# 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

---

D.Q. Hung · N. Mithulananthan (✉)
The University of Queensland, 4072 Brisbane, QLD, Australia
e-mail: mithulan@itee.uq.edu.au

M.R. Shah
The University of Manchester, PO. Box 88, M13 9PL Manchester, UK

D. Jayaweera (ed.), *Smart Power Systems and Renewable Energy System Integration*, Studies in Systems, Decision and Control 57,
DOI 10.1007/978-3-319-30427-4_6

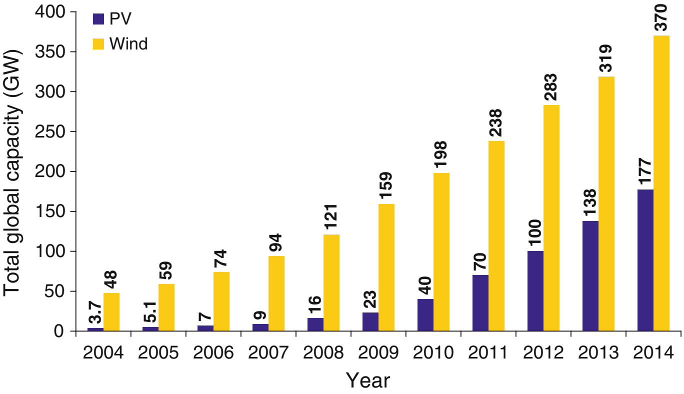

**Fig. 1** Solar PV and wind global power capacity, 2004–2014 (Renewables global status report 2015)

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

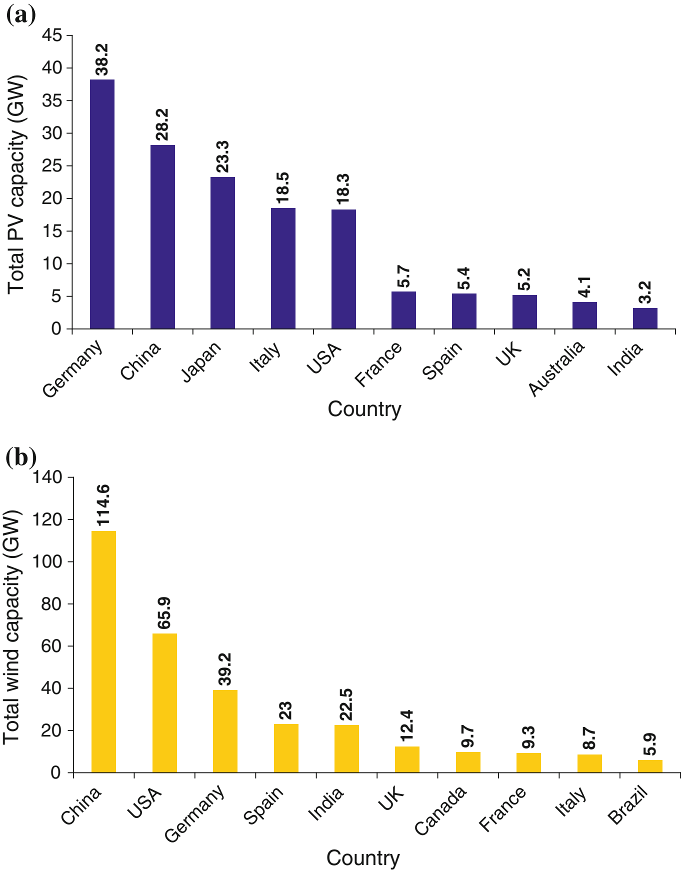

**Fig. 2** Renewables capacity, top 10 countries until 2014: **a** solar PV and **b** wind (Renewables global status report 2015)

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

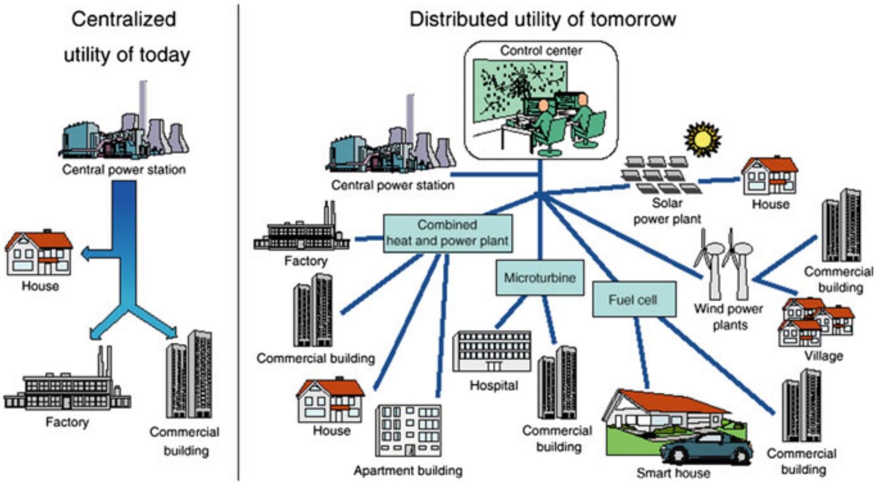

**Fig. 3** Passive power system (*left*) versus active power system (*right*) (*Source* ABB 2002)

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.

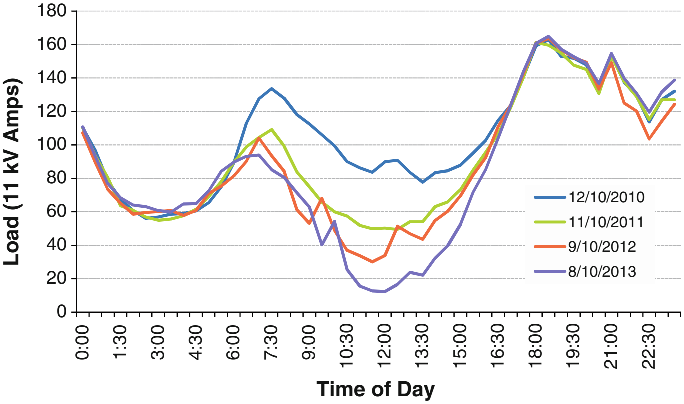

**Fig. 4** PV impacts on a Currimundi feeder load profiles on the Energex network (Energex Limited 2013)

## 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

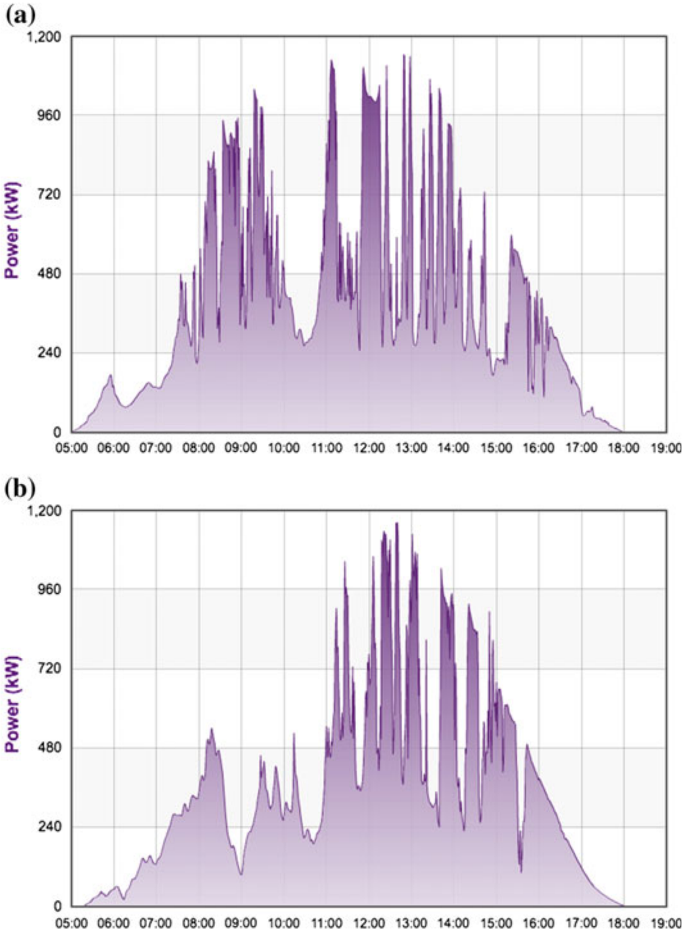

**Fig. 5** The instantaneous power outputs from combined solar PV panels at St Lucia campus, the University of Queensland, Australia on November 4 of years: **a** 2011 and **b** 2012

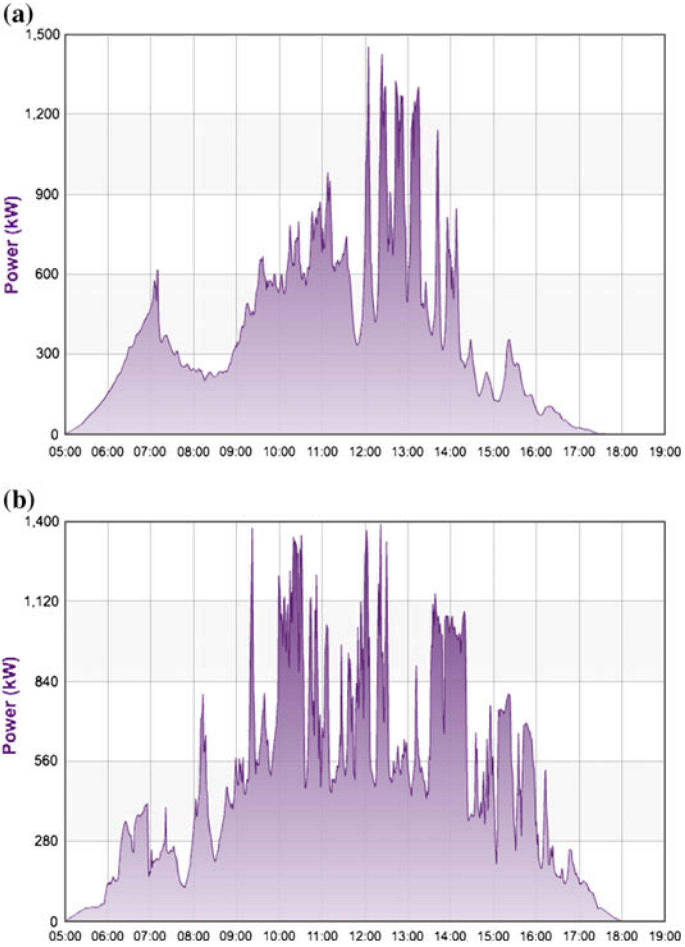

**Fig. 6** The instantaneous power outputs from combined solar PV panels at St Lucia campus, the University of Queensland, Australia on November 4 of years: **a** 2013 and **b** 2014

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 substation 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,

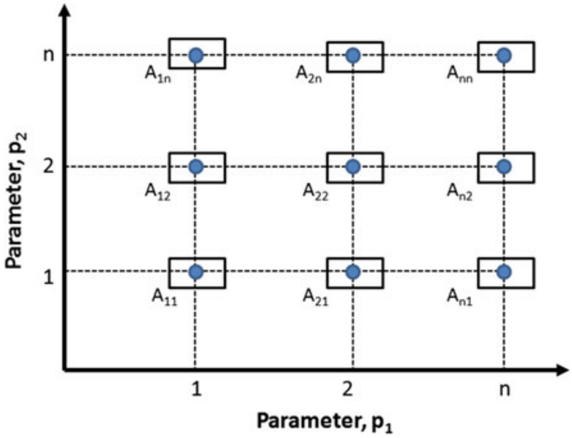

**Fig. 7** Matrix of grid operating condition (Mithulananthan et al. 2014)

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 ($\mu$) by a varying reactive power control scheme of each renewable generation cluster with underlying uncertainties in the system. System loads ($\rho_1$) and renewable generation variations ($\rho_2$) 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.

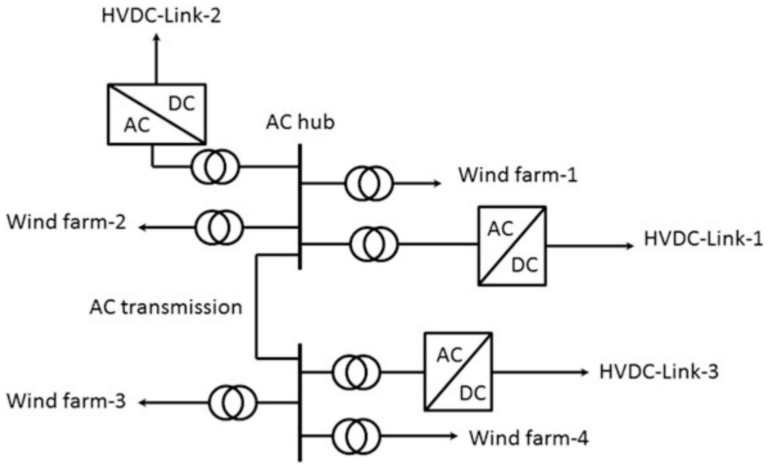

**Fig. 8** Proposed offshore AC grid model (Stevens and Rogers 2013)

### 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

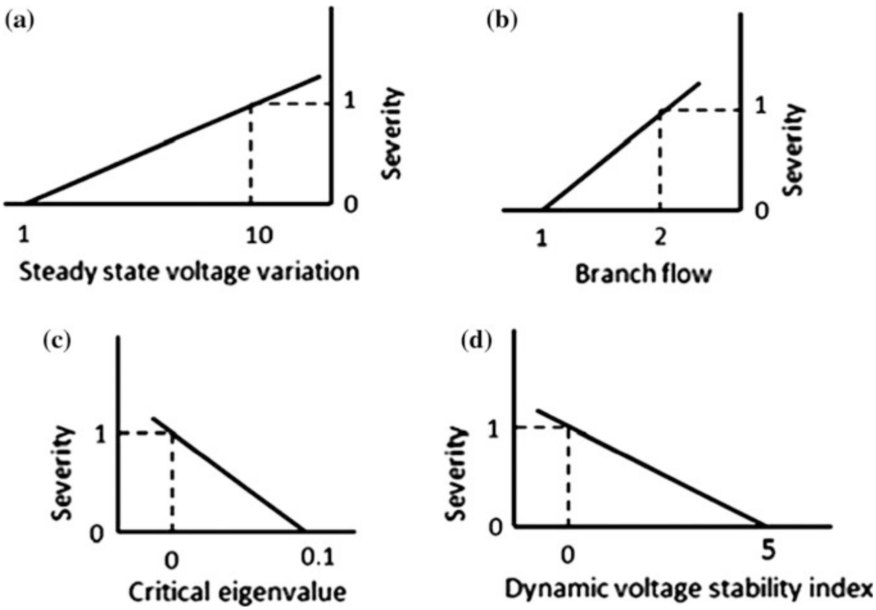

**Fig. 9** Continuous severity functions for risk assessment (Shah et al. 2015). **a** Steady-state voltage. **b** Line flow. **c** Static voltage stability. **d** Dynamic voltage stability

**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.

## References

Adeuyi, O.D., Jenkins, N., Wu, J.: Topologies of the north sea supergrid. In: International Universities Power Engineering Conference (2013)

Bank, J., Mather, B., Keller, J., Coddington, M.: High penetration photovoltaic case study report. National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy13osti/54742.pdf (2013)

Chidurala, A., Saha, T.K., Mithulananthan, N.: Power quality enhancement in unbalanced distribution network using Solar-DSTATCOM. In: Power Engineering Conference Australasian Universities (AUPEC), Hobart, TAS, 29 Sept 2013–3 Oct 2013

Dahal, S., Mithulananthan, N., Saha, T.K.: Assessment and enhancement of small signal stability of a renewable energy based electricity distribution system. IEEE Trans. Sustain. Energy **3**(3), 407–415 (2012)

Ela, E., Kirby, B.: ERCOT event on February 20, 2008. Lesson Learned, NREL (2008)

ElNozahy, M.S., Salama, M.M.A.: Technical impacts of grid-connected photovoltaic systems on electrical networks—a review. J. Renew. Sustain. Energy **5**(3), (2013)

Energex Limited: Energex distribution annual planning report 2013/2014 to 2017/2018. www.energex.com.au (2013)

Farhoodnea, M., Mohamed, A., Shareef, H., Zayandehroodi, H.: An enhanced method for contribution assessment of utility and customer harmonic distortions in radial and weakly meshed distribution systems. Int. J. Electr. Power Energy Syst. **43**(1), 222–229 (2012)

Farret, F.A., Simoes, M.G.: Integration of Alternative Sources of Energy. Wiley Online Library (2006)

Hung, D.Q., Mithulananthan, N., Lee, K.Y.: Determining PV penetration for distribution systems with time-varying load models. IEEE Trans. Power Syst. **29**(6), 3048–3057 (2014)

IEEE 1547: Standard for interconnecting distributed resources with electric power systems (2003) (October)

Infield, D.G., Onions, P., Simmons, A.D., Smith, G.A.: Power quality from multiple grid-connected single-phase inverters. IEEE Trans Power Del. **19**(4), 1983–1989 (2004)

Junyent-Ferre, A., Pipelzadeh, Y., Green, T.C.: Blending HVDC-link energy storage and offshore wind turbine inertia for fast frequency response. IEEE Trans. Sustain. Energy **6**(3), 1059–1066 (2015)

Katiraei, F., Aguero, J.R.: Solar PV integration challenges. IEEE Power Energy Mag. **9**:62–71, (2011)

Katiraei, K.M.F., Dignard-Bailey, L.: Integration of photovoltaic power systems in high-penetration clusters for distribution networks and mini-grids (2009) (January)

Managing the Risk in Renewable Energy: The economist intelligent unit report (2011)

Mithulananthan, N., Shah, R., Lee, K.Y.: Small-disturbance angle stability control with high penetration of renewable generations. IEEE Trans. Power Syst. **29**(3), 1463–1472 (2014)

Nanou, S.I., Patsakis, G.N., Pathanassion, S.A.: Assessment of communication—independent grid code compatibility solutions for VSC-HVDC connected offshore wind farms. Electr. Power Syst. Res. **51**, 121–138 (2015)

Nasr-Azadani, E., Canizares, C.A., Olivares, D.E., Bhattacharya, K.: Stability analysis of unbalanced distribution systems with synchronous machine and DFIG based distributed generators. IEEE Trans. Smart Grid **5**(5), 2326–2338 (2014)

Renewables global status report. http://www.ren21.net (2015)

Noone, B.: PV integration on Australian distribution networks. The Australian PV Association. http://apvi.org.au/wp-content/uploads/2013/12/APVA-PV-and-DNSP-Literature-review-September-2013.pdf. Accessed Sept 2013

Preece, R., Milanovic, J.V.: Risk based small disturbance security assessment of power systems. IEEE Trans. Power Del. **30**(2), 590–598 (2015)

Quezada, V.H.M., Abbad, J.R., Roman, T.G.S.: Assessment of energy distribution losses for increasing penetration of distributed generation. IEEE Trans. Power Syst. **21**(1), 533–540 (2006)

Quintero, J., Vittal, V., Heydt, G.T., Zhang, H.: Impact of increased penetration of converter control-based generators on power system modes of oscillation. IEEE Trans. Power Syst. **29**(5), 2248–2256 (2014)

Shah, R., Mithulananthan, N., Bansal, R.C., Lee, K.Y., Lomi, A.: Influence of large-scale PV on voltage stability of sub-transmision system. Int. J. Electr. Eng. Inf. **4**(1), 148–161 (2012)

Shah, R., Yan, R., Saha, T.: Chronological risk assessment aprroch of distribution system with concentrated solar power plant. IET Renew. Power Gener. **9**(6), 629–637 (2015)

Stevens, J., Rogers, D.J.: Control of multiple VSC-HVDC converters within offshore AC-hub. In: IEEE Power Tech. (2013)

Swanston, M.: Energex. Personal communications. July (2014)

Thomson, M., Infield, D.G.: Network power-flow analysis for a high penetration of distributed generation. IEEE Trans. Power Syst. **22**(3), 1157–1162 (2007)

Turitsyn, K., Sulc, P., Backhaus, S., Chertkov, M.: Options for control of reactive power by distributed photovoltaic generators. Proc. IEEE **99**(6), 1063–1073 (2011)

Vittal, E., O' Malley, M., Keane, A.: A steady state voltage stability analysis of power systems with high penetrations of wind. IEEE Trans. Power Syst. **25**(1), 433–442 (2010)

Vittal, E., O' Malley, M., Keane, A.: Rotor angle stability with high penetration of wind generation. IEEE Trans. Power Syst. **27**(1), 353–362 (2012)

WECC wind power plant dynamic modelling guide: WECC renewable energy modelling task force (2010)

Yaghoobi, J., Mithulananthan, N., Saha, T.K.: An Analytical Approach to Assess Static Voltage Stability of Distribution System with Rooftop PV Units. IEEE PES-GM, Washington DC (2014)

Yaghoobi, J., Mithulananthan, N., Saha, T.K.: Dynamic Voltage Stability of Distribution System with a High Penetration of Rooftop PV. IEEE PES-GM, Denver, Colorado (2015)

Yan, R., Saha, T., Modi, N., Masood, N., Mosadeghy, M.: Combined effect of high penetration wind and PV on power system frequency response. Appl. Energy **145**(1), 320–330 (2015)

Yeh, H.G., Gayme, D.F., Low, S.H.: Adaptive VAR control for distribution circuits with photovoltaic generators. IEEE Trans. Power Syst. **27**(3), 1656–1663 (2012)