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REVIEW PAPER

Impact of intermittent renewable energy generation penetration on the power system networks – A review

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Abstract
Entrance of intermittent renewable power energy sources has brought in benefits mainly associated with emission reduction to help the climate change cause and reduce pollution. However, entrance of renewable generation sources, mainly wind and solar generation that are intermittent energy sources by nature has not come without its own challenges. Future power grids will see continued elevation of intermittent generation with instantaneous penetration levels that may potentially be as high as 100% for some periods. This paper reviews published works and highlights technical challenges that require further research to ensure that power grids that will be dominated by inverter-based generation or purely powered by inverter-based generation continue to operate reliably and remain stable for all operating scenarios. The paper outlines further research opportunities in areas of power sytem security assessment, voltage and frequency management, power system stability, resource forecasting techniques for unit commitment, behind the meter generators and loads integration to grid, frequency and voltage support, power system flexibility assessment methods, protection schemes enhancement, power quality mitigation techniques and modelling requirements to support real-time power system operation.

Keywords Intermittent renewable generation · Power system stability · Power system flexibility · Voltage control · Frequency control · Power quality · Ancillary services

Introduction

Power systems and energy markets are undergoing rapid transformational change. Historically, the power systems around the world have been dominated by fossil driven synchronous generation power stations with passive customer loads. The emerging power systems are characterised by increasingly distributed generation, most of it being of the asynchronous type, with traditional fossil driven synchronous generators being retired [5]. According to the International Energy Agency (IEA) forecasts, by 2050 the global share of intermittent renewable energy sources will increase to 57% of the load served [62]. While intermittent renewable energy sources bring advantages of nil fuel costs and no carbon emissions [32], increased levels of intermittent renewable energy sources in the power grids has introduced new technical challenges in areas of power system security, power system stability and power quality [13, 52, 90, 94] that require investigation and development of solutions to address emerging challenges.

According to [94], 30% of electricity demand in Portugal was supplied by a mix of renewable generation types other than hydropower, and 29% of Spain's energy needs were met by renewable energy generation in 2014. Britain had 24.5 % demand supplied by renewable generation in 2015 [39]. Intermittent energy sources penetration accounted for more than 20% in Ireland and Germany [39]. In 2016, wind power production constituted 42% of electricity consumption in Denmark [86]. In South Korea, intermittent energy sources are expected to reach 53% of the peak load by 2030 [77]. The annual renewable generation penetration level is generally used to describe how much annual intermittent energy is produced on a yearly basis in a certain region or country. The instantaneous renewable generation penetration in some times of the day can be up to 5 times higher than the annual average penetration. For example, 100% of renewable energy instantaneous penetration was observed in Denmark at certain times when the annual average renewable energy production was only around 20% [87]; reliable operation of

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the system during those periods was dependant on support from transmission interconnectors to synchronous generation in neighbouring countries [51]. In some other parts of the world such as Hawaii, Texas, Ireland, South Australia and Tasmania, power systems frequently experience instantaneous renewable generation penetration levels in excess of 50–60% of total system demands [51]. Instantaneous penetration is an important factor when considering the impact of intermittent energy sources on the power system in real time [43]. Future grids are expected to be dominated by inverter connected distributed intermittent generation and controllable loads [13, 43], hence there is a need to study and understand the impact of inverter connected intermittent renewable energy sources on the power grid. Energy production forecasts made in 2016 show that several European countries are likely to experience 100% instantaneous renewable energy penetration levels by the year 2025 [51]. Figure 1 is an illustration of a traditional power grid powered by fossil fuel synchronous generation compared to the future power grid that is expected to be powered mostly by inverter connected renewable generation in Fig 2.

Renewable energy generation includes non-intermittent generation such as hydropower, biomass and geothermal which are more predictable energy sources and have no major technical issues to connect to the grid [66]. The focus of this paper is on intermittent renewable energy sources. Solar and wind systems constitute a large share of new intermittent renewable generation being installed in the power grids around the world [62, 84].

Electricity supply via large interconnected transmission networks involves ongoing requirements to balance power system variables to keep the system within safe operating limits, and to maintain balance between power demand from connected loads and power supply from generation sources. One of main technical challenges with the use of solar and wind generation is that both are reliant on intermittent natural sources of energy that are independent of load demand or control of the grid operator [84]. Integration of intermittent power generation sources can potentially impact the power system negatively [7]. As the intermittent non-synchronous renewable generation rapidly displaces conventional synchronous generation, it is prudent that the research community and industry engineering practitioners study and understand their impact on power system operation and power system planning [2, 91], and ensure that future power systems are adequately prepared to withstand such impacts.

The technical areas of impact that require attention as penetration of renewable energy generation increases include quality of power supply, reliability, system security, system stability, visibility and controllability of behind the meter power generation sources and flexible loads. For intermittent generators to be a secure and dependable alternative energy source to conventional synchronous generators, they need to have capability to provide network ancillary services similar to those that have traditionally been provided by synchronous generators such as load following services, dispatchable spinning reserve, adequate fault contribution, black start, transient stability (inertia) and voltage stability.

This paper provides a critical review of published works done on the technical impact of significant penetration of intermittent renewable energy into the power networks and the proposed strategies to mitigate the impact. The paper

Fig. 1 Present grids experiencing high penetration of renewables, still have significant amount of fossil fuel generators

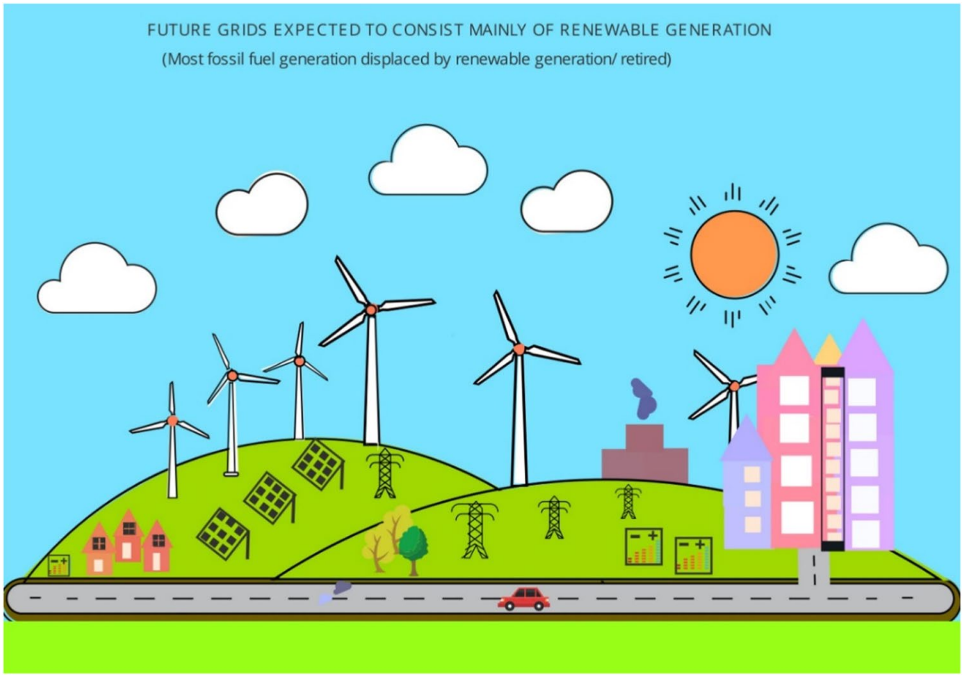


Fig. 2 Future grids expected to be powered by up to 100% inverter connected renewable generation

highlights research gaps where further work is required to quantify impact and develop appropriate strategic and technical measures to mitigate such impact. A broad-brush overview of pertinent technical issues relating to penetration of intermittent renewable energy sources are presented. The contribution of the paper is to serve as a reference resource for researchers and practitioners who need introduction to broad technical issues associated with elevated penetration levels of intermittent renewable energy sources and identify areas that require further research attention. Previous reviews on impact of intermittent renewable generation on power systems have focussed on specific subsets of technical themes relevant to the subject area. There are no previous review papers identified that provide a broad review of published works covering the breadth of technical issues arising from impact of penetration of intermittent renewable generation on power systems. Table 1 shows technical themes addressed by this review paper in comparison to previous review papers. This paper is organised as follows, Section 2 discusses the impact of intermittent renewable generation on Power System Security, Section 3 on Power System Stability, Section 4 on Power System Reliability, Section 5 on Power Quality, Section 6 on Demand and Supply Forecast and Section 7 on Power System Modelling.

Power System Security

Power system security refers to its ability to survive any credible system contingencies without loss of supply to customers [52]. The N-1 reliability standard that is commonly used around the world as a criterion of power system security requires that power supply should not be interrupted by any single contingency i.e. loss of any single plant item of any of the N plant items forming a network or subnetwork should not result in loss of power supply [98].

As renewable energy generation penetration increases, it is becoming more difficult to maintain the security and reliability of power networks, leading to increasing necessity for Network Operators to impose operational constraints on generation and use their market direction powers to maintain power system security and reliability as highlighted by the Australian Energy Market Operator (AEMO) [5]. Constraining generation is not desirable in a liberalised electricity market as it increases costs to the market that are eventually borne by consumers.

In a secure power system operating environment, operational criteria as dictated by relevant grid codes must be satisfied for pre- and post-contingency conditions; this includes steady state and transient voltage and frequency variations, electrical plant thermal loading and power system stability [55]. Power system faults are often unpredictable and unavoidable making security assessment an important requirement [11]. A number of researchers have looked at the power system security assessment and analysis problem in the presence of intermittent generation [11, 31, 49, 52, 98, 101].

In [52], a Monte Carlo approach described as a sequential time simulation was used to analyse overload security for a network with high penetration of wind generators and concluded that high penetration of wind generation increases uncertainty and could increase power system security risk, and also observed that security assessment depends on wind

Table 1 Themes addressed in previous review papers related to impact of intermittent renewable sources on power systems

Theme	References								This Review
	Abujarad et al. [2]	Haque & Wolfs [34]	Karimi et al. [41]	Mahmud & Zahedi [48]	Oree et al. [62]	Mohandes et al. [53]	Emmanuel et al. [22]	Fernandez-Guillamo et al. [27]	
Power system security	✓					✓			✓
Generation capacity/ spinning reserve	✓				✓	✓			✓
Congestion management									✓
Voltage regulation		✓	✓	✓					✓
Frequency regulation								✓	✓
Power system flexibility					✓	✓	✓		✓
Power system strength								✓	✓
Frequency stability								✓	✓
Voltage stability									✓
Rotor angle stability									✓
Small signal stability									✓
Power system reliability									✓
Power quality			✓						✓
Power system modelling	✓						✓		✓

speed correlation at various wind generation locations. A concept of 'Robust Security Region' which formulates the conditions required to satisfy N-1 criteria for power system planning and power system operation in an uncertain environment is proposed in [98]. The Robust Security Region is described as the operational zone of the power system where the system remains secure under environmental uncertainties. This work demonstrated that the Robust Security Region tends to shrink at high penetration levels of photovoltaic generation. However, this work did not discuss uncertainties from other energy sources such as wind generation.

In [31], Probability Mass Functions (PMFs) based on Monte Carlo Analysis were used to develop a linear model that predicts failure rates relative to wind and solar penetration (where failure was defined as violations of system limits in the load flow studies conducted by the authors), the authors found that there are critical intermittent generation penetration levels for which the likelihood of failure increases significantly.

Yardstick competition-based power system security assessment approach for a power system with intermittent generation is presented in [101]. The assessment approach is based on eight indicators that can be used to evaluate influence of intermittent generation penetration on grid security. The eight indicators include two static indicators and six dynamic indicators. The static indicators are active power margin and reactive power margin, and dynamic indicators being minimal damping ratio for small disturbance, lowest bus voltage, maximum rotor angle post fault, system accelerating power post fault, critical fault clearing time and frequency excursion safety margin. The methodology demonstrates for each indicator whether integration of intermittent generation at a particular bus improves or deteriorates power system security for a particular bus being studied. Case studies conducted by the authors in various provinces in China show varied impact on intermittent generation penetration impact at each bus studied, however, the study results did not include the electrical characteristics of buses studied to provide insight as to how the electrical characteristic of each node influenced the outcome at each location.

A detailed review of risk-based power system security assessment is presented in [11]. Recent trends show that power sytem security assessment has changed from a deterministic assessment approach to a risk-based assessment approach, there is need for further research in risk based assessment methods for power systems with a high penetration of distributed generation [11].

Generation Capacity and Spinning Reserve

Intermittent power production is characterised by large changes in instantaneous electricity production and limited certainty of energy resource forecast [12]. High intermittent generation penetration levels can cause higher ramp up/down-rates, greater variability, and greater generation scheduling errors. As a consequence, the system operator may need to hold a higher amount of generation reserve to ensure power system security [32, 62].

The uncertainty as far as reserve allowance for intermittent generation goes is treated the same as reserve to cater for imperfect forecast of power system loads; this can vary from small generator output changes due to variation of renewable energy source (e.g. wind or solar) to large variations such as the whole windfarm shutting down due to very high wind speed beyond its mechanical capability [12]. The overall impact is dependent of how well correlated different generators (solar farms and wind farms) are, i.e. whether variations at different generation sites occur simultaneously in the same direction, opposite direction or completely uncorrelated. Impact of intermittent energy sources diversification on reserve requirement was studied by Halamay, D.A et. Al. [32] and concluded that a diversified intermittent renewable generation fleet can yield less generation reserve requirements for a utility and reduce impact of variability.

Fluctuations in intermittent generation energy resource can vary with times of the day or seasons, and can be difficult to forecast using historical data [62]. Continual development of sophisticated resource forecasting techniques is required to effectively schedule generation and reserve requirements to cater for intermittent resource variability.

Brouwer et al. [12] found that for at least 30% of renewable energy penetration, wind power will increase the requirement for primary reserves by 0.3% to 1.0% of installed wind generation capacity, and it becomes greater as intermittent generation penetration levels increase. There is a market cost for providing spinning reserve requirements. Intermittent renewable generation also creates extra costs for balancing the system as a result of high ramping-up and ramping down requirements for base-load power plants, and reducing (constraining off) the amount of power generated by conventional power plants [57].

Several research groups have analysed the impact of large-scale solar and wind generation on reserve requirements and assessment methods for generations reserve requirements for power systems with high levels of renewable power penetration [32]. This is expected to be a continued area of research activity as the world becomes more reliant on intermittent renewable energy sources of generation.

Capacity credit of a generator is used by power system planners to quantify firm capacity that a generation unit adds to the grid. It quantifies the extra demand that can be served by the power system when that particular generator is in service. Oree, Hassen and Fleming [62] conducted a detailed review of Generation Expansion Planning with a high level of renewable generation penetration and deduced that capacity credit decreases with increasing wind power penetration. They provided case examples showing that for 100 MW of installed wind generation corresponding to 0.9% level of penetration, capacity credit would be 28% in contrast to 2000 MW of installed wind generation (equating to 18% penetration level) that yields only 13.6% of capacity credit.

A detailed review of unit commitment approaches in the presence of intermittent renewable generation is presented in [2]. The unit commitment decision includes the determination of the generating units that are required to run at each planned generation interval (minutes, hours, days) considering generation units start-up and shutdown requirements, system demand and spinning reserve capacity at minimum total production cost [2]; hence, unit commitment is an optimisation problem whose objective is to minimize the total running cost over a trading interval. Several researchers have worked on multiple new models of the unit commitment problem formulation while considering the stochastic renewable energy generation [26, 63, 69, 97]. A comparison of Unit Commitment models employed to manage systems with potential high renewable energy penetration is provided in Table 1 of reference [2], the weaknesses highlighted for each methodology/approach suggests that further research work is required to further enhance unit commitment models to accommodate high variability and uncertainty of intermittent renewable energy sources.

Transmission line capacity/ congestion management

Increased intermittent generation levels alter the power transmission line flows which increases the likelihood of breaching thermal limits of the transmission lines particularly at locations with high concentration of intermittent energy sources [60]; Congestion occurs when the transmission lines do not have adequate capacity to transfer power according to market requirements [67]; as a consequence, the need for transmission capacity augmentation increases [89].

Most conventional synchronous power stations, such as coal power plants, were built alongside transmission grids expansion/extensions prior to deregulation. As an example, the existing United States of America grid infrastructure was designed to connect coal reserves in the Appalachians with demand centres in eastern coastal areas, and not the renewable energy resource rich (wind and solar) areas in the Midwest and Southwest [37]. Similar experiences can be cited in other parts of the world; in Western Australia for instance, the south west of the state has historically been a strong hub for synchronous generation with strong transmission line interconnections to the load centres. However, new entrant intermittent generation in Western Australia is mainly developing in the windy areas north of Perth and sunny areas east of Perth. These areas consist of network of low system strength, often requiring curtailment of the active power output of these intermittent generators during congested periods.

The cost of grid congestion, particularly curtailed generation output (constrained off) compensation cost has gained public attention; however, these costs can be reduced by power network reinforcement [39]. Literature shows that there is a significant research interest in network congestion management strategies [36, 37, 76]. Active transmission line switching has been investigated and shown to reduce the transmission line congestion effect [28]. Line switching in [89] was applied on a Danish power network to influence output of intermittent generators into a less congested section of the network and therefore deferred investment on network augmentation. Switching out of transmission lines, while a solution for network congestion and voltage management, requires carefully consideration to ensure that it does not result in negative impact in overall power system reliability.

Stochastic planning and scheduling of Energy Storage Systems (ESS) to manage congestion in power system networks considering uncertainties related to solar and wind units has been investigated and reported in [36]. The methodology seeks to find an optimal ESS capacity, and charging and discharging pattern with an objective of minimizing congestion costs. A generation rescheduling algorithm used to modify generation outputs to mitigate line overloads is presented in [24]. The proposed generation rescheduling algorithm in [24] was tested on the Arizona transmission system. Other congestion management strategies currently used in the market include the Nodal Pricing congestion management method, Price Area Congestion management, Available Transfer Capability based congestion management, Flexible AC Transmission Systems (FACTS) application and Demand Side Management are reviewed in detail in [67].

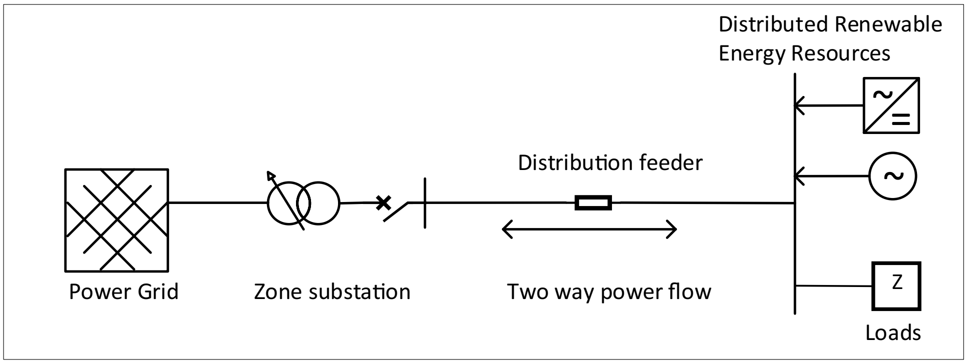
An evaluation method of dynamic line rating, considering large transmission line current fluctuations due to intermittent energy resources, to estimate transmission line temperature rise, is proposed in [81]. The authors suggest that the methodology may be applicable to real time systems for preventative control actions to alleviate line overloads through demand response mechanism such as load curtailment and behind the meter storage systems.

Voltage Regulation

Voltage regulation is one of the most significant technical limitations that can restrict the amount of renewable energy resource penetration into the distribution networks [48]. In distribution networks with high levels of imbedded renewable generation, unlike conventional distribution systems consisting of unidirectional power flow towards loads, bidirectional power flow may occur in the distribution systems. Resultant reverse power flow as shown in Fig. 3 may result in high voltages along the distribution system that may be difficult to control resulting in frequent violation of voltage limits [48, 66, 75]. Large scale photovoltaics in low voltage distribution networks were not considered when the networks were first constructed, such high levels of intermittent photovoltaics penetration may alter the voltage profile of distribution networks [34].

Various voltage control techniques on the distribution network are discussed in [66], these include onload tap changing of transformers, voltage regulators, capacitor banks and reactor banks switching, smart grid control techniques and energy storage applications. Onload Tap Changers (OLTC) are commonly used to control distribution feeder voltage by monitoring the transformer's terminal voltage, and transformer secondary current where line drop compensation function is provided [75], this type of control typically works well when power flow is in one direction, i.e. source to load. With bi-directional flows and rapid voltage variation due to imbedded intermittent renewable generation, the voltage situation along the feeder may become unpredictable and uncontrollable by conventional onload tap changers [48]. Continuous research and innovation in online tap changer voltage control schemes is required to cater for high penetration of intermittent renewable sources [75].

Fig. 3 Radial distribution system with imbedded intermittent distributed generation (bi-directional flow)



Low voltage distribution connected inverters under IEEE 1547 are usually operated at unity power factor, this means that they do not contribute any reactive power to the network, and therefore do not contribute towards any network voltage control efforts [25]. As a consequence, such feeders typically experience high voltage issues when there is high active power output from photovoltaics, particularly on weak feeders with low fault levels. Regulatory reform and technical solutions to enable behind the meter inverters to provide voltage support to the network are required.

Historically, reactive power support at the distribution level has been provided by switched shunt capacitor bank located in zone substations. The shunt capacitors are controlled via timers that typically switch in/out capacitor banks only a few times per day as the system load varies slowly and in a predictable fashion. However, with high penetration of intermittent renewables such as solar photovoltaics and wind generation, new operational techniques are required in order to accommodate random and large load rapid fluctuations [25]. In [25] a two-timescale optimization for switching of the shunt capacitors and inverter reactive power control is proposed.

Utility scale solar photovoltaic solar farms connected to a distribution system to supply and absorb reactive power during night time to control distribution voltages is proposed in [88]. Typically, during night time, the loading of the distribution feeders is very low and wind farms connected to the same feeder could be producing high active power output requiring voltage control. In this case the solar farm may be providing the service as an ancillary service over night. STATCOMs can also be used to manage voltage regulation and voltage fluctuation in distribution systems with intermittent renewable generation. Advanced voltage management techniques to keep the voltage profile within regulatory limits such as centralised control, decentralised autonomous control and decentralised coordinated control have been evaluated in [48]. The area of voltage control strategy development in the presence of increase intermittent generation penetration continues to be an active area of research [3, 25, 48, 75, 79, 88, 93].

Frequency Regulation

The power system must control the system frequency within prescribed limits. If the frequency is not managed, it may result in cascading failure with multiple power stations disconnecting from the network as the frequency spirals upwards or downwards at Rate of Change of Frequency (ROCOF) higher than what the system generators protection are designed to tolerate. System frequency can deviate from nominal if there is sudden connection or disconnection of customer loads or generation.

The most difficult time from a frequency regulation point of view is when few synchronous generators are connected to the power network, and there is high output from intermittent generations output, with the overall power system characterised by low system inertia [91]. The total amount of rotating mass across all interconnected electrical machines known as system inertia is proportional to system capability to withstand fluctuations in net load and generation; consequently a system with low inertia is susceptible to large frequency deviations [43]. This statement is corroborated by power system simulation study results presented in [10] that show that with increase of penetration of intermittent wind power generation with conventional synchronous generation displaced, there is an increase in system frequency deviations.

A number of Battery Energy Storage Systems (BESS) research activities to improve frequency regulation in power systems with high penetration of intermittent renewable energy generation are outlined in [86]. BESS applications as an ancillary service can have a positive impact on power system frequency stability by reducing frequency deviations [86]. However, the authors of [86] acknowledge that at present conventional generators are still required to support the power system in terms of frequency regulation even though results show that systems with integrated BESS systems can have system frequency that is more stable with fewer frequency fluctuations.

Renewable energy aggregator entities to facilitate multiple small-scale renewable energy generators and energy storage systems to provide frequency regulation services to the electricity market is proposed in [100]. Such an aggregator would manage the scheme participants using Dynamic Schedule and Control Strategies (DSCS) employing a real time forecasting block for wind speeds and solar radiation, and frequency regulation block to respond to the grid frequency variations. Given the rapid uptake of distributed roof top solar systems that are making a significant proportion of total generation, it appears like there is a lot of merit in power system operators being able to harness these generators for frequency and voltage regulation with appropriate control and communication systems as enablers.

Demand Side Management strategies to provide system reserves for system frequency regulation is a developing area of research [15]. Reserve capacity in a power system could be provided by turning on or off groups of electricity loads, particularly residential loads, to regulate system frequency. A detailed review of demand side capability to regulate frequency and associated control algorithms are presented in [15, 16]. Field experimental results using demand of electrical appliances with programmable thermostats as a frequency controlled reserve is presented [18]. The experimental results, though performed on a modest load of 10 kW, show that the frequency response was significant relative to the power demand of each of the load.

Grid code in Western Australia currently require intermittent connected generators to only respond to a high frequency event by reducing their active power output, there is no requirement to increase output from intermittent generators if frequency is falling [23]. The inability or lack of requirement for intermittent generators to increase their output when frequency is falling to support grid frequency requires detailed analysis to determine impact as penetration levels of intermittent generation soars. In Australia's National Electricity Market (NEM) jurisdiction, a new grid code has just been introduced to make it mandatory for both synchronous and non-synchronous generators to have primary frequency response capability [1]. However, there is no requirement imposed for such generators to have reserve or storage to respond to a low frequency event; further more, generators can apply for an exemption if they can show enough cause that the new rule is too onerous. The New Zealand code requires that when an underfrequency limit is reached when the system frequency is still falling, each power station must take reasonable steps to increase power production from each generating unit that is capable to increase production [21]. Intermittent generators may be physcally unable to respond if energy sources are low during the under frequency event. In the United Kingdom [58] and Ireland [20], inverter connected generators are expected to have under frequency response capability to help manage grid under frequency events. The research community should continue developing strategies to ensure that inverter connected intermittent generators contribute reliably to grid frequency management.

Power System flexibility / load following capability

Power system flexibility is defined as the capability of a power system to respond to load variation and maintain generation-load balance in real time [53]. With increased penetration of intermittent generation sources, the power system has to be flexible enough to also accommodate both anticipated and unanticipated fluctuations due to time varying energy sources [4, 8]. The weather pattern is a significant factor in behaviour of power systems with high penetration renewable energy sources. Both wind speed and solar irradiance varies significantly over the course of the day and across seasons. A case study completed by AEMO [5] shows that the power system ramping rate requirements are now much higher compared to previous years when there was insignificant amount of intermittent generators in the power system. AEMO reports that the ramp rates for the period from March 2017 to August 2017 were 20% to 75% higher than the corresponding period in the year 2010 [5]. This is corroborated by the review conducted by Akrami et al. [4] showing similar observations in the United States and the Philippines which also concluded that increased renewable energy penetration requires increased power system flexibility.

During periods of high renewable energy generation on a power network, dispatchable generation capable of programmable and dependable ramp rates is displaced; as a consequence, there may be difficulties in balancing power supply and electricity demand on the grid [6]. The generation fleet of a power system with high penetration levels of intermittent generation must have generation resources that possess fast cycling and ramping capabilities to be able to follow load effectively [59, 62].

California , Denmark, Great Britain, Ireland and Texas use a day ahead generation unit commitment approach, which schedules the generation portfolio to meet requirements of forecast ramps [6]. In Australia, the same approach is used, where the system operator forecasts a lack of reserve to manage required ramp rates in a future dispatch period; the system operator can use their powers to direct a certain generator or load to take a particular action to ensure power system ramp requirements are met [6]. Any market intervention has cost to the market to cater for generation constrained on and generation constrained off payments.

Operational flexibility is identified as an area that requires further research [62]. Matters that require further investigation include further development of metrics to evaluate the system flexibility requirements and flexibility availability in power systems, operational flexibility economic value assessment and associated costs, sources of flexibility in power system including storage devices and interconnection to adjacent power networks, and methods to assess the minimum level of flexibility to accommodate certain levels of intermittent generation penetration [62].

The contribution of smart grid technologies is expected to increase in importance in the future as more intermittent renewable energy sources are introduced to the network since smart grid technologies can help to manage supply demand balance, and hence reduce power system variability [62]. Demand side response technologies can be used to shift system demand to periods coincident with intermittent renewable generation. This can also help to lower the ramping requirements of the conventional synchronous generation; this includes taking advantage of emerging load types loads that have inherent flexibility in their demand profiles such as residential utility scale storage systems and electric vehicle charging [43].

Metrics to assess the impact of intermittent renewable generation on the power system demand profile to be balanced by conventional schedule generation sources were developed in [84] and applied in case studies on the Californian bulk power system. The authors concluded that the balance fleet of generation that provides load following services will be subject to long periods of part loading as they have to hold reserves to accommodate sudden ramps down and up of intermittent sources, and there will be increased periods of excess generation that may go to waste as excess generation will need to be curtailed in the absence of storage devices.

A comprehensive review of power system flexibility for power systems with high penetration of intermittent renewable energy sources was conducted by Mohandes et al. [53]. The review looked at sources of flexibility in a power system and impact of intermittent renewable energy sources, and available metrics for quantifying flexibility. Power system flexibility metrics were also reviewed in detail in the review paper produced by Emmanuel et al. [22]. The metrics for power system flexibility adequacy include available generation or demand response capacity in MW required to respond to a ramp event, and rate of response of generation output or load curtailment in MW/minute [22]. Akrami et al. [4] investigated market design in relation to provision of power system flexibility sources for different planning time horizons. They see further research opportunities in market design philosophies to incentivise market participants to provide more power system flexibility. Mohandes et al. [53] suggest that the use and optimisation of flexibility sources connected at distribution level of power systems is an open issue that requires further research. Typically, distribution connected flexibility resources displace transmission flexibility resources. Various operational models to manage the challenges posed by distribution connected resources are emerging [53]. Introduction of Distribution System Operators (DSO) to work in collaboration with Transmission System Operators (TSO) to ensure adequate flexibility reserves without violating distribution network constraints is one such emerging model that promises positive results for power system security management.

Power System Strength

There are two aspects that characterise power system strength. Firstly there is system impedance which consists of the system generators' impedance, system transformers' impedance, transmission lines' and loads' impedances; secondly, there is the inertia from all rotating machines [87]. A weak system is characterised by high system impedance and low system inertia. A weak system has reduced capability to maintain stable frequency and to stabilise the voltage variations. In Europe, power system inertia reduced by 20% on average between 1996 and 2016 due to renewable generation connection [27].

Impact on system strength is an important factor when assessing impact of inverter connected generation integration. Synchronous machines act as a source of system strength. Grid following inverter connected generators do not contribute to system strength, their overall effect is to reduce system strength [51]. Short-Circuit Ratio (SCR) methods are used to analyse the strength of the power system at the inverter connected generation interconnection points with a system with short circuit ratio less than 3 considered to be a weak system [92]. A power system with a short circuit ratio above 3 is considered to have sufficient strength to minimize the variation of system frequency and system voltage post contingent [50].

When inverter connected renewable energy generators are installed electrically close to each other, power system strength can be lower than evaluation given by conventional short circuit ratio methods, this highlights the need to pay special attention to areas with concentrated levels of inverter connected renewable generators in close proximity [42]. Several methods to improve assessment of power system strength in the presence of inverter connected intermittent renewable energy generation have been proposed. A Site Dependent Short Circuit Ratio (SDSCR) method for analysing the relationship between system strength and static voltage stability is introduced in [92] and its efficacy is compared with other short circuit ratio calculation methods used in the industry which includes the Weighted Short Circuit Ratio (WSCR) method, Composite Short Circuit Ratio (CSCR) method and Inverter Interaction Level Short Circuit Ratio (IILSCR) method. The IILSCR method to estimate system strength with inverter connected renewable energy generators connected in adjacent locations to each other by reflecting the interaction between the adjacent generators is presented in [42].

Usage of increasing numbers of inverter connected renewable energy generation coupled with increasing retirements of conventional synchronous generators has led to reduced levels of short-circuit power in power systems [50]. Unlike asynchronous inverter connected generation, conventional synchronous generators can produce fault currents up to six-times their rated current. The large amounts of fault currents is used as a signature for certain faults types and is the basis for a number of protection design philosophies [43]. The wind turbine inverter (type IV) has limited maximum short-circuit current output of 1.1–1.2 per-unit [50]. Greater penetration of intermittent inverter connected generators with lower fault contribution will require a re-think of how some protection systems are currently implemented to ensure adequate protection sensitivity to clear faults.

Impacted fault detection schemes include overcurrent relays and rate of change of frequency (ROCOF) detection relays as reduced system fault levels and system inertia may make it difficult to implement such schemes. In scenarios with a high penetration of inverter connected generation, unbalanced faults have resulted in maloperation of distance protection [51]. German grid codes include a requirement to inject a component of negative-sequence current to manage this issue [51]. In some jurisdictions such as Denmark, synchronous condensers have been implemented to provide both fault current, voltage control and inertia to the power network [43, 50]. Anti-islanding protection schemes will also require a re-think. Active anti-islanding protection actively tries to push grid voltage and power frequency out of system normal operating range so that the generation unit trips if grid parameters being influenced move outside set limits. In a grid with high levels of intermittent generation, which is therefore, potentially weak, it may be difficult to implement active anti-islanding techniques [43]. Communication based anti-islanding techniques where a permissive signal is sent to the generation unit or phasor measurements are compared across the grid have been proposed [43].

Power System Stability

Power system stability can be classified into three main groups, voltage stability, frequency stability, and rotor angle stability of which each of these main groups can be divided into two subgroups, namely transient stability and small-signal stability [43]. Power system stability is a core functional requirement of any power system, research attention is required to develop appropriate mitigation strategies to ensure no/minimal deterioration of power system stability as penetration of the inverter connected intermittent generators increases.

Frequency Stability

Frequency stability is defined as power system capability to maintain steady frequency during normal operation and its capability to restore system frequency to nominal level during system contingencies that result in large load and generation imbalance. When a large generator is lost in a power system network, rapid frequency decline may occur, the kinetic energy of synchronous generators helps to slow down the rate of change of frequency (ROCOF), this provides an operating margin to allow quick-start generators or demand side management load resources to correct the resultant imbalance between supply and demand [38]. In a power system, frequency variation is related to active power flow, the smoothing of system frequency variations can be accomplished through active power control [94]. Power electronic inverters which interface the renewable energy sources to the power grid are static and have no rotational energy (negligible inertia), therefore, high penetration levels inverter connected generation can reduce the inertia of power grid[94].

A power grid with a large penetration of synchronous generation experiences slow system dynamic changes, this makes it easier for grid-following inverter connected generators to track the system voltage angle and frequency accurately. Power systems with high penetration of inverter connected generators experience faster system dynamic changes which may result in inverters not properly synchronizing with the system [51].

One limitation of wind generators is that they experience delayed active power recovery post large voltage dips in the order of hundreds of milliseconds, to the contrary conventional synchronous generators have fast active power recovery post voltage dips, in the order of a few milliseconds [6, 71]. Figure 4 shows that wind generators experience delayed power recovery compares to synchronous generators. As the inverter connected wind generation increases, focus will be required to develop operational strategies that ensure satisfactory active power recovery of the system following system disturbances. The need for fast active power recovery is not a significant concern in highly meshed power grids, however, for weakly interconnected power systems or islanded systems fast recovery rates are necessary to support frequency recovery [51].

Potential solutions for delayed active power recovery may involve use of distributed reactive power support devices such as STATCOMS and static var compensators (SVCs)

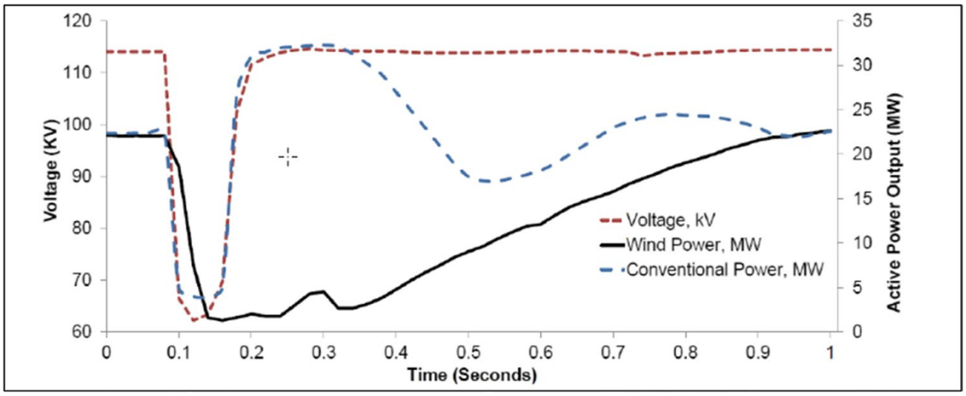


Fig. 4 Active Power recovery of conventional synchronous generation and inverter connected wind generation[6]

to reduce the depth of the voltage dips during faults and use of fast spinning reserves to compensate for wind power reduction during active power recovery delay periods [71]. Severe frequency nadirs may occur in the power system during delayed active power recovery periods if the resultant generation short fall exceeds available capacity of the largest generator (primary reserve) [71].

Some research work has been done to address the power frequency fluctuation issues, Virtual Synchronous Machines (VSMs) have been proposed and investigated to address frequency fluctuations by emulating inertia using energy storage [94]. The VSM method was first introduced in 2007 [9] and has subsequently been investigated by several researchers as a means to stabilise grid frequency [13, 19, 94]. The VSM method appears to be a promising future research area for voltage and power system frequency control [94]

In the literature, it is evident that research community is now pursuing the concept of grid-forming inverters with sufficient battery storage support and capability to support the operation of a power system under normal, and abnormal conditions without relying on synchronous machines, including periods when 100% of system demand is serviced from inverter connected generation only [51]. Ideally, such grid forming inverters would not be prone to adverse interactions when connected to weak grids, and will have robust fault ride through capability and higher fault contribution capability. Research work presented in [45] demonstrates the potential for grid forming inverters; the presented simulation results show grid forming inverters provide damping to frequency deviations in a mixed system compared to grid following inverters that tend to worsen frequency instability issues in a power grid as their penetration levels increase. Grid-following inverters require a “stiff” grid ac voltage at their terminals [43] to maintain stable operation. Grid forming inverters present an option worthy of development to their full potential to connect intermittent renewable generation to weak transmission power grids.

Grid Codes may require revision to ensure that new inverters connected with new entrant generation are mandated to come with grid forming capabilities in readiness for a possible future where loads may be serviced for 100% of time by intermittent inverter connected renewable energy sources during certain periods of the day. Some research work to develop control for future grid forming inverters suitable for parallel operation with other grid forming inverters in large scale interconnected power systems is reported in [17]. A variety of grid forming inverter control techniques have been proposed including droop control and virtual inertia [43]. Further research is required to ensure that inverter connected generation systems do not impact frequency stability of power systems negatively but make a contribution to frequency stabilisation during system disturbances.

Voltage Stability

For a system to be considered stable from a voltage stability perspective, the system should be able to maintain steady voltages within the target operating range on all its buses during normal and abnormal operating conditions [72]. The system should be able to control voltage and power concurrently when sudden changes in system loading occur. [29]. Voltage instability issues led to a whole system blackout in Japan in 1987, the United States of America and its neighbour Canada in 2003, and in Sweden and Denmark in 2003 [33]. Voltage stability is therefore an important element to be managed and understood in a power network as the power network changes due to high penetration of intermittent renewable generation.

Voltage stability limits analysis in the presence of solar generation using P-V curves method, Q-V curves method and dynamic voltage stability analysis was performed in [33]; however, the analysis did not consider wind power intermittent generation. Voltage instability assessment can typically be completed via dynamic studies; however, for deterministic load systems, steady state studies can be used to determine the distance between the system operating point and the knee point of the P-V curve to assess voltage stability margins [29].

Given the variability of renewable energy, stochastic methods have been used to evaluate the uncertain behaviour of power systems with high penetration of intermittent generation as deterministic methods cannot consistently replicate their characteristics [96]. A global sensitivity analysis (GSA) method to analyse the influence of various variabilities (wind generation, PV generation and loads) on voltage stability is presented in [96]. The authors tested the method on an IEEE 9-bus system and an IEEE 118-bus system. A stochastic multi-objective optimal reactive power dispatch in a power system with intermittent generation considering system load and generation variability is investigated using ε-constraint method and fuzzy approach in [54]. A decision making two-stage stochastic optimization model for systems with uncertain load and generation conditions was implemented. A voltage stability constrained multi-objective model for wind generation planning also solved using the ε-constraint method and a Pareto optimal set selected using a fuzzy approach is presented in [61]. There appears to be a strong interest in the research community to investigate and apply stochastic methods to assess voltage stability in power systems with intermittent energy generation.

Rotor Angle Stability

Rotor angle stability is the ability of synchronous generators that are connected to the same power network to remain in synchronism following power system disturbances [43].

Inverter-based generators are static machines and therefore do not have a rotor angle. They synchronize to the grid using phase-locked loop (PLL) controllers, a large disturbance on a power system may lead to loss of inverter synchronism with the grid which may lead to system instability and outages [65]. When the ratio of the renewable power sources is increased, thereby displacing conventional synchronous generation, the transient rotor angle stability deteriorates due to decrease of the system inertia [77]. The authors in [56] used the transient rotor angle severity index methodology and dynamic studies to demonstrate that the transient rotor angle stability of the system deteriorated as the penetration of invertor connected photovoltaic systems increased when simulated faults were applied at critical locations of the network. The dynamic transient response characteristics of an inverter are dependent on their internal factory programmed control logic, not the inverter's physical properties. In synchronous machines, the physical characteristics of the generator, such as inertia and electrical parameters, determine their transient behavior [43]. In a system predominantly supplied by inverter connected intermittent generation, the rotor angle instability of the remaining rotating electric machines such as synchronous condensers and synchronous motors can occur frequently with increased severity because of reduced inertia in the power system [43].

Literature shows that the rotor angle stability enhancement in networks with increasing penetration levels of inverter connected intermittent renewable generation is an active area of research. In [35] thyristor-controlled series capacitor (TCSC) has been investigated to improve the rotor angle stability in a power system with wind turbines, results show TCSC can contribute to improve power system stability under power system contingencies. Reference [80] discusses various applications of back to back system based voltage source converters by various research groups to improve power system stability including angle stability. Back to back system-based voltage source converters can be used to enhance performance at the connection point of a renewable energy system as they increase transmission transfer capacity and enhance power system stability [80].

Small signal stability

Small signal stability pertains to ability of power system generators to remain in synchronism when subjected to small disturbances such as small changes to system load. Instability modes may be due to controls of equipment such as conventional generation excitation systems, inverters, and static var compensators interacting with mechanical dynamics of generator shaft systems [44]. A disturbance is regarded as small if the system mathematical equations that describe its response to such a disturbance can be linearized.

The linearized power system equations take the general form of:

$$\Delta\dot{x} = A\Delta x + B\Delta u$$
$$\Delta y = C\Delta x + D\Delta u$$

Where A is the state matrix, B is input matrix, C is output matrix and D is matrix that defines proportion of input which appears directly in the output. x is the state vector, u is system inputs vector and y is outputs vector [44]. The eigenvalues (λ) of matrix A are used to evaluate and quantify small signal stability of a power system. The roots of the characteristic equation below are eigenvalues of matrix A:

$$\det(A - \lambda I) = 0$$

The eigenvalues can be real or complex, and generally take the form:

$$\lambda = \sigma + j$$

From the eigenvalue we can determine the damping ratio ξ of the power system oscillations using the relationship below:

$$\xi = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}}$$

Typically grid codes specify small disturbance oscillations damping ratio requirements of a power system, for example the West Australian Technical Rules [23], specifies at least 0.5 for required damping ratio for electromechanical oscillations as a result of a small disturbance.

Renewable intermittent energy sources penetration has an impact on power system small signal stability [74]. While inverter connected generators do not contribute to power system electromechanical oscillations directly, they do influence dispatch of synchronous generators which has a bearing on small signal stability of a transmission network [95]. Depending on the amount and variability of intermittent renewable generation in a power system, it is possible for critical eigenvalues to cross the imaginary line and therefore be considered unstable, and requiring countermeasures to stabilise it [14]. A significant amount of research is being carried out to understand how conventional power systems, consisting mainly of synchronous generators, respond to penetration of inverter connected generation, and more specifically impact of such penetration on power system's electromechanical modes of oscillation [95].

A study in [64] presented a comparison on a system with synchronous generators in one scenario, and the same system with some synchronous generators replaced with grid following inverter connected generators to simulate a range of renewables penetration levels in other scenarios. The study found the system with synchronous generators was stable to small signal disturbance and the system with high level of inverter connected generation was not stable for the same disturbance, calculated small signal eigenvalues showed that the modes responsible for the oscillations were dependent on the inverter controls.

In [73], synchronous power controllers (SPC) are investigated for transmission level connected inverter connected photovoltaic generation under a range of penetration levels. Their studies show improved damping ratio under small signal disturbances when SPC are used. Reference [82] demonstrated that a synchronous generator equivalent electromechanical swing dynamic behaviour characteristic represented by the classical Phillips– Heffron model can be extracted from all type of voltage source converters. Such models are necessary to analyse small-signal stability. The authors in [82] provided a classification of control strategies that have been developed for voltage source converters to emulate rotating inertia and damping of oscillations. The strategies developed provide a small-signal modelling framework for virtual rotor angle stability of voltage source converters.

A multistage optimization technique using particle swarm optimisation (PSO) to optimize small signal stability with renewable energy penetration levels is presented in [74]. Various stochastic small signal stability analysis methods and models for determining optimal operation of power systems with high levels of intermittent energy generation penetration have been proposed by various researchers [95]. An overview of such stochastic methods used for small signal stability analysis are presented [95]. Given recent and ongoing research activity in area of small signal stability analysis of power systems with increasing levels of intermittent generation penetration, it is expected that this area will continue to be an active area of research in the future.

Power System reliability

Power system reliability encompasses two attributes, power system security and power system adequacy which represents the capability of a power system to satisfy aggregate power and energy demand of all consumers [30]. When surplus power is generated from intermittent renewable energy sources, it will be more difficult to maintain power supply reliability to current N-1 standards[98]. Wind power stations are designed to shut down as a safety measure when the wind speed is very high meaning that a significant generation plant can stop without warning during high speed wind gust periods [66]. Little wind generation output is expected in low wind resource availability situations, and very little output is expected from solar farms if there is heavy cloud cover over the panels. Future generation adequacy determination when large penetration of intermittent renewable generation is present will rely heavily on the assumptions and renewable energy resource forecasts. Numerous studies have been done to propose methodologies to determine power system generation adequacy under high penetration levels of intermittent renewable generation such as stochastic modelling of power plant availability using calibrated historic data reported in [30].

Three reliability indicators are often used for power generation systems, namely interruption frequency, average outage duration and probability of unavailability [102]. Assessing the reliability of electric power system with intermittent renewable generation is an important area of research in power system modelling and analysis [102].

In [102], economic evaluation of power system reliability and approaches for determining reliability indicators are reviewed, the reliability indicators determination approaches being the analytical method, the simulation method and the hybrid method. The simulation method was found to be the most commonly used approach to evaluate reliability of power systems with intermittent generation because of its high computational efficiency.

Poor power system reliability has a cost for the businesses and the community, as an example, the September 2016 black system event in South Australia resulted in total state business trade and production losses estimated at close to AUD $120,000 per minute during that event [5]. Hence, research efforts to continually improve the reliability of power systems as intermittent generation penetration levels increase are warranted.

Power Quality

Power quality problem in a power system is any deviation in current, voltage and frequency from their prescribed operating ranges which may lead to maloperation or damage of customer equipment[47]. From an intermittent generation penetration perspective, the main power quality concerns are voltage and frequency fluctuations due to uncontrollable variability of energy sources, and harmonics introduced by electronic inverters used to connect renewable energy generation to the grid [94]. An extensive literature review on emerging power quality issues as a result of intermittent renewable energy penetration into power grid has been conducted and reported in [94]. It shows that power quality investigations on the impact of penetration of intermittent renewable energy is an active area of research that needs further development to identify and implement solutions to address emerging power quality challenges.

Harmonics

Grid-connected inverters without effective harmonic filters can generate significant current harmonics into power networks [40, 85], thereby distorting supply current and voltage sinusoidal waveforms which may lead to overheating of power transformers and cables, maloperation of electric motors, increased power system network losses, and limited life of wind turbine generators and solar photovoltaic modules [83]. Current harmonics can also cause the voltage harmonics [41].

There are three control methods used for harmonic compensation identified in [94], these are voltage control method (VCM), current-control method (CCM), and hybrid-control method (HCM). The output of current harmonics from grid connected inverters can be reduced by increasing the inductance of the filters, however, this comes with a disadvantage of cost and size of devices. The other approach is to increase the inverter switching frequency to minimise current harmonics output, however, the higher the inverter switching frequency, the higher the switching losses and component overheating [85].

Conventional methods such as passive filters are not able to mitigate harmonics completely [68], hence a significant number of researchers have looked at alternative power harmonics mitigation methods [40, 68, 70, 83, 85]. A technique to reduce current harmonics in grid-connected inverters using Pulse Width Modulation (PWM) with a variable switching cycle is presented in [85], with the optimal switching cycle being determined by a genetic algorithm (GA) to achieve balance between switching losses reduction and current total harmonic distortion (THD). A shunt connected PV-STATCOM to mitigate current harmonics and voltage sags was investigated in [68]. A fuzzy logic controlled active power filter to minimize the harmonics is investigated in [70]; the author showed through MATLAB simulations that this approach could mitigate harmonics, however, no validation against experimental data or field measurement data was presented. A detailed review of advances in switch reduction of active power filters (APF) for managing power quality issues including comparison of different topologies and evaluation based on the total harmonic distortion (THD) and harmonic mitigation is presented in [83]. A detailed review of harmonic analysis, modelling and mitigation techniques is given in [40]. As the inverter connected generators dominate the power networks, it is expected that harmonics management and mitigation will continue to require attention of researchers.

Flicker and voltage sags

Voltage fluctuations in a power system are related to available reactive power support, thus reactive power control can be used to smooth voltage fluctuations [94]. Voltage fluctuation issues can be addressed by conventional methods that involve network reinforcement and reactive power compensation using series compensation methods (e.g. Thyristor-controlled series compensators) or shunt compensation methods (e.g. STATCOMS and shunt reactors) [94]. Energy storage systems (e.g. super capacitors, batteries and flywheels) are used to overcome the intermittency problem by maintaining constant network voltages and reducing voltage fluctuation [34, 83]. The distribution static compensator (DSTATCOM) with battery storage has been successfully used to compensate for reactive power, voltage variations, load unbalance and current harmonics in distribution power systems [47]. STATCOMs are expected to continue playing a prominent role to support integration of intermittent renewable energy into the power system.

Solid state onload tap changers have a fast response characteristics which can be used to correct network problems such as voltage sags and flicker [34]. Solid state onload tap changers overcome the slow response problem of mechanical onload tap changers for applications with fast voltage fluctuation such as distribution feeders with high levels of intermittent generation. However, solid state onload tap changers suffer from a discontinuity problem due to the limitation in the number of electronic switches and their step wise control philosophy. An on-load voltage regulator based on electronic power transformer to achieve fast and continuous voltage control has been proposed in [34].

Voltage unbalance

Voltage unbalance is defined as the ratio of the negative sequence voltage to the positive sequence voltage [46]. An ideal power system should have a balanced set of three phase voltages. Single-phase photovoltaics and single-phase loads of a low voltage distribution network that are not evenly placed across the three phases create an unbalanced system operation. The resultant unbalanced voltages and currents increases power losses, protection maloperation, and reduces network hosting capacity [99]. A factor of 6 to 10 times current unbalance can occur as a result of just 1% voltage unbalance; motor windings can experience high temperature rise as a result of voltage unbalance which could reduce their operational life [41]. As penetration of single-phase inverter connected photovoltaics increase, it is likely that voltage unbalance on the distribution networks will increase [41], this will require research attention to develop analysis techniques and mitigation techniques.

Literature review shows that there is already a significant amount of ongoing research to develop strategies to manage voltage unbalance issues in power networks. Application of series dynamic voltage restorer and shunt DSTATCOM devices to mitigate voltage unbalance issues in distribution network were investigated in [78], the authors showed that the DSTATCOM performed better that the dynamic voltage restorer to address the voltage unbalance. An approach to use single-phase inverters distributed in a delta formation among different phases of a network have been used to improve voltage unbalance in the three-phase four-wire systems in [99], a consensus-based distributed algorithm was used to coordinate the distributed inverters. A genetic algorithm to perform phase swapping to achieve an optimal transformer phase arrangement to minimise voltage unbalance is proposed in [46].

Demand and Supply forecast

Variability in both supply and demand side has brought in an additional challenge for long-term and short-term forecasting of energy demand and supply resource availability. With penetration of behind the meter roof top solar, the apparent system demand has an added layer of variability dependent on the natural load demand variation by consumer equipment and load offsetting behind the meter solar photovoltaics. The same is true for large-scale intermittent power supply, forecasting of supply becomes increasingly complex as the penetration of weather dependent renewable generation grows. Higher penetration of intermittent energy poses challenges to the generation unit commitment process, it is therefore important to have effective strategies that produces robust generation unit commitment decisions to ensure system security and reliability [2].

There are developments to improve weather and generation forecasting techniques to help to accurately predict wind and solar energy resources at various timescales [94]. The Australian Energy Market Operator (AEMO) [5] is conducting trials to improve short-term forecasting techniques using Light Detection and Ranging (LIDAR) technology, sky-cam and cloud monitoring. AEMO are also using high resolution data (1-minute samples) from the Bureau of Meteorology recorded from various observation sites, and using data science techniques and probabilistic forecasting capability to improve intermittent resource forecasting outcomes.

Power System Modelling

Accurate power network models and load models are necessary to ensure accurate analysis of power system issues in networks with elevated penetration level of inverter connected intermittent generation. Updated models of distribution feeders to accurately model the network and assess DER hosting capability of these networks are required and some work to develop such models is under way in Australia [6].

Electromagnetic transient (EMT) models have higher accuracy compared to phasor domain models. In inverter-dominated power systems consisting of fast inverter controllers, EMT modelling is necessary to evaluate their performance; however, EMT simulations are computationally intensive and therefore take longer to compute compared to phasor domain simulations. While EMT simulations are vital for power system planning studies, they are impractical for real-time control-room applications such as dynamic security assessment. Fast real time simulations with comparable levels of accuracy to EMT simulations are required for control room applications and are subject of ongoing research [51].

Summary

Figure 5 provides a summary of power system categories identified in this review that are impacted by a significant penetration of intermittent inverter connected generation, and outlines areas that require further research attention to ensure successful integration of this emerging technology.

Conclusion

A broad and critical review on the topic of intermittent generation penetrating into power networks has been presented in this paper. The review focuses on all aspects of technical impact including system security, system voltage, system frequency, system reliability, system transient stability, system strength and power quality. Brief discussions are provided under each topic. The high pace of renewable energy penetration into power networks require that research keep pace with developments and continue to offer solutions to any emerging challenges to ensure that renewable energy sources are integrated successfully for the benefit of the broader community and the environment. Researchers should therefore continue to look at technical challenges introduced by penetration of intermittent renewable sources in order to develop solutions that ensure stable and reliable operation of power networks. Special attention is required to study future large scale power grids that will potentially be powered by grid forming inverters without any support from synchronous generation. This review has highlighted the following areas that require further research:

(1) Recent trends show that power sytem security assessment has transformed from a deterministic assessment to risk-based assessment methods. The literature shows that several researchers are already looking into risk based assessment methods; there is a need for further research to further develop risk based assessment methods for power systems with high penetration levels of intermittent generation.

(2) Given fluctuations in intermittent energy resource availability, continual development of sophisticated resource forecasting techniques is required to effi-

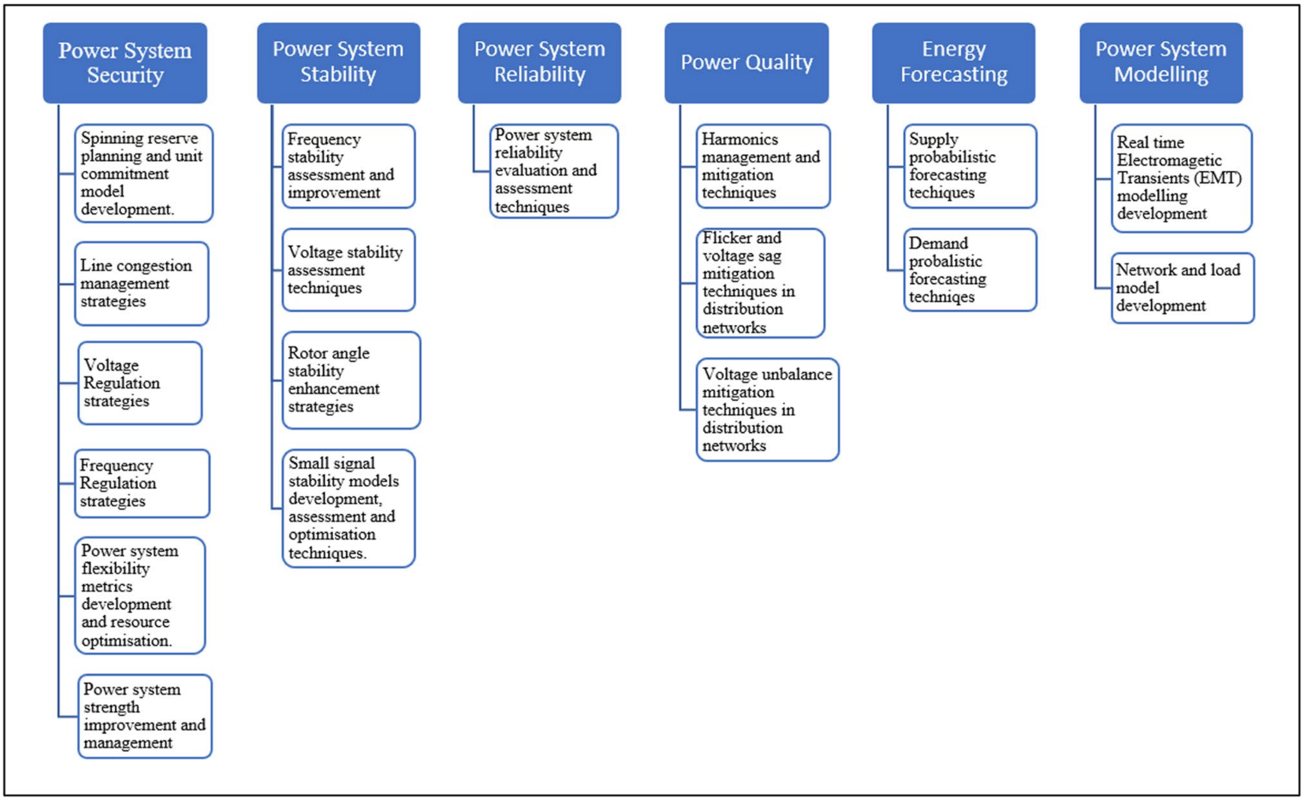


Fig. 5 Outline of technical areas that require further research work to mitigate impact of inverter connected generation penetration

ciently schedule generation and reserve requirements to cater for intermittent resource variability. This includes further development of unit commitment models to accommodate high variability and uncertainty of intermittent renewable energy sources.

(3) The change of distribution load profile from unidirectional to bi-directional and resultant voltage profile challenges calls for further research and innovation in voltage control strategies to manage high penetration of intermittent renewable sources in distribution networks.

(4) With rapid uptake of distributed roof top solar systems that are making a significant proportion of total generation, there is opportunity for power system operators to harness these generators for frequency and voltage regulation with appropriate control and communication systems as enablers. Efficient and cost-effective wide area control strategies to manage behind the meter generators and loads to support grid frequency and voltage require continued research focus.

(5) Operation and control strategies to ensure that inverter connected intermittent generators contribute reliably to grid frequency support, particularly under frequency events require development.

(6) Further development of metrics and strategies to evaluate power system flexibility requirements to ensure adequate ramp rates in power systems are required, including further development of methods to assess the minimum level of flexibility to accommodate certain levels of intermittent generation penetration.

(7) Greater penetration of intermittent inverter connected generators with lower fault contribution and resultant lower grid inertia will require protection systems to be enhanced to adapt to changed grid conditions, these include anti-islanding protection and over current protection.

(8) Robust power system control and stability management strategies need to be developed in preparation for potential periods where large grid loads may be serviced for 100% of time by intermittent inverter connected renewable energy sources using grid forming inverters.

(9) As penetration of intermittent inverter connected generation increases, resultant power quality issues (harmonics, flicker and voltage unbalance) require robust analysis methodologies and mitigation strategies to be further developed.

(10) Energy storage, in particular battery energy storage, is expected to play a significant part to address voltage

stability, frequency stability and reliability issues in power grids dominated by inverter connected generation.

(11) Development of significantly faster simulation models with accuracy of the EMT models is required to assess inverter-dominated power system suitable for real-time control-room applications such as dynamic security assessment.

It is envisaged that this work will be helpful to the students, engineering academics, researchers and utility engineers who want to get a broad understanding of emerging technical issues resulting from significant penetration of intermittent renewable energy sources

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