium-ion batteries. But prevention of self-ignition of these batteries is required for obvious safety reasons.
- Advanced Ni-Cad and Edison Ni-Fe alkaline batteries can easily withstand deep discharge to cycle life for 60–80 %. As reported in Sichuan Changhong Battery Co. NF-S solar nickel-iron battery specification performance literature (2011), the nickel-iron battery even under 100 % complete deep cycle can achieve 1000 cycles, while for a 50 % discharge provides 3200 cycles; and under continuous light discharge of 20 % of capacity it achieves 8,500 cycles before reaching the 80 % state of original full capacity. As noted by DeMar (2011), even at this state of life capacity, provided the battery pH remains above 9.5, the Ni-Fe battery will only continue slowly to fade in its capacity in a linear fashion, and not collapse like other batteries. The nickel-iron battery does not collapse at the normal 70–80 % of the original capacity that plagues most other batteries. This is due to the high pH alkaline electrolyte environment preventing corrosion in the cell, and the slow leakage of iron from the iron electrode as described by Demodov et al. (2006). Instead of total battery replacement, a low cost alternative is to add an additional 20 % string of batteries to return the now enhanced battery set for another complete cycle life. The current Edison pocket plate battery is also easy to rebuild to restore the iron electrode, which is quite different to the expensive recycling required for other batteries types.

Helwig and Ahfock (2015) using HOMER ENERGY software modeled the following domestic PV and small BESS parameters for the current costs of batteries:

- For a present value discount rate 6 %, and an excess sustainable energy grid sell-back rate of $0.06/kWh.
- Typical domestic usage is 22 kWh/day.
- Typical average domestic annual cost (Queensland) of electrical energy of $2,700/year.
- 10 kW PV array and 7.5 kVA co-gen (95 % efficiency) inverter.
- Charge controlled rectifier 85 % efficiency.
- BESS types: 200 Ah advanced AGM VLA, Li-Ion SMART Battery SB-100 Ah, Nickel Iron NS 220 Ah (i.e. 13 cell set based on Helwig and Ahfock (2011) sizing method to optimise the cell string).
- 30 year system life (benchmarked to PV array typical lifetime).

- The above systems were also modelled with the option of adding one or two operationally safe 300 W carbon fiber blade marine-grade wind turbines to investigate the effects of increasing generation diversity factor.
- PV and wind data were as per NASA weather data for the Queensland locality.

The model returned the results summarized in Table 2. Examining the results shows that over the expected system life of 30 years, using a BESS with PV or other renewable sources can significantly reduce domestic energy costs. As a benchmark for the $LCOE/kWh cost results, general electricity domestic rates are nominally $0.23 per kWh, non-peak time of day tariff costs are $0.14 per kWh, while peak time of day tariff costs generally vary from $0.28–0.32 per kWh. However, there remains the more than double capital cost up front that may limit current penetration of such distributed small BESS. This model confirms Germany's current policy of Government offset grants for such systems up to 10 kW PV array rating with BESS, on the agreement that the domestic or small industry supplier must self-use 40 % of the energy produced (Stetz et al. 2015).

Micro-grids and islanded small sustainable energy supplies are also becoming more viable in nations with the capacity to self-produce sustainable energy sources and batteries. In fact in India, such islanded green-energy micro-grids may in the future provide more reliable energy sources to rural areas than the overloaded national energy grid. For a completely sustainable energy supply, here the BESS size is determined by autonomy period required. BESS autonomy period, and therefore BESS capacity may be reduced or battery life increased by including small back-up battery charging sources such as biogas driven internal combustion engine alternators, or now available very long lasting small micro-gas turbine permanent magnet alternator chargers. With reducing costs of renewable sources decreasing the $ LCOE/kWh of energy produced from these systems the price of the BESS is still the single most expensive item. The BESS cost remains a critical element to improve to achieve similar grid connected energy costs. A modelled comparison of islanded micro-grid (e.g. for a time shared small cluster based Indian village) or a stand-alone domestic supply in the developed world was undertaken by Helwig and Ahfock (2015) to compare the cost of energy to that of a sustainable source with ESS that was grid connected. Figure 2 provides the summary of this HOMER Pro© software model.

The RAPs (Remote Area Power supply) or islanded autonomous micro-grid sustainable energy supply requirement was to provide 95 % of all energy demand over an entire year, allowing for ±10 % variations from standard demand, and ±15 % hourly and daily variability from the average NASA surface solar and wind energy data. As can be seen from the research results, islanded systems with BESS shown in Fig. 2 do cost more due to the longer autonomous period operation requiring more battery energy storage. The optimal model output of nickel iron battery $ LCOE of $0.34/kWh of this model was based on previous work by Helwig and Ahfock (2011), and the Changhong NF-S nickel-iron battery specification literature (2011). This compares to the much smaller BESS grid connected system outcome for the same Ni-Fe battery $ LCOE of $0.14/kWh; and

Table 2 Model results for 7.5 kW inverter with 10 kW PV plus BESS system (Helwig and Ahfock 2015)

BESS	Block Ah	Hours automy period	Battery life to 80 % SOL (years)	NPC $	Renewable (%)	LCOE ($/kWh)	Self-consumption (%)	$ Cost of energy/year
Domestic tariff	–	nil	–	–	–	Time of day tariff	nil	$2,697
None	–	nil	–	$15,400	84	$0.082	35	$777
AGM VLA solar: 88 x	200	27.5	20	$35,400	92	$0.146	46	–$380
Li-Ion smart batt: 28 x	100	23	9.82	$46,200	90	$0.272	38	$128
Ni-Fe (NS): 132 x	200	42	13.1[#]	$35,000	100	$0.150	50	–$458
BESS + 2 × 300 W carbon fibre wind turbines	Block (Ah)	Automy period	Battery life to 80 % SOL (years)	NPC $	Renewable (%)	LCOE ($/kWh)	Self-consuption (%)	$ Cost of energy/year
Domestic tariff	–	nil	–	–	–	Time of day tariff	nil	$2,697
None	–	nil	–	$16,000	84	$0.079	34	$651
AGM VLA solar: 88 x	200	27.5	20	$36,000	92	$0.140	45	–$458
Li-Ion smart batt: 28 x	100	23	9.52	$46,800	84	$0.272	38	–$56
Ni-Fe (NS): 132 x	200	42	14.1[#]	$35,600	100	$0.142	45	–$580

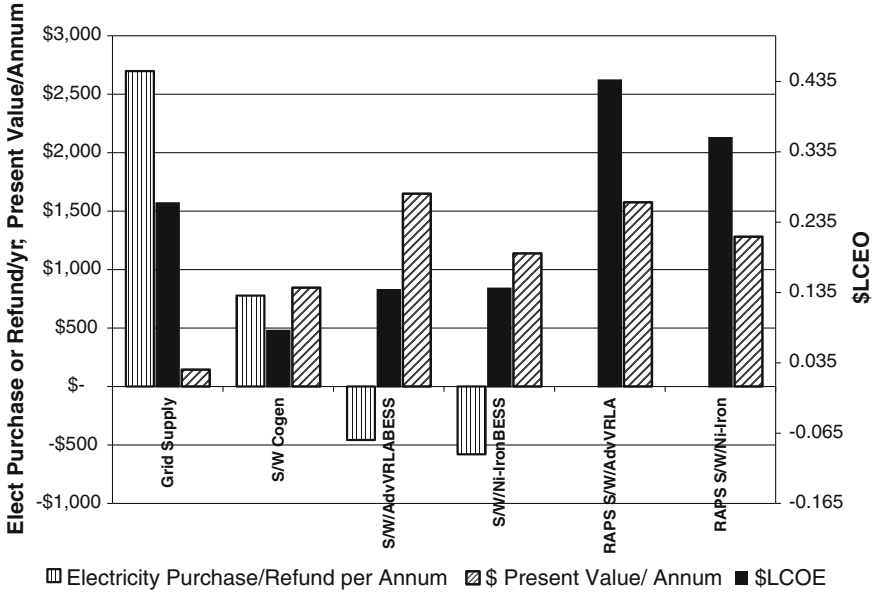[#]Note 20 % of battery capacity added at each interval

Fig. 2 Costs of sustainable energy sourced RAPs or islanded supply with BESS compared to grid connected PV/Wind/ESS systems

demonstrates the impact of the price of BESS autonomy period has on renewable energy overall costs.

In regards to the model performance outcomes, such small autonomous energy supply systems can provide from 10–25 MWh of sustainably sourced electricity using 5–10 kW solar arrays and small, safe wind generators. Excess energy production varies from 22 to 45 %, with annual shortfalls in energy supply and BESS storage varying from 1.4 to 4.5 %. As energy costs continue to increase, and BESS become cheaper per kWh of storage, it is possible even in developed countries that more domestic supplies will become islanded. This is especially so with time of day peak tariffs where smaller stand-alone battery storage may provide peak shaving energy or even temporary islanding of domestic supplies during such costly tariff periods.

Excess energy production for a single RAPs supply does not present a problem, but requires a SMART load interface with the energy supply system to minimise wastage of energy. Excess energy for a micro-grid that may extend for 10 km with a cluster of small rural loads does present some challenges for the sustainable power sources. Such generation source inverters cannot always operate in maximum power tracking mode when such generation excesses occur. When the BESS or any switchable loads like water pumping or heating cannot balance the peak PV array generation, then voltage control (as opposed to maximum power tracking) requires implementation for the co-generation inverter. This voltage control can be achieved by various combinations of switching in a stepped-value reactive load, gain

variation of the PV array's boost/buck DC-DC converter, or reducing the DC-AC inverter stage output from maximum power tracking point by decreasing the mark-space ratio of the inverter switching bridge.

However, both of these examples for autonomous supplies and micro-grids point to the ongoing need for smart communications systems whether at domestic load supply interface to switchable deferrable loads, or potential communications over supply wire for micro-grids. Automation and optimisation of renewable supply, energy storage and SMART switchable loads demonstrates the need for continuing development of cheap communications platforms interfaced to the local inverter/charger and BESS operation. Load despatch control with switchable load intelligence also requires communication protocols to be integrated into low cost and easily installed systems.

Finally, BESS applications also suit development for integration into remote weak grid connected rural power supplies such as is the case for single-wire earth return (SWER) systems as investigated by Helwig and Ahfock (2013). Here correctly placed and sized BESS storage from renewable sources can bolster electrical supply resilience and voltage regulation during peak load periods. Such resilience aids in further development of automated precision farming methods where energy and water are linked for increasing agricultural output efficiency in remote areas. Continuing development in this area is required to bolster national and global food security. The need for increasing remote agricultural region output may also drive weak grid connected low cost local renewable farm supplies or cluster farm micro-grids. Again local ESS and load control intelligence is required to take advantage of local renewable energy supplies and energy from agricultural waste.

2.1.4 Germany's Energiewende

Germany's national strategic energy plan to create and increase renewable energy generation source penetration to 60 % by 2050, will begin with the creation of two HV DC "Energiewende" as reported by Morris and Pehnt (2015). This will form a 'Y' connection from the Baltic Sea where growing mainly sea-based wind energy sources exist, to the densely populated NW region of Germany, again with both linked to Southern Germany where the major PV energy sources are expanding. This HV DC link will connect many thousands of large and small renewable, hydro-electric, PHESS, distributed BESS and conventional sources. One of the more unusual characteristics of the HV DC link proposed for construction is its potential ability to be connected to multiple energy storage systems, and itself appear to the energy dispatch controller as a single DC link ESS. By using this form of integrated DC energy storage, there is the equivalent of 'spinning reserve' built into the system, but it remains totally disconnected and isolated in terms of control from the AC frequency control required for the existing distribution networks. State of the art high power converter and inverter technology along with traditional transformer technology will see this integrated energy storage system work with the

HV link to absorb for storage and dispatch energy to all parts of Germany's industry and domestic needs regardless of the locale's weather events.

This should be the first potential demonstration of integrated HV DC energy storage that could form a pattern for continued global connection of renewable and energy storage systems. The use of DC-AC inverter technology also allows controlled dispatch of modified HV AC distributed power that can automatically compensate for system load power factor and power quality resulting in reduction of system losses in existing AC distribution networks. The transition however will come at the price of an energy surcharge in Germany, which is needed to fund the implementation of this system. As reported by Thomas and Boston (2014), it will be the clash between political will to accomplish this, versus the impact of energy cost trends on international competitiveness of German industry that will determine how quickly such a HV DC Y link will be developed and implemented. However, the development of such an integrated energy collection, storage and distribution system does allow for enormous possible future growth in industrial development and employment in Germany. It is an opportunity for significant applied research and development in the power generation and distribution industry linked to and driven by the renewable energy sector's growth.

2.2 *Ongoing and Future of Integrated ESS Research*

Following are some identified areas of needed ongoing applied research related to energy storage integration into sustainable energy generation applications:

- For micro-grids that may have a weak back-up grid connection, the integration of industrial communication protocols for control of bi-directional flow of energy as needed when there is a generation shortage or excess energy production in the micro-grid operation. All integrated energy storage in micro-grids therefore need communications protocol capabilities to be able to provide state of charge, state of life capacity and protective safety functions. More applied research for integration of communication protocol interfaces and further engineering design to produce cost effective integrated inter-disciplinary engineering technology is required for this application. Resulting improvements will help with the future market penetration for distributed energy storage systems for micro-grids and islanded supplies.
- Micro-grids and their integrated storage require further applied research to provide economical and socially equitable energy micro-metering with in-built remote control of rotational supply that is both kWh usages based and variable energy access time/s.
- Trans-ocean/transcontinental energy links to develop and tap reserves of PV and other renewable generation sources for energy storage, for example the deep-sea based hydro generation reservoirs connecting between major trade connected regions and even eventually the entire globe.

- Modulisation of distributed BESS with intelligent control/monitoring/communications technology integrated into easily used architectural construction units. Such applied research and development with built in system intelligence for BESS 'health', charging/discharge, state of life capacity and state of charge with industrial communications protocol capabilities is very much needed. This will allow further assimilation of distributed SMART BESS systems into large energy supply networks, multi-story buildings and industrial applications to assist with high starting transient disturbances (such as large pump motors or large climate control units), provide time-shift storage for peak time of day tariff periods from locally generated renewable energy sources; and provide backup power for industrial complex building safety/security systems and emergency lighting. For such integrated BESS technology units, each battery type has its own risks and criticality outcomes as shown in Table 3. Safety of such systems and specific design of the integrated systems for easy renewal at end of life, i.e. for rebuilding or recycling, requires significant applied research and development for each battery type. As reported by Coates (2007), Mikolajczak et al. (2011), Arora et al. (2012) and Battelle et al. (2012), significant work remains to be carried out on the lithium-ion battery for such configurations, given the problems already experienced in the aircraft, military applications, electric-vehicles, laptop and phone communications industries. Here significant numbers of spontaneous self-combustion have occurred due either to overcharge or thermal run-away due to high discharge or ambient temperatures. Current safe LiPo4 Lithium-ion batteries are available in the United States (SMARTBATTERY 2015) with individual cell monitoring and cut-out of individual cells if any begin to show signs of critical failure development; but these types of Li-ion batteries come at a premium cost with this safety feature added.
- Modelling of HV DC distribution links with integrated energy storage in response to sustainable generation source penetration into large long electrical energy distribution systems. Similarly there is a need for modelling and cost effective designs for development of LV DC networks for small micro-grids. These applications present many opportunities for investigation by simulation and design/cost optimisation.
- Modelling of dynamic response, protection response and control response potentially of many active inverter generation sources in larger HV and LV distribution networks. The inclusion of many fast acting (i.e. 10–30 ms) significant inverter active sources has the potential for voltage and reactive power oscillations to result from load disturbances. Large scale system models will be needed to provide overall local control response strategy/s to a voltage or frequency disturbances.

Table 3 Safety risk/criticality outcome comparison: gel and advanced glassmat VR Lead Acid, Lithium-ion, Nickel-Iron, Zinc-Bromide Redox and Nickel-Cadmium battery general performance characteristics at 2–3 h discharge rates

Comparison of deep discharge storage battery type at $C(2_h)$ and $C(3_h)$ discharge rates

Characteristic	Gel & Adv. Glassmat VR lead acid	Lithium-Ion	Nickel-iron	Zinc-Bromide Redox	Nickel-Cadmium
Open circuit cell voltage	2.13	3.6–3.9#	1.21–1.31*	1.83	1.25–1.40*
High discharge rate turn around efficiency	68 %	75 %	65 %	68 %	65 %
Cell voltage at end of high discharge rate (C_{2hr})–(C_{3hr})	1.65 (gel) 1.75 (adv. glassmat)	2.45	0.9	1.3	0.9
Low discharge rate C_{20hr} turn around efficiency	75 %	90 %	72 %	72 %	68 %
Cell voltage at end of low discharge rate	1.75 (gel) 1.85 (glassmat)	2.75	1	1.3	1.0
Watt-hr./kg	30	150	30	50–70	20
Cycle life	250–1100 (gel) 3000–4000 (adv. glassmat)	1500–3000	2000–9000	2000–3000	500–2000
Recommended DoD	20–30 % (gel) 40–70 % (adv. glassmat)	30–65 %	20–90 %	20–85 %	20–65 %
DoD memory problems	Nil	Nil	Nil	Nil	Yes
Withstand long periods @ low SoC	No	No	Yes	Yes	Yes
Suffers from thermal run-away	Yes	Yes	No	Requires Heat Exchanger	No
Maintenance free	Yes	Yes	No	No	No
Max. charge rate	0.07 × Capacity	0.2 × Capacity	0.2 × Capacity	0.2–0.25 × Capacity	0.12 × Capacity

(continued)

Table 3 (continued)

Comparison of deep discharge storage battery type at C(2_h) and C(3_h) discharge rates

Characteristic	Gel & Adv. Glassmat VR lead acid	Lithium-Ion	Nickel-iron	Zinc-Bromide Redox	Nickel-Cadmium
Tolerance to over-charge	*Gel type: No Tolerance Adv. Glassmat: Some Tolerance*	No Tolerance	**Very Good**	**Battery must disconnect when fully charged**	**Very Good**
Optimal depth of discharge	*10–30 % (Gel)* **10–60 % (AGM)**	**25–60 %**	**20–90 %**	**50–80 %**	**20–80 %**
Recommended autonomy period	**To 4 months**	**To 6 months**	*14 days*	**6 months–year**	*5 days*
Specific fire hazard	*Thermal run-away; hydrogen venting necessary*	*Thermal run-away and self-ignition/explosion*	**Hydrogen venting necessary**	*Release of bromide*	**Hydrogen renting necessary**
Personal hazard	**Acid electrolyte**	*Vented gaseous lithium compounds and potential flourine gas front solid elec trolyte separator*	**Alkaline electrolyte**	*Bromide Gas*	**Alkaline electrolyte**
Environmental hazards	*Heavy metal of lead*		–	*Bromide/Electrolyte*	*Heavy metal Cadmium*

depends on type of Lithium-Ion Battery

*As these batteries accept and can store some overcharge—the lower voltage is for the fully charged state, while the upper voltage is for the overcharge state

Indicates desirable characteristic

Indicates risk characteristic

Indicates non-desirable characteristic

(Sichuan Changhong Battery Co. 2011; CHEMTREC 2010; Corey/RedFlow Limited 2011; Ironcore Batteries 2011; Ritar Batteries 2011; ZBB Energy Corporation 2011; Argonne National Laboratory 1990; GNB 2011)

3   Conclusions

The integration of large scale potential land-based and sea-based PHESS, large embedded PV arrays or windfarms with close coupled BESS in large existing grid networks, or smaller numerous distributed BESS in micro-grids and optimisation of autonomous remote area remains an exciting area of research. Research is likely to remain centred on such specific system elements and their integration into larger system models to optimize performance, stability, and costs.

Large storage may be associated with HV DC link network energy buses (i.e. similar to Germany's "*Energiewende*"), and the development of this technology provides greater opportunity for integration of energy storage systems to provide artificial spinning reserve. For large energy storage systems, this may provide the first impetus for not just national networks of energy distribution, but global regional interconnection with energy storage using the sea's hydro-static head.

Integration of smaller distributed energy storage, with industrial communications protocols and intelligent program logic controllers or micro-controllers to oversee optimal battery charging and discharge, battery life state of capacity/health and real-time state of charge is the other area of applied research that is much needed for domestic, micro-grid and autonomous RAPs.

The hybridization of energy storage, regardless of size, with super-capacitors, industrial communications capabilities and integration with power electronic inverter and converter technologies can potentially significantly increase the overall efficiency of existing electrical energy network distribution systems.

Concurrent with this shift from carbon based energy to environmentally sustainable energy generation (with ESS) is the need for practical research to better quantify the potential future global connection of sustainable energy sources and storage. This should also initiate research and development into providing more equity for emerging nations to affordably access to renewable energy sources whether from local sources, or globally connected sources. For the 30 % of the world who have no access to any electrical energy source, practical applied research is much needed for small and cheap green-energy generation and storage development potentially using less efficient, but affordable "do-it-yourself" wind, PV or battery technology.

There are many opportunities for applied electrical and power industry research in this area for integrating large energy storage on global scales, distributed small energy storage development, and a market for these products. There are great potential spinoffs to create new 21st century global job opportunities in developed, developing and emerging nations to replace those that will be lost from the traditional 19th and 20th century industrial carbon and hydro-carbon based energy production. There are also engineering and scientific cross-disciplinary opportunities for applied research opportunities to explore in sustainable energy generation and ESS as they become embedded in technologies for potable water supply security, water recycling, agricultural efficiency, and food security. Such energy storage systems with intelligent control and communication platforms will

potentially have significant roles to play in the automation, precision farming mechatronics and the opening of highly efficient additional remote and small domestic farming enterprises.

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