Chapter 3
Renewable Energy Integration: Opportunities and Challenges

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Abstract Renewable energy (RE) is staring to be used as the panacea for solving current climate change or global warming threats. Therefore, government, utilities and research communities are working together to integrate large-scale RE into the power grid. However, there are a number of potential challenges in integrating RE with the existing grid. The major potential challenges are as follows: unpredictable power generation, week grid system and impacts on power quality (PQ) and reliability. This chapter investigates the potential challenges in integrating RE as well as distributed energy resources (DERs) with the smart power grid including the possible deployment issues for a sustainable future both nationally and internationally. Initially, the prospects of RE with their possible deployment issues were investigated. Later, a prediction model was proposed that informs the typical variation in energy generation as well as effect on grid integration using regression algorithms. This chapter also investigates the potential challenges in integrating RE into the grid through experimental and simulation analyses.

3.1 Introduction

Growing concerns about energy security, energy cost and climate change have intensified the interest in harnessing energy from renewable sources. Conventional stationary energy sector consumes mostly coal, petroleum oil and natural gas (methane) as fuel to generate required electricity demand. However, a significant amount of electricity is generated from nuclear energy in few developed countries. At present, stationary energy sector is the major contributor of greenhouse gas (GHG) emission and coal-fired power stations made Australia one of the highest

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per capita GHG emitting countries. Currently, renewable energy (RE) fulfils 15–20 % of world's total energy demand. Therefore, to reduce the GHG emission and to get energy from naturally free sources, it is urgent to maximise the RE utilisation by bringing higher percentage of RE into the national energy mix. Among different RE applications, hydroelectricity is matured and most exploited although it is strictly location-specific application. Other most promising sources of RE are wind and solar, and these two are the largely installed distributed energy generators in the world.

To integrate large amount of electricity from these sources into the grid, main concerns are the variability in energy from these sources. Traditionally, electricity generates from large generating stations which then transmitted to the distribution network and finally to the end load. Introduction of distributed generation (DG) changed this scenario as many distributed energy resources (DERs) are to be installed at the low-voltage (LV) distribution network (DN). The nature of DERs connected near the load introduces both-way power flows at the point of common coupling (PCC) in the network. Large-scale integration of such DERs can influence system reliability and power quality (PQ).

Efficient, time forward prediction can help in effective integration into the grid for better load management as RE sources are intermittent in nature. Moreover, RE particularly solar and wind potential varies with space and time; therefore, it is vital to identify the suitable location for such installation. However, the characteristics and frequent variability in RE can have serious impacts on load where energy storage can help in load management and fluctuation reduction. Therefore, this chapter describes the potential of RE, integration into the grid and impacts on the grid due to integration of these RE sources.

3.2 Current Power System

Currently, more than 80 % of the world's energy is produced from fossil fuel that pollutes surrounding environments each and every day, which causes global warming. According to the report of the international energy agency (IEA), the world electricity generation was 14,781 billion kWh in 2003 and is projected to be 21,699 and 30,116 billion kWh in 2015 and 2030, respectively, an average increase rate of 2.7 % annually [1]. GHG emissions from electricity generation are approximately 40 % of total emissions as most of that industry uses fossil fuels, particularly coal and oil, and hence are a leading contributor to global energy-related CO_2 emissions [1, 2].

The major energy resource productions in Australia are coal, uranium and natural gas. In 2007–2008, Australia's energy production (including exports) was dominated by coal, which accounted for 54 % of total Australian energy production. Over the past 10 years, from 1997–1998 to 2007–2008, energy production in Australia increased at an average rate of 3.5 % a year, compared with 3.2 % over the past 10 years [3]. Australian primary energy consumption consists predominantly of

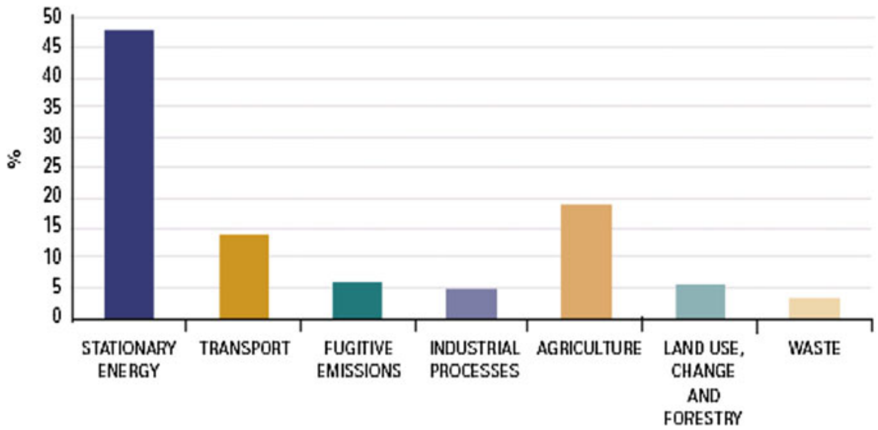

Fig. 3.1 Total Australian emissions by sector [4]

petroleum and coal. There are numerous environmental issues associated with fossil fuel extraction and usage—resource depletion, land damage and sterilisation at the extraction site, pollution during transport, smoke and smog production and acid rain [4]. It is seen that the major source of emissions is stationary energy production and the bulk of these are due to the burning of fossil fuels, in particular coal for electricity production as shown in Fig. 3.1 [4]. Australia's abundance of coal imposes environmental costs in the form of GHG, including 200 million tons of carbon dioxide equivalents (CO_2-e) released from the energy sector in 2008, more than a third of Australia's total CO_2-e emissions [3].

There is an urgent need worldwide as well as Australia to search for alternative energy sources which are free from GHG emissions. RE offers alternative sources of energy which are in general pollution free, climate friendly, unlimited, technologically effective and environmentally sustainable and started to be used as remedy for solving global warming worldwide. Therefore, an essential new research direction is to deploy large-scale RE into the energy mix for a sustainable climate-friendly environment.

3.3 Renewable Energy

Advantages of RE sources are enormous as they are free from GHGs and related global warming effects. RE is defined as an inexhaustible and sustainable energy source, and particularly in this modern environment, it is associated with climate change initiatives [5, 6]. Therefore, policy makers, power system planners, researchers and power utilities are working together worldwide to reduce GHG emissions, and hence, in 1997, a treaty was formulated called the Kyoto Protocol [7]. The objective of the Kyoto Protocol is to reduce GHG emissions into the atmosphere to a level that would prevent dangerous anthropogenic interference with the climate system [7]. Over the years, renewable energies have experienced one of the largest growths in percentage terms. In 2009, the world's RE production share has been calculated as 19.46 %. Hydroelectric is the largest contributor among the renewables, accounted for over 83 % of RE share. Wind, solar and biomass altogether accounted for only 15 % of the global RE contribution; hence, wind and PV (the most promising RE sources) have still modest energy production [8]. However, there was a rapid growth of RE generation including solar PV, wind power, concentrating solar thermal power (CSP), solar water heating systems and biofuels from 2005 to 2010 and grew at average rates ranging from around 15 to nearly 50 % annually. Cost reduction in wind turbine, PV systems and biofuel processing technology contributed to the rapid growth. By early 2011, at least 119 countries have taken initiative and made renewable support policy at the national level while only 55 countries in early 2005 [9].

Australian production of RE is dominated by bagasse, wood and wood waste and hydroelectricity, which altogether accounted for 87 % of RE production in 2007–2008. Wind, solar, and biofuels accounted for the remainder of Australia's RE production. Solar energy is mostly used for residential water heating, and this accounts for 1.5 % of final energy consumption in the residential sector. RE production increased by 6 % in the 5 years from 2002–2003 to 2007–2008 and increased by 3 % from 2006–2007 to 2007–2008 [3].

A range of policy measures have been introduced in Australia to increase electricity generation from RE sources to achieve the national goal of introducing 20–25 % RE into the energy mix. The RE sources that have experienced the greatest growth under the Australian governments' mandatory renewable energy target (MRET) are wind energy and solar energy. At the end of October 2009, there were 9 renewable electricity projects at an advanced planning stage and a further 80 projects at a less advanced stage; of these, 8 are advanced wind energy projects and 71 are wind energy projects at a less advanced stage [3]. There are 5 proposed solar energy projects in Australia, the largest of which is an 80 megawatt solar plant at Whyalla, South Australia. The largest hydroelectric power scheme in Australia is the Snowy Mountains Scheme that generates about 50 % of Australia's hydroelectric power. There is one geothermal project in operation in Australia at Birdsville, Queensland [3].

Recently, the Australian government has taken clean energy initiative (CEI) for the deployment of a range of renewable and clean energy technologies that includes [10].

- Carbon capture and storage (CCS) initiatives: CCS flagships programme accelerates the deployment of large-scale integrated CCS projects in Australia that will reduce emissions from coal use.
- Solar flagships: Solar flagships programme supports the construction and demonstration of large-scale, grid-connected solar systems in Australia that play a key role in electricity generation.

- Australian Solar Institute (ASI): ASI provides solar research and development facility and ensures collaboration with researchers in universities, institutions and industry.
- Australian Centre for Renewable Energy (ACRE): ACRE is promoting the development, commercialisation and deployment of RE technologies.
- Renewable Energy Future Fund (REFF): REFF supports the development and deployment of large- and small-scale RE projects.

In Australia, the Intelligent Grid Program [11, 12] was launched on 19 August 2008, being established under the CSIRO's Energy Transformed Flagship, and it focuses on the national need to reduce GHG emissions. Based on the focus of Australian Government Energy Policy, this study has concentrated mostly on large-scale integration of wind and solar energy into the grid.

3.3.1 Solar Energy

Solar energy is the most readily available and free source of energy since prehistoric times. Grid-connected Photovoltaic (PV) systems and DG offer various advantages over conventional generation by providing more effective utilisation of generated power. Increased penetration of PV– DG must also maintain utility grid reliability. Major components of a grid-connected PV system are shown in Fig. 3.2 [13].

An inverter system is required to transform the DC voltage produced from PV arrays. The fundamental requirements of an inverter are to limit the harmonic distortion and to ensure a constant output voltage. Sine wave inverters are mostly used for grid-connected PV systems due to the power output, system efficiencies and harmonic distortion limit [13, 14].

Currently, solar photovoltaic is the fastest growing power generation technology and an estimated 17 GW of PV was added worldwide in 2010, which was less than 7.3 GW in 2009. The annual average growth rate of solar PV exceeded 49 %, over 2005–2010 periods, which is shown in Fig. 3.3 [9].

Compared with other parts of the world, Australia is one of the best locations for solar energy as it has huge open lands and longer periods of sunshine. A total of 837 MW of PV was installed in Australia in 2011, more than twice the installed capacity added in 2010. Australia's total PV capacity has increased significantly

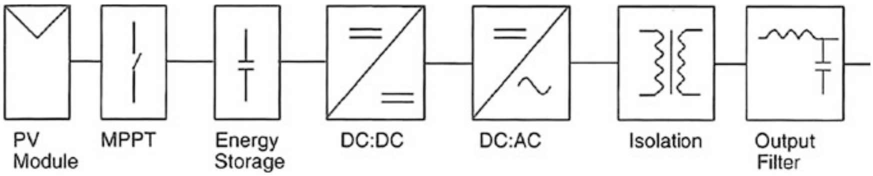

Fig. 3.2 Connection diagram for a grid-connected PV system [13]

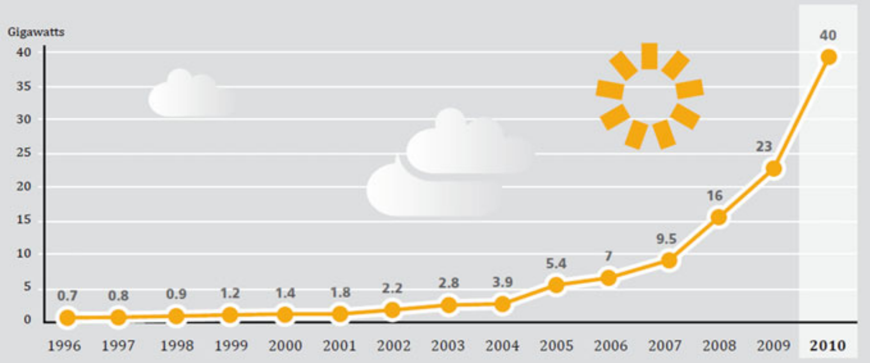

Fig. 3.3 Existing world capacity of solar PV [9]

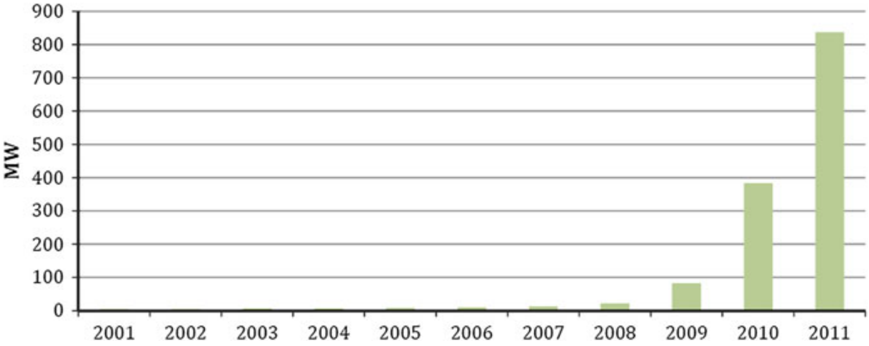

Fig. 3.4 Annual Australian PV installations 2001–2011 [15]

over the last decade and in particular over the last 2 years as shown in Fig. 3.4 [15]. This is due to a combination of factors: government renewable energy target (RET) to get 20 % electricity or 45,000 GWh from RE, solar homes and communities plan (SHCP), solar flagships, greater public awareness, feed-in-tariff, a drop in the price of PV systems, a strong Australian dollar and highly effective marketing by PV retailers [9, 15].

Solar PV systems are expected to play a promising role as a green energy source in meeting future electricity demands to build an environment-friendly sustainable power system.

3.3.2 Wind Energy

Over recent years, there have been dramatic improvements in wind energy technologies, and wind is increasingly becoming an important energy source. Wind energy can be exploited in many parts of the world, but is the most cost-effective in

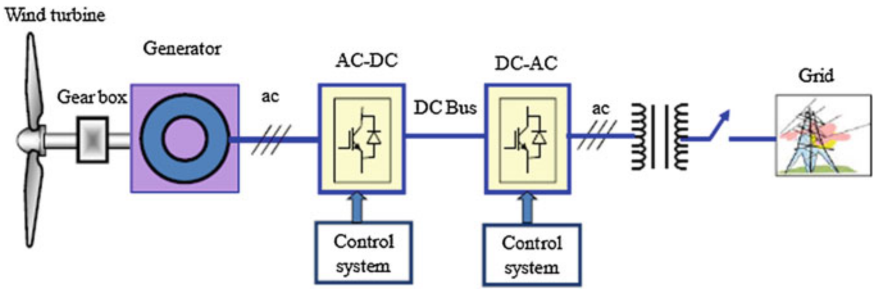

Fig. 3.5 Grid-connected wind energy system [17]

windy climates, where average wind speeds exceed 6.5 m/s. Winds are caused due to the temperature variation in the earth's surface and in the atmosphere, and in the rotation of the earth about its axis and its motion around the Sun [16].

The wind farm is composed of several wind turbines which have basic electrical components: an aerodynamic rotor, a mechanical transmission system, an electric generator, a control system, limited reactive power compensation and a step-up transformer as shown in Fig. 3.5. The generator is used for converting the mechanical power obtained from the wind turbine to electrical power. A wind turbine comprises rotor/blades for conversion of wind energy into rotational shaft energy, a nacelle with drive train that contains the generator and gear box, a tower that supports the rotor and drive train and the necessary electric equipment for connection to the grid. The majority of wind turbines offered today is of the three-bladed upwind horizontal axis type and installations intended to connect at the PCC at medium or high voltage [16, 17] of the network.

Power production from wind turbines is dependent on wind speed (v), air density (ρ) and the rotor swept area (A). Therefore, the maximum power P available from the wind can be represented as Eq. (3.1) [18].

$$P = \frac{1}{2}\rho A v^3 \tag{3.1}$$

However, the actual amount of energy production will be less as it is not possible to extract all available energy by the turbine, and therefore, a power coefficient (Cp) is defined. The ideal or maximum theoretical efficiency Cp of a turbine is the ratio of maximum power obtained from the wind to the total available power in the wind. The factor Cp = 0.593 is known as Betz coefficient or limit [18, 19]. From Eq. (3.1), it is seen that wind speed has a significant role in the amount of energy that can be produced from a wind source.

Wind energy is the fastest emerging energy technology, and total cumulative installed capacity of wind energy in the world by 2000 was 17,400 MW, while in 2011, the cumulative installed capacity is 237,669 MW as shown in Fig. 3.6. Annual installed wind capacity in 2000 was only 3,760 MW; with rapid growth, annual installed capacity in 2011 was 40,564 MW. In 2010, the rate of increase in wind energy generation globally was 24.1 %, though there had been a slight

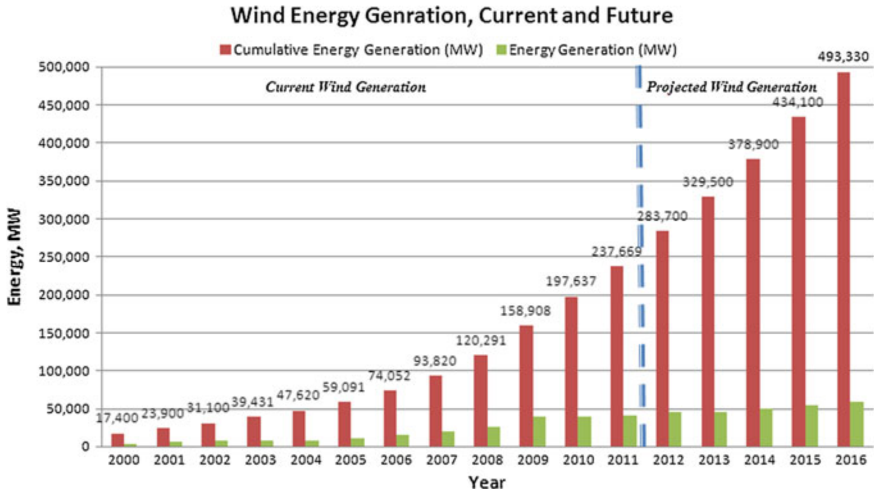

Fig. 3.6 Global wind energy installed capacity, current and projected [21]

decrease in the growth rate than earlier due to the worldwide financial crisis [20]. According to the Global Wind Energy Council, the growth rate of wind energy will increase rapidly, and over the 5 years to 2016, global wind capacity will rise to 493 GW from the 237 GW available at the end of 2011 as shown in Fig. 3.6 [21]. While the capacity installed in 2011 was 40.6 GW, the capacity predicted to be installed in 2016 is 59.24 GW; hence, the average projected annual growth rates during this period will be 13.65 % [20].

Australia has been slow to adopt wind energy to the extent that Europe has; however, in Australia, there are several large wind farms that have been commissioned or are in advanced stages of planning. In particular, after implementation of the national RET in January 2010 with the mandate of generating 20 % or 45 TWh of electricity from RE sources by 2020, Australia has taken a wide range of initiatives to install large-scale wind energy plants around the country. In 2010, Australia's total installed capacity of wind energy was 1,880 MW, this being an increase of 167 MW from 2009. In the last decade, the growth rate of wind energy production was 30 % annually on average [20]. State-wise installed capacity of wind energy in Australia is given in Fig. 3.7 [21].

Large-scale generation of solar and wind energies reduces global warming as well as energy crisis worldwide and releases the pressure on other sources. Solar and wind energy generation is distributed over areas where solar radiation and wind speed are favourable to generate electricity. Australia has strong weather condition for solar PV and wind energy. Therefore, in large scale, such DER integration into the grid is imminent.

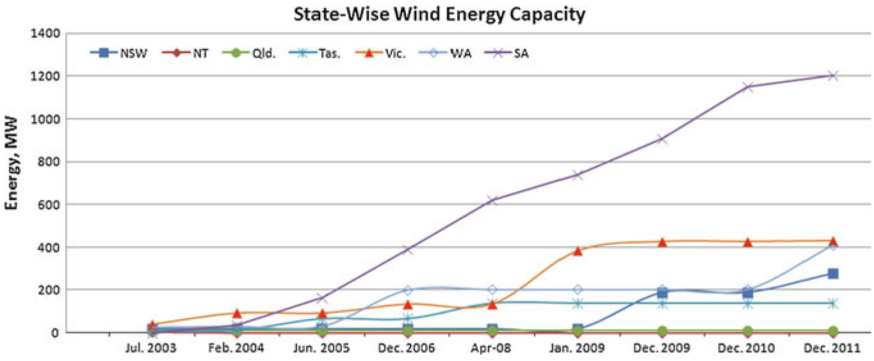

Fig. 3.7 State-wise installed wind energy capacity in Australia [21]

3.4 Distributed Energy Resources: Integration Challenges

DERs are electricity generation units, typically in the range of 3–50 kW, installed in low-voltage (below 25 kV) distribution systems at or near the end user. Solar and wind are the two promising sources of DER. They have the potential to improve reliability, PQ and global warming and reduce power generation, transmission and distribution costs. Grid-connected DERs support and strengthen the central bulk power station to meet the peak demands or to support major consumers. Moreover, DERs provide power to remote application where it is not possible to deliver power from traditional transmission and distribution lines [22, 23]. A typical snapshot of an integrated distributed energy system is shown in Fig. 3.8 [24].

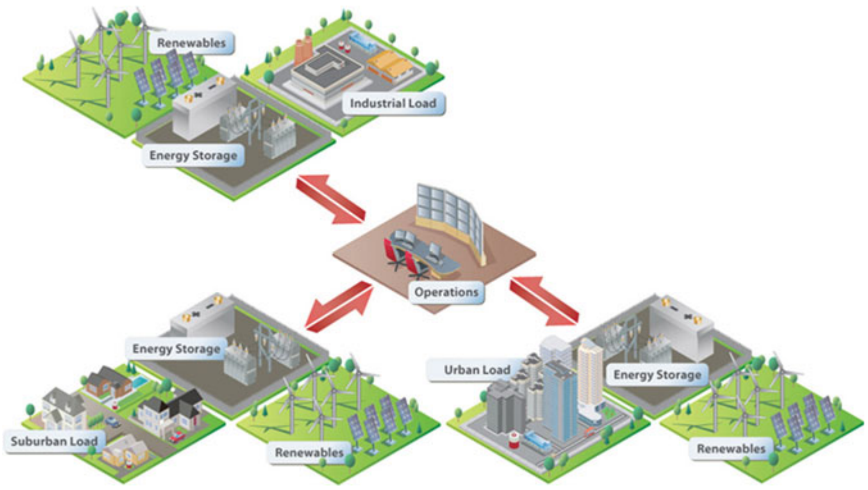

Fig. 3.8 Integrated distributed energy system [24]

Many of the DER technologies, such as those that depend on solar power and wind power, are inherently renewable in nature. Generation of wind and solar power varies frequently as wind speed and solar radiation primarily depend on weather conditions, and hence, it is difficult to predict the power outputs available at certain times of the day. The hour-to-day uncertainty in DEG is significant; therefore, prediction is required for load management and distribution or to schedule the generation in advance, generally hours to a full day ahead of time, in order to meet the expected load demand [22, 23]. Therefore, forecasting technologies is critical for grid operator to carry out operational planning studies and ensure that enough resource is available for managing the variability in RE output. Currently, physical, statistical and hybrid and combination of physical and statistical model is available to predict the wind speed and solar radiation as well as energy generation from these sources which can be used for adequate management of load demand systems [8].

The existing power systems are vulnerable for effective integration of DER. The lack of smart technologies in present network put the entire electricity system in risk. A modern smart power grid will bring benefits through seamless integration of DER to the smart grid. The use of smarter grid operations allows greater penetration of variable energy sources through more flexible management of the system. Fortunately, smart grid has the potential to mitigate some of the difficulties encountered by DER generation [8]. Therefore, it is a critical need today to introduce smart grid technology that accommodates RE to reduce overall GHGs, improves demand management, encourages energy efficiency, improves reliability and manages power more efficiently and effectively.

Large amount of intermittent generation from RE sources brings some uncertainties in both the generating sources and the DN behaviour. The variability nature in solar and wind energies has an impact on system operations, including voltage and frequency, and in general PQ. Moreover, both of these RE sources are unable to provide energy for the whole day. The major potential challenges observed are as follows: voltage and frequency regulation, reactive power compensation and active power control. Appropriate design of electrical circuits with control systems mitigates these problems and ensures PQ improvements in the power system [25, 26].

Therefore, it can be clearly indicated that the major potential challenges to facilitate large-scale DER into the energy mix are as follows:

- Unpredictable power generation; need forecasting technology to know possible power generation from RE sources in advance.
- Week grid system; need smart technology that can integrate DER into the grid.
- Impact of PQ and reliability.

Next sub-subsections have explored all the stated problems with suitable solutions.

3.4.1 Forecasting and Scheduling

The variability in DER requires knowing the relevant long-term weather patterns which can be used to develop better procedures and capabilities to facilitate integration into a “smart” national power grid. Accurate forecasting and scheduling systems are essential for appropriate and satisfactory use of DER and to establish sustainable load management systems for the smart grid.

The inherent mismatch between the DER output and the load may lead to significant energy wastage. For example, electric power can be generated from solar energy only at daytime, generally for a maximum of 8 h in a day, and fluctuates randomly with the movement of clouds. During daytime, load demand in residential areas is at its minimum which causes wastage of energy. A storage system is useful as it can store excess energy and provide power when energy shortages occur. The existing energy storing technologies include batteries, flywheels, supercapacitors and superconducting magnetic energy storage (SMES) [25, 26]. Integration of large-scale storage technology with the RE sources into the grid can ensure PQ and uniform power delivery. But the ancillary components (converters, filters, controllers, etc.) with the storage system have some effect on the overall power system.

Finally, a load demand management system is required that can be used by grid operators to accomplish operational planning and delivering smooth power supply to the consumers. A typical architecture of the load management system is shown in Fig. 3.9, which increases overall efficiency and quality of the system.

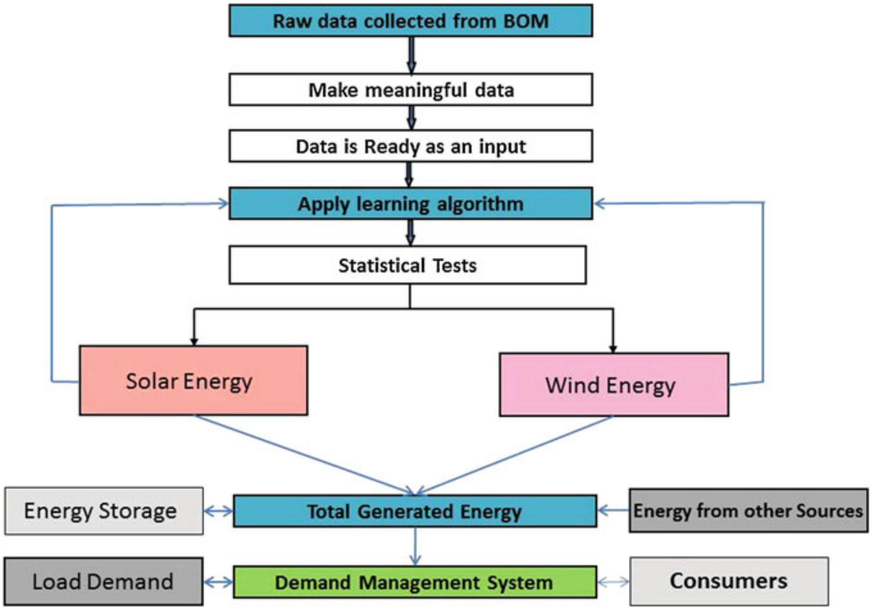

Fig. 3.9 Typical snapshot of load demand management system

Several research studies have been undertaken to assess solar irradiation and wind speed, as well as production of energy from these sources. Authors developed models [29] to forecast daily distribution of solar radiation and hourly distribution of wind speed as well as energy generation from these sources using ten popular regression algorithms. Meta-based learning random subspace (RSS), RegressionByDiscretization(RegDes), regression-based learning linear regression (LR), simple linear regression (SLR), statistical learning–based algorithm sequential minimal optimisation (SMO) regression (SMOReg), neural network–based multilayer perception (MLP), RBFNetwork (RBFN), lazy-based learning IBK, tree-based learning M5Rules and RepTree with bagging techniques [27, 28] were considered in the study for developing the prediction model. The most suitable algorithm was proposed based on the performance metrics [27] of the algorithms that include the correlation coefficient (CC), mean absolute error (MAE), root mean square error (RMSE) and computational complexity. Proposed algorithms with classical data-splitting options were used to predict the daily distribution of solar radiation and hourly distribution of wind speed. Details of the model are available in Ref. [29].

Initially, CC, MAE and RMSE have been measured for each of the models. From Fig. 3.10, it has seen that in terms of CC, the model developed with RSS performs the best. For RMSE measures, SMOReg is the best performing algorithm, while MLP is the worst. Therefore, it is really difficult to select the most suitable algorithm for this application. To select the most suitable model for this application, ranking performance for a given model has been estimated, and it has seen that RSS has ranked 1, while bagging technique has ranked 2 and MLP has ranked 10. Finally, the effect of ranking average and computational complexity was observed by changing the values of β that measures relative weighted performance. From Fig. 3.11, it has been observed that considering computational complexity and average accuracy RSS is the best performing algorithm for all β values and bagging technique with RepTree is the second performing algorithm to predict daily solar irradiation as well as solar energy production.

Similar models have been developed using the same ten regression algorithms with wind speed data. From the results, it was concluded that bagging technique with RepTree is the most suitable and RBFN is the second choice for predicting hourly distribution of wind speed as well as production of wind energy. The prediction model is therefore expected to play an important role for grid operator in controlling load demand management and smooth delivery of power supply to the consumers.

Existing electricity grid has experienced difficulties in integrating RE sources with the power grid. The high-voltage transmission grid imposes significant constraints on the deployment of new RE sources such as wind, solar and geothermal power. The use of smarter grid operations allows for greater penetration of variable energy sources through more flexible management of the system. Fortunately, an operational smart grid has the potential to mitigate some of the difficulties encountered by RE generation. In the next section, smart grid technologies have been explored along with their integration techniques with RE.

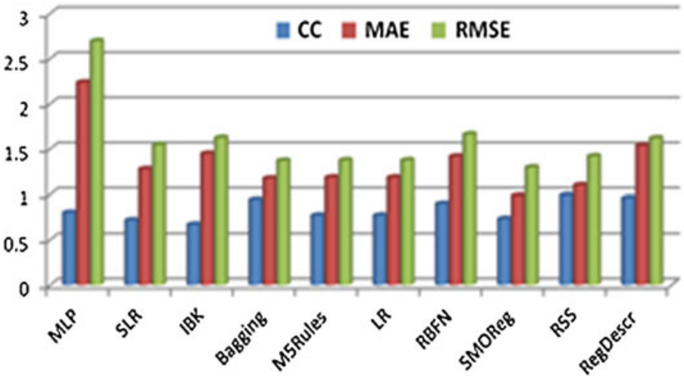

Fig. 3.10 Comparisons of performance metrics with different algorithms for prediction of daily solar irradiation

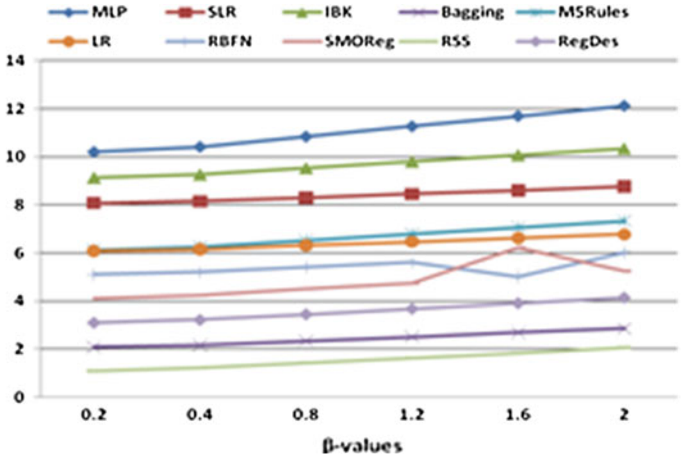

Fig. 3.11 Relative weighted performance of the algorithms with respect to β for prediction of solar irradiation

3.4.2 Smart Grid

Smart grid is the combination of centralised bulk power plants and distributed power generators that allows multidirectional power flow and information exchange. Its two-way power flow and communication systems create an automated and energy-efficient advanced energy delivery network. On the other hand, in traditional power systems, power flows only in one direction, that is, from generating station to customers via transmission and distribution networks [4, 30]. Brief comparisons between an existing grid and a smart grid are given in Table 3.1.

Table 3.1 Comparison between existing grid and smart grid

Existing grid	Smart grid
Mostly electromechanical	Digital in nature
One-way communication	Two-way communication
Mostly centralised generation	Distributed generation
Sensors are not widely used	Sensors are widely used
Lack of monitoring only manual	Digital self-monitoring
Failures and blackouts	Adaptive and intelligent
Lack of control	Robust control technology
Less energy efficient	Energy efficient
Usually difficult to integrate RE	Possible to integrate large scale RE
Customers have less scope to modify uses	Customers can check uses and modify

The European and North American vision for Smart Grid technology has evolved over the past decade and has begun to achieve a level of maturity. The USA's Centre for American Progress imparts a view of a clean electricity or clean energy "pipeline", which produces large-scale renewable electricity, delivers electricity nationwide on a new high-capacity grid, deals with all power generation and distribution with new robust information technology methods and allows consumers to contribute energy to the grid [30]. In April 2003, the department of energy (DOE), USA, declared its vision "Grid 2030" that energises a competitive North American Market place for electricity. It planned to connect everyone to abundant, affordable, clean, efficient and reliable electric power anytime, anywhere. It provides the best and most secure electric services available in the world [31].

The European Union Advisory Council established Smart Grid European Technology Platform in 2005, to develop the weak grid with smart grid technology and overcome the drawbacks in the existing power systems. The Smart Grid European Technology Platform [32] vision for flexible (fulfilling customer needs), accessible (access to all network users, particularly for RE sources and high-efficiency local generation with low carbon emission), reliable (assuring security and quality of supply) and economic (cost and energy efficient management) grid to meet the challenges and opportunities of the twenty-first century and fulfil the expectations of society.

Australia is lagging behind compared to the USA and Europe in an attempt to integrate RE sources and build smart grid infrastructure. The Australian government has already taken the initiative with large-scale investment to develop their electricity infrastructure as well as deploy smart grid technology to integrate large-scale RE into the grid [33].

The Australian government has adopted the Smart Grid, Smart City initiative and invested $100 million to create a large-scale smart grid platform, which optimises societal benefits by prioritising applications and undertaking a commercial-scale deployment that tests the business case and main technologies [11]. Integration studies are continuing to improve performances and facilitate large-scale RE penetration into the energy mix.

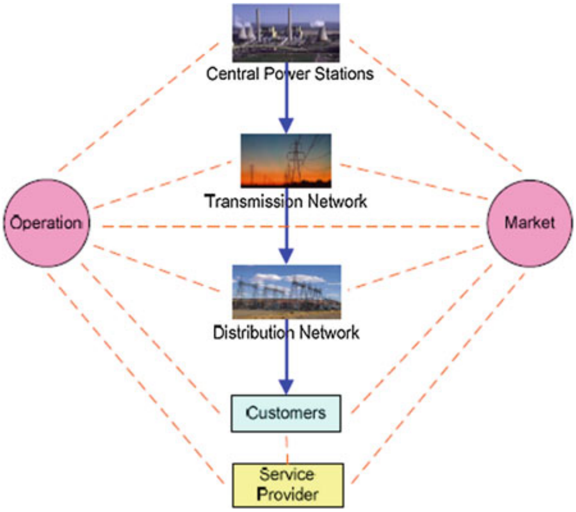

Fig. 3.12 Typical smart grid model [34]

Smart grid technologies includes the following: automation technologies for the smart power delivery; new advanced communication technologies; distributed energy and storage technologies such as solar, wind turbine, fuel cell; advanced metering infrastructure (AMI); power electronics-based controllers; appliances and devices which are demand-response ready. Smart grid has the enhanced and robust communication and computing capabilities that make this an attractive technology for the future power system [34–36].

Recently, Zahedi [34] proposed a smart grid model that is useful to understand the architecture and power flow of the smart grid as shown in Fig. 3.12. This model is expected to be used as the basis in the design of smart grid infrastructure that defines characteristics, requirements, interfaces and performance of the grid [34].

However, due to the intermittent nature of DER, integration of these sources with the grid introduces technical challenges which need to be overcome to obtain a sustainable, climate-friendly power system for the future. Issues that need to be considered to integrate RE in particular wind and solar energy with the power grid are standardised PQ, efficiency, reliability, cost of the energy conversion, appropriate load management, safety and security. Therefore, there is a prime need today to reduce these potential technical challenges for a successful integration of large-scale RE into the grid, though it is not an easy task. In the next section, the observed potential challenges on large-scale RE integration have been presented.

3.4.3 Impacts of Renewable Energy into the Grid

Integration of large-scale DER in particular wind and solar energy with adequate PQ into the grid is a challenging task due to the intermittent and weather-dependent nature of these resources. The integration of variable generation sources presents unique challenges on system performance, and the key factors include [25]:

- RE generator design parameters and power movers' type.
- RE power generation's expected types of run.
- Position of the RE plant's connection to the grid.
- Variability in production of RE sources with changing weather conditions.
- Characteristics of the grid including the loads connected to it.

3.4.3.1 Power Quality Problems

With the increased penetration of RE to the grid, the key potential technical challenges that effect quality of power observed include voltage fluctuation, power system transients and harmonics, reactive power and low power factor that detracts overall PQ of the power systems [25, 26] as shown in Fig. 3.13. These problems mostly occurred for wind and solar energy. Biomass, hydro- and geothermal energy sources are more predictable, and they have no significant problem on integration with the smart grid [25]. Details of the observed problems are given below:

Voltage fluctuation: Voltage fluctuation or instability as well as voltage sags/dips, noise, surges/spikes and power outages is the common problem encountered during integration of large-scale solar or wind energy into the grid. Variability in wind speed or solar irradiation with time is grid connection issues, and faults during operations and starting of large motors, etc., are also responsible. Large penetration of solar or wind power can lead to voltage control or the stability problem of power systems [16]. Periodic disturbances to the network voltage are denoted as flicker. The level of flicker is quantified by the short-term flicker severity value Pst, and allowable voltage change as a function of frequency is Pst = 1 [37, 38]. IEC Standard 61000-4-15 [39] provides a functional and design specification for flicker measuring instruments to measure the correct flicker perception level for all practical voltage fluctuation waveforms. The IEC Standard

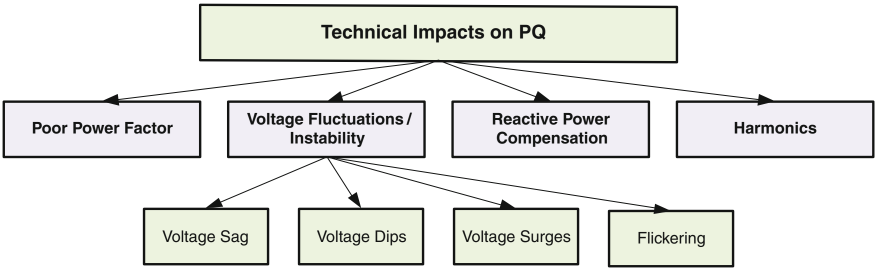

Fig. 3.13 Major potential technical impacts of integrating RE into the grid

61000-4-21 [40] provides a uniform methodology that ensures consistency and accuracy in the assessment of PQ characteristics of grid-connected wind turbines.

Reactive power compensation: The consumption of reactive power by induction generators is a common problem which affects the grid PQ. An induction generator requires an increasing amount of reactive power as the amount of power generated increases, and it is essential to provide reactive power locally as close as possible to the demand levels. Due to the fluctuations in the active and reactive power, the voltage at PCCs fluctuates. The most widely used reactive power compensation is capacitor compensation, which is static, low cost and readily available in different sizes [37, 41]. Reactive power compensation is typically implemented by using a fixed capacitor, a switched capacitor or a static compensator [42]. The power factor of the wind turbine can be improved significantly by appropriate compensation that enhances overall efficiency and voltage regulation of the system. Precise reactive power compensation considering proper size and proper control can remove voltage collapse and instability of the power system and enhances the overall operation of wind turbines.

Harmonic distortion: Power electronic devices, together with operation of nonlinear appliances, inject harmonics into the grid, which may potentially create voltage distortion problems. These results increase power system heat losses and reductions in the life of nearby connected equipment. Harmonic currents create problems both on the supply system and within the installation [43, 44]. Harmonic voltages cause voltage distortion, and zero-crossing noise in the network. The degree of distortion of an AC voltage or current is known as the total harmonic distortion (THD) and defined as the ratio of the sum of the squares of the individual harmonics to the fundamental harmonics as expressed by [43]:

$$\mathrm{THD} = \frac{\sqrt{i_2^2 + i_3^2 + i_4^2 + \,\ldots\ldots + i_{n-1}^2}}{i_1} \tag{3.2}$$

Harmonics is one of the most dominant attributes that need to be kept to a minimum level to ensure good PQ of networks. Harmonic distortion can be minimised by good control algorithm design in the current control loop. Different types of filters are also used to mitigate harmonic distortion. The limits of different harmonic orders are specified in the Australian standard AS 4777 [45].

Appropriate design of electrical circuits with control systems mitigates voltage fluctuations, harmonic distortion, reactive power compensation and power factor improvements and ensures PQ improvements in the power system. Advanced inverter, controller and interconnection technology are starting to be used that allows RE to operate safely with the utility. Custom power devices such as static var compensators (SVCs), shunt active power filters (static synchronous compensators (STATCOMs)), series active power filters (dynamic voltage regulators (DVRs)) and a combination of series and shunt active power filters (unified power quality conditioners (UPQCs)) are the latest developments in interfacing devices between grids and consumer appliance. These devices reduce voltage/current disturbances and improve the PQ by compensating the reactive and harmonic power generated or absorbed by the load [46, 47]. Extensive planning, design and research need to be undertaken in different areas to mitigate the problems introduced by integrating large-scale RE into the grid.

In the next section, existing research that investigates the observed potential technical challenges with their mitigation techniques on integrating large-scale DER into the energy mix has been explored.

3.4.3.2 Existing Research on Integrating DER with the Grid

Wind and solar energy is the most promising DER which are free from GHGs and encourage interest worldwide. Wind generation is one of the fastest growing and cost-effective resources among the different RE sources. Small-scale photovoltaic technology is also cost-effective in providing electricity in rural or remote areas, in particular a country like in Australia.

A. Solar Energy Integration

The asymmetrical solar irradiation due to weather conditions, seasonal variation and geographical location produces voltage fluctuations in the output power of PV systems at the point of common connection (PCC) to the DN. Performances of PV modules also depend on load resistance, solar irradiance, cell temperature, cell shading and the crystalline structure. Under high PV saturation solar irradiance, temperature and shading can cause drastic swings in network operational performance in the event of cloud cover or low light situations, hence producing voltage and power fluctuations and decreased PQ.

This voltage fluctuation is exacerbated in single-phase PV systems as voltage increases both in phase and in neutral, hence causing phase imbalance in the network. However, PQ problems do not depend only on irradiation, but are also based on the overall performance of the solar PV system including PV modules, inverters, power electronic converters and connected consumer loads, etc. [25, 48].

Irregular power flows from PV systems and the use of power electronic converters inject harmonics into the power system network. This harmonic current flowing through the impedances of a DN causes voltage distortion. The fundamental requirements of an inverter are to limit the harmonic distortion and ensure a constant output voltage. Nonlinear loads connected to the DN also introduce harmonics. Many loads connected to the power system network require reactive power. However, a PV inverter is not able to fulfil this reactive power demand, hence causing low power factor in the network [48, 49]. Therefore, the most common impacts due to PV energy integration into the grid are voltage fluctuations, harmonics and poor power factor.

Suitable mitigation measures must be applied to the PV systems side to reduce voltage fluctuations and harmonics injection, and improve the power factor of the network for large PV systems into the grid. Significant researches are undertaken by various agencies throughout the world to investigate and mitigate the impacts on power system networks and to deploy large-scale PV into the grid [48, 49].

Asano et al. [50] analysed the impact of high penetration of PV on grid frequency regulation which responds to short-term irradiance or transients due to clouds. However, the break-even cost of PV is high unless PV penetration reaches 10 % or higher [50]. Therefore, PV integration needs to be increased and its impacts must be identified and mitigated [46, 50]. Recent studies by Ergon Energy (power utility operator in Queensland), and Chant et al. [51] have explored the issues involved in small-scale PV penetration in urban networks. It was found that increased penetration exhibited increased voltage rise on LV networks and increased harmonic distortion, and as a result, load rejection occurs.

A comprehensive study was carried out by Fekete et al. [49] that analysed the harmonic impacts on both winter and summer seasons with 10 kW PV penetration on the DN. Measured results provided basic guidelines that included the following: harmonic distortion of the PV current was low during high generation, and harmonic distortion was high in the period of low generation; odd current harmonics have significant impacts compared to even harmonics, and voltage harmonics had negligible impact on the DN.

In summary, experimental observations for PQ impacts of the integrated PV system are given in Table 3.2 [52]. However, the effects may become more prominent with the increase in PV penetration.

B. Wind Energy Integration

Integration of wind energy into the grid creates potential technical challenges that affect PQ of the systems due to the intermittent nature of wind energy. With the increased penetration of wind energy into the grid, the major PQ problems encountered in wind farms due to the design variations in wind turbines are [42, 53]:

- Uncontrollable reactive power consumption and low power factor.
- Variations in wind speed cause power fluctuations on the grid.
- In a weak grid, power fluctuations cause severe voltage fluctuations as well as significant line losses.
- Injection of harmonics into the grid which may potentially create voltage distortion problems.

Potential technical difficulties occur not only due to the design of wind turbine types but also due to the intermittent nature of the wind source, electrical equipment and the grid connection characteristics and also due to grid quality issues [42]. The interactions between the wind turbine, the power network and the capacitor compensation are essential aspects of wind generation to optimise reactive power as well as active power, power factor and harmonic impacts [42, 53]. Developments in turbine technology have allowed harnessing more energy from the wind by improving the turbine height and increasing the swept area with larger blade sizes. Improved blade design has allowed the harvesting of very low and very high wind speeds and also increases the amount of power per swept area. Power electronic

Table 3.2 Power quality impacts of the PV clusters on distribution networks [52]

PQ concern	Observation	Consideration	Impact
Voltage variation	1 to 2 % increase at light load and high solar irradiation	Network configurations Number of feeders Voltage regulation method	May exceed the standard limit
Voltage unbalance	1–2 % variation due to uneven distribution of PV inverters on three phases and shading effect	Geographical and electrical distributions of PV installations in the area	Minor impact
THD voltage	5th, 7th and 11th harmonics slightly increase	Harmonic content of the grid voltage Series impedance of the grid	Normally below the standard limit
THD current	Harmonic distortion cloud increases at low solar generation	PV inverter topology Design of current control loop for the inverter Grid stiffness	May exceeds the standard limit; undesirable switch-off of PV inverter
Flicker	May occur at fast alternations of clouds and sunshine	Grid impedance	No noticeable impact

converters used in wind turbines are the main cause of harmonic current. With low levels of wind energy penetration, the overall effect on smart distribution system operations is limited, and if the penetration levels increase, more advanced control of the power system will be required to maintain system reliability. Table 3.3 details the potential challenges in integrating both small-scale wind energy and large-scale wind energy into the grid.

Theoretical aspects of the flicker algorithm, wind turbine characteristics and the generation of flicker during continuous and switching operations of wind turbines are evaluated in many researches [41, 54, 55]. From simulation results, it was shown that voltage fluctuations were widely affected by the grid strength and ratio of grid internal impedance. The impact of wind speed, turbulence intensity, grid voltage quality and the number of turbines operating in a grid-connected system are investigated and observed higher flicker levels at low wind speeds which exposed a large number of voltage dips. Flicker emission increases with the increase in wind turbulence intensity.

Rosas [16] investigated the impacts of wind power on the power system and observed that power converters can actively control the reactive power consumption which increased the voltage stability of the power system. From the literature [47, 56], it was found that DFIGs are the most efficient design for the regulation of reactive power and the adjustment of angular velocity to maximise the output power efficiency. These generators can also support the system during voltage sags, though this converter-based system injects harmonic distortion into the systems. However, the newly proposed Z-source inverter (ZSI) can mitigate the PQ problems for future DG systems connected to the grid [56].

Table 3.3 Potential challenges of integration of wind energy with the smart power grid [16]

Integration scale		Problems	Causes
Large scale	Small scale	Steady-state voltage rise	Wind speed variation
		Overcurrent	Peaks of wind speed
		Protection error action	Peaks of wind speed
		Flicker emission during continuous operation	Dynamic operation of wind turbines
		Flicker emission during switching operation	Switching/start-up operation of generators
		Voltage drop	In rush current due to switching operation of generators
		Harmonics	Power electronic converters
	Power system oscillations		Inability of the power system controllers to cope with the power variations from the wind farm and loads
	Voltage stability		Reactive power limitations and excessive reactive power demand from the power system

Characteristics of harmonics into a wind energy integrated power system were investigated with variety of configuration and operating condition [57]. PQ behaviours, in particular voltage sags and harmonics injection into the network, were investigated in [58] on integrating wind energy into LV and medium-voltage networks.

In order to enhance the terminal voltage quality, SVCs were used for reactive power compensation of wind power induction generators [59]. The use of STATCOMs with modified control strategies during normal and transient conditions has been addressed in [60] and [61], respectively. STATCOMs are superior compared to other flicker mitigation methods such as SVCs and series saturated reactors, STATCOMs being faster, smaller and having better performance at low-voltage conditions [62, 63].

STATCOM-based control mechanism is used to reduce the PQ problems as well as harmonics on integrating wind energy into the grid [64, 65]. Hybrid battery and supercapacitor energy storage systems are expected to play a major role in power smoothing, PQ improvement and LV ride through in a wind energy conversion system [17]. Kook et al. [65] developed a simulation model implemented using the power system simulator for engineering (PSS/E) that explored potential mitigation techniques to reduce the level of impacts on integrating wind energy into the grid through application of an energy storage system (ESS) [65]. Moreover, storage can play the vital role by load shifting to support the peak load demand when solar and wind are unable to generate energy.

Finally, the investigation (both experimental and simulated environments) was conducted to identify the impacts of large-scale RE integration into the grid, and suitable mitigation measures were proposed to reduce the level of impacts that ensure adequate PQ in the DN.

3.4.3.3 Impacts of DER Integration: A Case Study

Impacts of solar PV integration into the grid were investigated in experimental and simulation mode.

A. Experimental Analysis

To analyse the impacts of PV integration into the grid, experiments were undertaken at the renewable energy integration facility (REIF), CSIRO in Newcastle, Australia [66]. PQ parameters such as voltage fluctuations, reactive power compensation, harmonics and power factor of networks were investigated with varying PV penetration and load conditions. Details of the experiments were available in Ref. [67].

From the experimental results, it was observed that increased PV penetration causes voltage rise at the load and injects harmonics into the network which cause malfunctioning of devices and deteriorates the PQ of the network. The harmonic content of the network increases with the increase in PV penetration and system size. Figure 3.14 clearly indicates that neutral current is very large for both 11.3 and 7.5 kW PV penetrations and fluctuates significantly from the original sinusoidal wave. Experimental results showed that the neutral current for a PV system is large compared to an individual PV module and inject harmonics into the unbalanced system. It has also been observed that harmonics injection increases with increasing PV penetration, that is, with the increase in PV penetration from 7.5 to 11.3 kW.

Experimental results showed that the waveform of phase voltages is not purely sine waves and they also differ in amplitude and phase angle for both 7.5 and 11.3 kW PV integrated systems and observed voltage fluctuations as well as harmonics due to PV and loads.

From the FFT analysis, it was found that harmonic injections from all even harmonics are within the range stated in AS4777 standard [45]. However, the 3rd and 9th harmonics exceeded the regulatory standard, while injections from the 7th and 15th harmonics just reached the threshold levels as shown in Fig. 3.15. All other harmonics are within the allowable limits.

Minor voltage harmonics were observed in the network due to PV connections and load conditions. Observed THD is only 0.0128 (1.28 %), and second harmonics cause the most effect which is only 0.6 % of the fundamental voltage. It can be seen that in a few cases, the current harmonic distortion is beyond the allowable limits of AS 4777 [45].

B. Simulation Analysis

Considering reliability and flexibility of the modelling analysis and facilitate large-scale PV integration into the grid, different modelling case scenarios were developed using PSS Sincal [68] under the following configurations:

- Case 1: PV 9.5 kW, microturbine 28 kW, load 30 kW (considered harmonics injection only at PV).

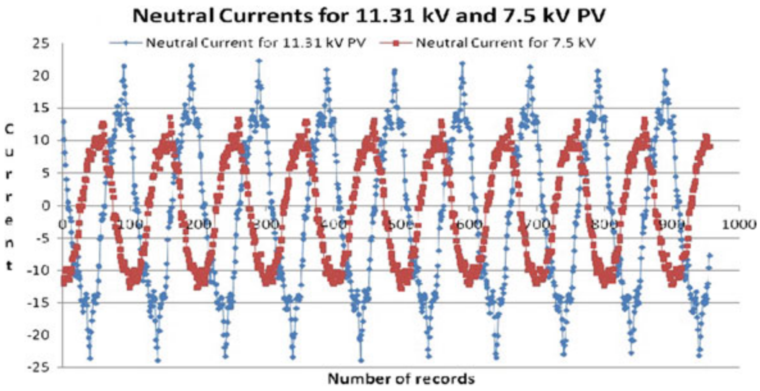

Fig. 3.14 Neutral currents with 11.3 and 7.5 kW PV penetrations

- Case 2: PV 19.1 kW, microturbine 28 kW, load 30 kW (considered harmonics injection only at PV).
- Case 3: PV 30.0 kW, microturbine 28 kW, load 30 kW (considered harmonics injection only at PV).
- Case 4: PV 30.0 kW, microturbine 28 kW, load 30 kW (considered harmonics injection both for PV and load).
- Case 5: PV 30.0 kW, microturbine 28 kW, load 60 kW (considered harmonics injection both for PV and load).
- Case 6: PV 30.0 kW, load 60 kW (considered harmonics injection both for PV and load).
- Case 7: PV 30.0 kW, microturbine 28 kW, active load 60 kW and reactive load 30 kVar (considered harmonics injection both for PV and load).

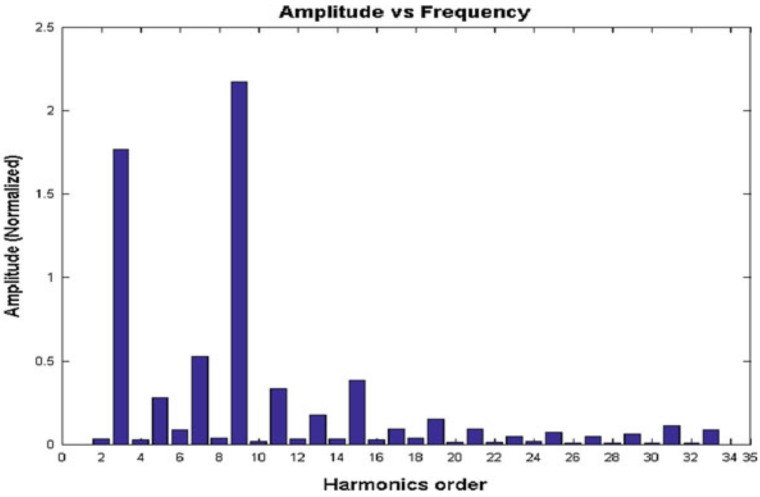

Fig. 3.15 Current harmonic distortion

- Case 8: PV 30.0 kW, microturbine 28 kW, active load 30 kW and reactive load 60 kVar (considered harmonics injection both for PV and load).

The typical schematic view of the developed model is shown in Fig. 3.16 in which major components are the infeeder, transformer, PV arrays, load, microturbine, busbar and lines. Minor voltage fluctuations observed in different case scenarios, however, significant harmonic currents injected into the network was observed which need to be mitigated for an adequate and reliable power supply. The voltage on the HV side of the network remains relatively constant even under high PV penetration, but minor voltage variations were observed in the LV side of the DN.

Harmonic distortion on the network has been demonstrated to have a minimal effect on the system under light PV penetration. Modelling results show that increases in PV generation cause an increase in THD. THD for different case scenarios is shown in Fig. 3.17. It can be concluded that THD increases with the increase in PV generation into the network and THDs for Case 1, Case 2 and Case 3 are, respectively, 1.1, 2.2 and 3.8 % across the LV network and 1.3, 2.6 and 4.4 % across the point of the PV inverter connection. It has been observed that harmonic injection from the PV in Case 3 almost reaches the threshold limit of 5 % defined by IEC 61000-2-4 as well as Australian standard AS 4777 [45]. Load harmonics were added from Case 4 to Case 8 of the modelling to analyse the adverse harmonic impacts due to connected consumer loads. Figure 3.17 indicates that THD increases significantly due to added load harmonics. The only difference between Case 4 and Case 5 is the amount of load connected, and from Fig. 3.17, it is clearly indicated that harmonic distortion increases with the increase in load.

Grid supplied all the required reactive power as the PV and the microturbine could not supply any reactive power in the network for Case 1. The PV system and the microturbine can fulfil the load demand only from 11:30 a.m to 1:30 p.m as maximum PV energy was being generated in this time. However, with the increase in PV generation in Case 3, it can be seen that the PV and microturbine combined can fulfil the load demand with a surplus of energy that can be fed back to the grid except in the evening when there is no generation from PV and maximum load demand occurs. However, with the increased load demand in Case 5, the PV and microturbine cannot fulfil the load demand from 6:30 p.m to 11:45 p.m as shown in Fig. 3.18. Requirements for reactive power by the consumer loads cause poor power factor regulation as well as making the system unbalanced as PV cannot supply any reactive power to the network.

C. Mitigation of Impacts

A custom power device STATCOM was designed and integrated into the system to compensate reactive power demand as well as mitigate voltage disturbances and harmonic distortion and improve the PQ of power systems. The storage system was designed using the DC-Infeeder module in PSS Sincal with realistic losses between the array and the inverter and considered inverter efficiency.

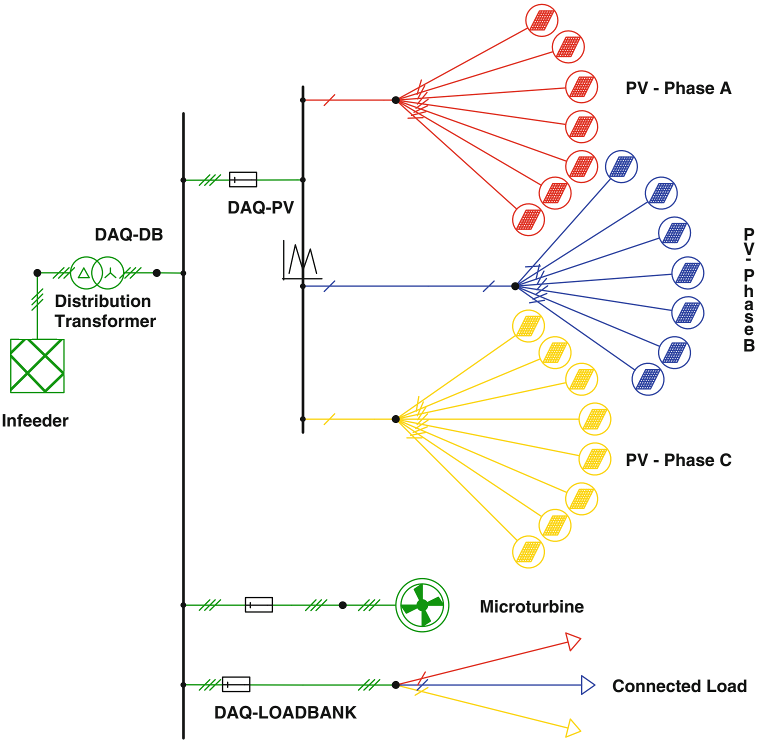

Fig. 3.16 Schematic view of the developed model

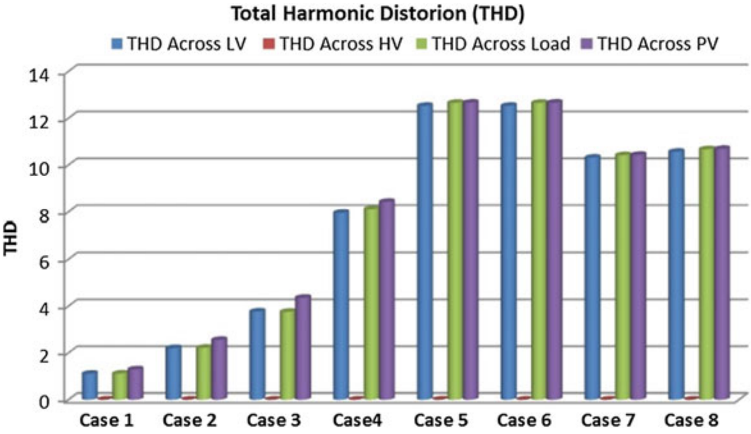

Fig. 3.17 Total harmonic distortion (THD)

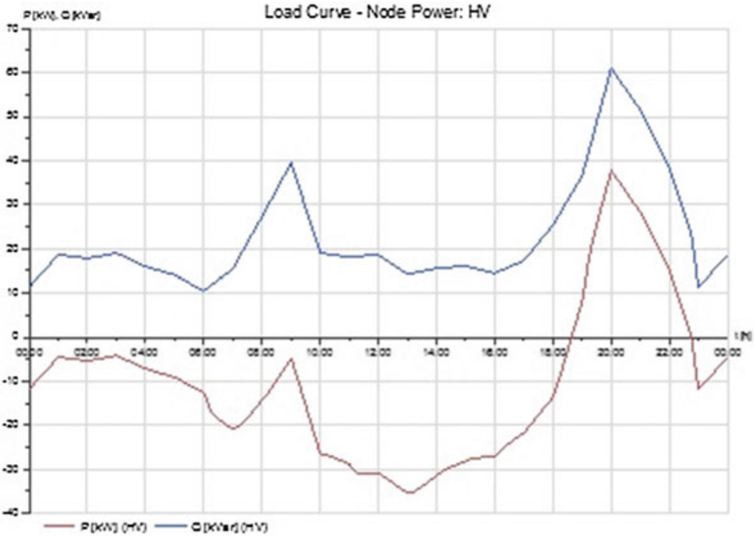

Fig. 3.18 Load curve across DT in a 30-kW PV and 60-kW load (Case 5)

It can be concluded that integration of an ESS into the model improves the power generation from PV sources and reduces dependency on the grid. However, the storage system requires power to charge itself during the day while PV generation was maximum with minimum load demand and it can deliver its stored power in the evening and reduces grid dependency. From simulation results, it can be seen that energy generation was increased after integrating energy storage. Integration of an optimised STATCOM compensates reactive power of the network as shown in Fig. 3.19, which improves the power factor as well as reduces voltage fluctuation and harmonic distortion.

From model results, it can be seen that the STATCOM stabilised the phase voltages, and in this case, the phase voltages were close to the nominal rated voltage. STATCOM reduces the harmonic distortion significantly, and it was observed that without STATCOM, THD is 12.5 %, and with STATCOM, THD is 0.2 %.

3.5 Benefits of RE

Increasing the share of RE in total power generation will not only reduce carbon emission and slow down the climate change but also reduce energy generation costs and energy crisis and also has a significant impact on the socio-economic development worldwide.

Authors carried out a feasibility analyses using the hybrid optimisation model for electric renewable (HOMER) [69] which showed the potential of RE in Australian region considering the production cost, cost of energy and emission

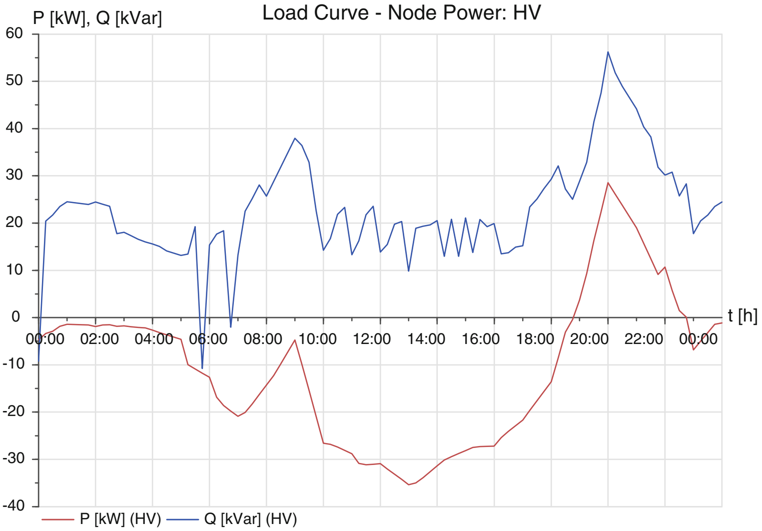

Fig. 3.19 Load curve across DT in a 30-kW PV and 60-kW load with storage and STATCOM (Case 5c)

reduction [70]. From the study, it is clearly observed that Australia has enormous potential for substantially increased use of RE. A large penetration of RE sources into the national power system would reduce CO_2 emissions significantly, contributing to the reduction in global warming. It is also indicated in various studies that RE not only reduces the GHG emission but also plays a major role in reducing energy crisis worldwide as these sources are unlimited and reduces costs of energy generation [70, 71].

From the statistical analysis [70], it was estimated that for wind energy generation, Tasmania is ranked 1 (most suitable) and the Northern Territory is ranked 7 (least suitable) out of the seven states of Australia. On the other hand, it can be seen that the Northern Territory is ranked 1 and Tasmania is ranked 7 out of the seven states of Australia for solar energy generation. The three best potential locations for wind energy generation in Australia are Macquarie Island in Tasmania, Wilsons Promontory in Victoria and Cape Leewin in Western Australia. The three best potential locations for solar energy generation are Weipa in Queensland, Alice Springs in the Northern Territory and Karratha in Western Australia. From the study, it was also evident that Flinders Reef in QLD is the best place considering the combined energy generation from both solar and wind resources; contribution from RE is 90 %. This proposed model will be of benefit to researchers and power utilities to further assess the prospects of RE sources and suitable locations for both wind and solar energy generation in Australia and thus assist to achieve the national goal of introducing 20–25 % energy from RE sources by 2020 [70, 71].

RE generation would also bring indirect benefits like income generation, employment creation and improvements in local air quality and other enhancements for quality of life. According to Clean Energy Australia 2010 report by Clean Energy Council, more than 55,000 jobs are expected to be created in RE by 2020. Due to increased growth of PV, Germany has employed 40,200 in 2006 and 50,700 in 2007 in photovoltaic sector. Job creation is an important part of economic development activity and strong economies as the creation of employment not only benefits the community through the income earned from those jobs, and it generates spin-off benefits known as the multiplier effect [5]. A review of some 30 studies of employment in the energy sectors in North America showed that RE projects can create twice as many jobs as conventional energy projects, per dollar invested [72]. According to [73], the economic advantages of RE technologies are twofold: (1) they are labour intensive, so they generally create more employments for the same amount of investment than conventional electricity generation technologies and (2) they use primarily native resources, so most of the energy per dollars can be kept at home.

3.6 Conclusions

Recent environmental awareness resulting from the conventional power station has encouraged interest in the deployment of large-scale RE in the energy mix. Current power systems are not capable of mixing RE sources as the systems were not developed for such integration. The use of smart grid operations allows for greater penetration of variable energy sources through more flexible management of the system. RE sources not only reduce GHG emission significantly which plays a key role in developing a sustainable climate-friendly environment but also reduce the energy generation costs and energy crisis worldwide.

Therefore, considering the current scenario, substantial research, planning and development work have undertaken worldwide, to facilitate large-scale integration of RE into the energy mix. Large penetration of RE sources into the grid causes significant voltage and power fluctuation, harmonics injection as well as frequency deviation in the network which reduces the PQ. Appropriate design and control of power electronic devices not only ensures the reliability and availability of power delivery but also improves the voltage stability and power system stability and thus ensures continuous increase in RE into the power network. Findings of this study are expected to be used as guidelines by the policy makers, manufacturers, industrialists and utilities for deployment of large-scale RE into the energy mix.

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