Grid Integration of Renewable Energy Systems

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

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

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1 Introduction

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

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

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

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

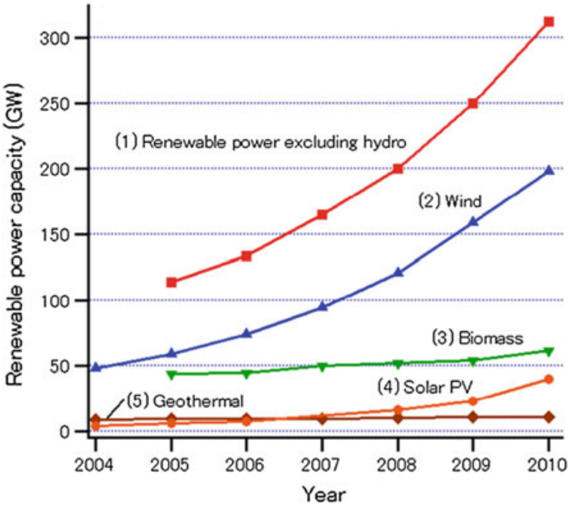

Fig. 1 Global installed capacity of various renewable energy technologies from 2004–2010 (*source* REN21)

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

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

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

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

2 State of the Art in Grid Integration of Renewables

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

2.1 Wind Turbine Generators

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

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

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

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

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

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

The first two types are more common in older wind turbines. Most modern wind turbines are variable speed connected to the DFIG. The DFIG provides the added benefit of being able to provide reactive power to the grid and low voltage ride through capability during grid disturbances. Older wind turbines do not have low voltage ride through capabilities and are likely to disconnect from the grid when the voltage drops below 20 % (Eriksen et al. 2005).

2.2 Photovoltaics

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

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

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

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

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

2.3 Other Renewable Energy Generation Technologies

A number of other technologies such as mini and micro hydro, solar thermal, bio energy and geothermal also used in practice as distributed generation. However, they may not necessarily present the same grid integration challenges as PV or wind as the demand shares of them are limited. It is common to consider hydro power as a form of storage instead of generation. As such (Brower et al. 2014) presents key renewable energy statistics both with and without hydro power. Due to the controllable nature of hydro power, it does not present the same integration challenges. Technologies such as solar thermal or bio energy uses renewable energy to indirectly produce fuel which may be used in ways similar to conventional generation. As a result, these technologies are controllable and don't have a high level of uncertainty such as with PV or wind.

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

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

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

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

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

4 Short Term Operational Challenges

A power system is dynamic and the imbalance between generation and load is continuously changing mainly due to load variations. Stability issues arise in a power system whenever there is a momentary imbalance between generation and load. Traditional synchronous generators cannot change their power output instantaneously to match the load and as a result, they speed up or slow down to supply the shortfall until the speed changes. The momentary change in speed causes changes in frequency. However, due to the large number of rotating machines in a power system there is a high inertia which can absorb momentary changes in load. Most generators have some capability to speed up or slow down which results in spinning reserve. Furthermore, the variations in load are fairly predictable as human energy use follow patterns. Based on this, system operators can allocate additional rapid response generation units during expected periods of high demand.

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

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

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

5 Long Term Capacity Planning Challenges

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

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

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

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

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

While the aforementioned methods have been discussed in the context of wind generation in literature, they can also be applied to PV and any other form of renewable generation. Amelin (2009) used an empirical study to compare the methods and concluded that the obtained capacity credit is highly dependent on the choice of method. All the methods consider different aspects of capacity e.g. the first three methods consider the effect on system load whereas the last definition considered the effects on available generation.

6 Network Congestion

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

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

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

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

While the aforementioned methods addressed the challenges of network congestion in deregulated markets, they do not necessarily reduce the level of congestion. In a congested network, there will be a reduced level of competition and prices will be distorted compared to the uncongested case. However, schemes such as the aforementioned ensure that in the event of congestion, the added cost is allocated as equitably as possible amongst market participants to ensure that competition is not hindered excessively.

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

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

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

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

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

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

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

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

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

7 Grid Code on Renewable Generation Connection

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

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

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

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

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

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

8 Key Enabling Technologies for Grid Connection of Renewables

The feasibility of grid connection of large quantities of renewables is largely dependent on the economics of enabling technologies. As such there are significant efforts to utilise more efficient and lower cost technologies. It is also important to optimise the management of these technologies so that they are not used more than necessary. This section describes the state of the art of some key technologies which will influence the grid integration of renewables.

8.1 Storage Technologies

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

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

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

capacitors and do not rely on chemical processes as in the case of batteries. Compared to conventional capacitors, EDLCs have extremely high capacitance ratings (350–2700 F). They achieve this by using a high permittivity membrane and porous carbon electrodes to maximise surface area. While they may not be able to store a high amount of energy like batteries, they can charge and discharge very quickly making them ideal for voltage regulation. EDLCs require minimum maintenance and have a high number of charge/discharge cycles.
- Battery based storage—The storage of electrical power in batteries in electrochemical form is well known. Batteries produce direct current electricity and thus require a power electronic inverter to interface with the grid. Battery life is measured as the number of charge/discharge cycles and the discharge rate is limited by the type of battery. Different types of batteries exist. Lead acid batteries are still common for low cost applications as they are rugged as long as low energy density and cycle life are not an issue. Lithium-ion batteries have the advantage of high energy density, no memory effect, and low self-discharge. However, Li-ion batteries are quite expensive for large scale applications. They are the most promising technology for use in electric vehicles and plug in hybrid vehicles. Sodium Sulfur batteries are also a promising technology due to their high power and energy density and ease of mass production. They are also cheaper than Li-ion batteries. Flow batteries are a promising technology that work similar to fuel cells and decouples the power output from the amount of storage.
- Superconducting magnetic energy storage (SMES)—SMES uses a coil of superconducting wire to store electrical energy in a magnetic field. SMES can release high amounts of energy in a fraction of a cycle and have high efficiency. SMES has a high cost due to the requirements for refrigeration as well as superconducting wires. Thus, they are mainly used for short term storage e.g. power quality applications
- Vehicle to grid (V2G) storage—Vehicle to grid storage relies on using batteries in parked electric vehicles as storage. This is dependent on development of battery technology and adequate grid reinforcement, coordination and control are also required to supplement V2G schemes.

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

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

Using multiple sources necessitates additional coordination requirements to ensure that multiple sources can operate as a single source. Often this requires power electronic converters. The multiple sources may be connected directly if their voltages are synchronised. Alternatively, they may be separated by a power electronic converter to provide more flexibility. A third option is to let each source have its own power electronic converter which allows for the highest degree of flexibility.

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

8.2 Demand Management

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

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

8.3 Dynamic Ratings

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

While initial studies such as these showed promise, Howington and Ramon (1987) identified a few major challenges which made it infeasible to use real time DTR on a system wide scale. One of the challenges was the accurate monitoring of all sections of a line. Since lines span long distances and have different weather conditions throughout the line, the level of monitoring is vital and this was deemed to be cost ineffective. Secondly, the increased risk associated with operating assets above the rated capacity led to reliance on the accuracy of DTR algorithms and the level of monitoring, neither of which was reliable enough to make it economically feasible.

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

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

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

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

It is expected that within the context of a smart grid, a sophisticated level of monitoring and communication will be readily available thus addressing one of the biggest impediments to implementing DLR. Despite the renewed interest in DLR, and the availability of smart grid infrastructure to support implementation of DLR, there is still reluctance by utilities to adopt modern dynamic line rating methods on a large scale. To account for real time variation in thermal line ratings most ISOs in North America use more than one rating to account for different weather conditions based on the relationship between temperature and ampacity outlined in IEEE Std 738-2012 (2013). There are separate ratings for hot and cold weather as well as normal and emergency situations. However, these are also fixed ratings and actual ampacity may be significantly different from these ratings. While this method takes into account the temperature dependence of line ampacity to a limited extent, it may not necessarily reflect the true operating conditions of the line and hence underutilise the network capacity. In modern power systems which consist of multiple competing entities and fast changing power flows due to presence of intermittent renewable generation, congestion and inefficient allocation of available network capacity can result in unfair advantages to some participants over others. DLR can exploit the advanced real time monitoring and control capabilities of smart grids to potentially alleviate network congestion by dynamically releasing latent capacity, and ensuring a more equitable allocation of costs between market entities.

8.4 Smart Grid

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

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

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

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

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

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

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

9 Case Studies

9.1 The London Array

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

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

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

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

9.2 Australia's Rooftop PV

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

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

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

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

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

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

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

10 Conclusions

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

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