INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
T.R. Ayodele et al., Vol.2, No.4, 2012

Challenges of Grid Integration of Wind Power on Power System Grid Integrity: A Review

T.R. Ayodele*[‡], A.A. Jimoh*, J.L Munda*, J.T Agee*

*Department of Electrical Engineering, Tshwane University of Technology

Ayodeletr@tut.ac.za, JimohAA@tut.ac.za, MundaJL@tut.ac.za, AgeeJT@tut.ac.za

[‡] Corresponding Author; T.R. Ayodele*, Department of Electrical Engineering, Tshwane University of Technology, Private Bag X680 Pretoria 0001, Staatsartillerie Road, Pretoria West, South Africa, +27735605380, Ayodeletr@tut.ac.za

Received: 11.07.2012 Accepted: 01.08.2012

Abstract- Wind Energy Conversion Systems (WECSs) exhibit variability in their output power as a result of change in their prime movers (wind speed).This introduces a new factor of uncertainty on the grid and poses a lot of challenges to the power system planners and the utility operators in terms of the power system grid integrity i.e. power system security, power system stability and power quality. This paper discusses the various challenges of wind power when integrated into the grid and identifies different mitigating strategies for its smooth integration. This paper therefore enables the specifications for mitigation/integration technologies to be appreciated and quantified.

Keywords- Challenges, Intermittency, Grid Integration, Wind Power, Wind Energy Conversion System.

1. Introduction

Efforts are geared towards grid integration of renewable energy sources into a grid as a result of environmental concerns and the quest for energy security [1]. Among the renewable energy sources, wind energy stands out because of its technological maturity, good infrastructure and relative cost competitiveness [2]. At present, the wind power growth rate stands at 20% annually and it is predicted that 12% of the world's electricity may come from wind power by the year 2020 [3].

However, grid integration of the Wind Energy Conversion System (WECS) can potentially affect the power system negatively due to the fluctuation in wind power. The WECS exhibits variability in its output power because of the stochastic nature of wind resources as a result of incessant changes in weather conditions. This intermittent and diffuse nature of the wind power introduces a new factor of uncertainty on the grid and may have a negative impact on the grid integrity i.e. the power quality, the system security and the system stability. The dynamics and the control of conventional generators in a power system vis-à-vis grid interaction are well understood and falls under the control capability of the utility operators. Wind energy is controlled by nature and this can have a repercussive effect on the power system. For wind generators to effectively replace the normal conventional generators, then, it must be able to provide the same ancillary services provided by the conventional power plant by controlling the nodal voltages, ensuring load following, maintaining grid frequency, and contributing to fault current. Wind power penetration is still low (20% maximum in Denmark); the ancillary services are majorly supported by the conventional power plants. When the penetration level is increased, the technical impact on the grid integrity may arise which needs to be well understood.

This, therefore, implies the need for certain technologies to enable smooth and proper integration of WECSs to the grid. As such the necessary specifications for such technologies need to be properly understood and quantified. This paper sets out to address this. It discusses the various challenges of WECSs when directly integrated into the grid and sets out to define the parameters and variables necessary for smooth integration through different mitigating strategies.

2. Impact of Wind Power on System Security

The security of a power system is regarded as the ability of the system to withstand disturbances without causing a breakdown of the power system [4]. For wind power generators to contribute to the security of a power system, they must have the ability to contribute to both the voltage and frequency control in stabilising the power system following a disturbance, they must be able to ramp up or down to avoid insecure power system operation, they must be able to ride through disturbances emanating from the power system, they must be able to avoid excess fault levels while still contributing to fault identification and clearance, and they should be able to operate in island mode when the supply from the grid is lost [5].

Wind power generation is often faced with difficulties with regards to reliability in terms of the generation, planning and scheduling of the supply of electricity [6]. There is always a lack of confidence by the utility operators in the system's capability to meet peak demands. Although, no electricity system is 100 percent reliable, intermittent generation will increase the level of uncertainty and therefore also the reserve capacity band of the power system which in turn increases the generation costs. The effect is minimal at low penetration levels, but could be challenging at high penetration levels [7, 8]. Among these challenges are the effects on the power imbalance, reserve management, voltage control and system stability.

2.1. Power Imbalance

WECS generate electricity when wind speeds exceed a certain minimum and the WECS output depends on these wind speeds. Wind speeds cannot be predicted with high accuracy over daily periods, and the wind often fluctuates from minute to minute and hour to hour. Consequently, electric utility system planners and operators are concerned that variations in the output of WECS may increase the operating costs of the system [9]. This concern arises because the system must maintain a balance between the aggregate demand for electric power and the total power generated by all power plants feeding the system. The variability and the unpredictability of wind power can cause a power imbalance on the grid [7, 8, 10, 11]. Their output power may not be available to meet the demand when needed, while there could be an excess when the demand is low, thereby causing an upset on the grid. [12] reported a loss of 4000MW (58% of capacity) in Germany in December 2004 and a loss of 2000MW (83% of capacity) within 6 six hours in Denmark in January 2005 as a result of large changes in wind power output due to a forecasting error. A penalty cost is often attached to the deviation in the scheduled and actual energy delivered to the grid to cover the reliability aspect of intermittent generation [12].

In line with the above, several publications exist on the generation adequacy of a power system incorporating intermittent wind power. A method for capacity adequacy evaluation of power system containing wind energy, solar energy and energy storage was presented in [13]. Also, an approach to generating capacity reliability studies, using the autoregressive moving average (ARMA) time series was presented in [14]. The technique is used to illustrate the effect of adding increasing amount of wind capacity to conventional generating system using the Loss of Load Expectation (LOLE) and Loss of Energy Expectation (LOEE) indices. The generating capacity credit attributed to wind power is expressed in terms of peak loading-carrying capability at the criterion risk level. An assessment of the generation adequacy of the Irish system incorporating wind energy capacity was studied in [15] using the application of both the LOLE and Monte Carlo simulation. Further readings on the adequacy assessment of power systems consisting of intermittent wind generators can be found in [16-20].

2.2. Impact of Wind Power on Reserve Management

Electrical power is expensive to store. Hence, the power produced at the generating station must be consumed by the load. Therefore, there must be a power balance between all the generating plant and the load demand. Any imbalance would affect the frequency of the system which could lead to loss of synchronism in certain cases [21]. The accomplishment of a power balance between the load and the generating plants is more challenging in the case of wind power generation due to its unpredictable nature especially when the generating ratio is high. A system of high wind power integration would expand the reserve capacity due to the variability of the primary resources [22]. A conventional power plant is expected to provide for this variability. This has an effect on both the operational costs and the ancillary service costs of the power system. An extra reserve of 3-6% of the rated capacity of the wind plant is required in a 10% wind integration and 4-8% approximation for 20% wind integration [23]. In a United Kingdom study, an additional balancing cost due to 10% integration of wind power cost £40 million (£2/MWh) and £200 million per annum (£3/MWh) for 20% wind integration. A national grid assessment study on the impact of 30GW wind capacity integration by the year 2020 on the reserve capacity indicates that 30GW levels of wind generation will increase the short-term operating capacity to 10.5GW from the 2009 (4GW capacity) at an additional cost of about £418 million per annum. This translates to approximately £5.4/MWh of wind generation [24]. A summary of studies conducted by the U.S. or on behalf of the U.S. utility which provides valuable insight into the issue of wind power impacts on overall electric system operating costs can be found in [9].

2.3. Impact on the Power System Voltage Control

The nodal voltage distribution on a power system network must not be less than an acceptable limit. The reactive power contribution capability of a power plant determines its nodal voltage control. A conventional generator has a way of controlling the reactive power to ensure a proper voltage distribution at the different nodes of the network. Most WECS make use of induction generators which are not capable of injecting reactive power to the grid [21]. This often forms one of the limitations of wind power integration.

3. Impact of Wind Power on Power Quality

The degree of deviation from the normal sinusoidal voltage and current waveforms in power system network determines the quality of the power transmitted on the grid [25]. The liberation of the electricity market has resulted in power quality becoming an issue of focus in recent times. Power quality components of a power system comprise of flickers, harmonic distortions, voltage imbalance, voltage sag and voltage swells.

The level of tolerance of power quality depends on the kind of load installed by the customer, that is, how sensitive the load is. The occurrence and frequency of power quality problems depend on the strength of the network, type of consumer load fed by the network, electronic equipment utilised, geographical location of the area, length of the network, load behaviour, climate change and the operational practice of the utility operators [26].

Poor power quality could lead to losses on the grid, malfunctioning of the electrical equipment and even a loss of synchronism that could lead to network failure. Low power quality has negative consequences on the economic and social life of a modern society. A power quality survey conducted in Europe revealed an estimated loss of approximately 150B€ in a year [27], while an estimated loss of between 119b$-188b$ per annum was reported in the United States of America [26].

Variable speed wind generators, that is, WECS made of doubly fed induction generator (DFIG) and synchronous generator (SG), require power converters to achieve controllable grid integration. These converters are sources of harmonics especially in grids with low short circuit capacity. In addition, most wind resources are found very far from the city where access to strong grids is limited. The grid in this area is initially planned for unidirectional power flow. Wind power integration could have a negative impact on the steady state operation of these kinds of grids.

Fixed speed wind turbines produce power pulsation due to shear effects and tower shadows and this could result in a voltage fluctuation that could cause flickers on the grid [28]; however, the effects are reduced in variable speed wind generators.

There are certain standards in place to ensure uniform power quality measurement. These standards specify how a power quality measurement should be conducted and the level it should not exceed. The standards are IEEE 519-1992, IEC 61000-4-30 and EN50160. IEEE 519-1992 deals with the practices of and requirements for harmonic control in electrical power systems. It specifies the limits of harmonic voltage and current at the point of common connection between the end user and the distribution utilities. The standard requires the participation of both the utilities and the customers. IEC 61400 describes the adequate measurement methods for ensuring voltage and current quantities. It provides the aggregation periods and the measurement formulars. The EN50160 code is mostly adopted by European countries and it sets the standard level for different power quality components which should not be exceeded [29]. IEC issued a standard in 2001 (IEC 61400-21) for the measurement and assessment of the power quality in wind turbines. The standard defines power quality characteristics of wind turbines and proposes a measurement procedure [29]. Apart from the international standards, there are also various national grid codes in order to ensure quality power supply.

3.1. Harmonics

Harmonics can be injected both at the generation and the consumer end. At the consumer end, harmonics are caused by non linear loads such as television, personal computers, compact fluorescent lamps, and so forth. At the generation level, sources of harmonics include the Flexible Alternating Current Transmission System (FACTS) such as reactive power compensators and power electronics devices. Others include adjustable speed drives, generator speed controls, HVDC installations, and underground and submarine cable installations. Most of these are found in the power conditioning devices of integrating WECS into the grid. They could cause distortion to the voltage and current waveform of a power system. Also, the power electronic converters in use by the variable speed WECS such as DFIG are sources of harmonic. This serves as a drawback to these types of WECS.

Harmonics increase line losses and cause excessive heating of equipment which decreases their lifetime [30, 31]. Sub-harmonics could cause flickers that result in an uncomfortable visual effect on the eyes, imbalance and core saturation of transformers and thermal aging of induction motors. IEEE 519-1992 is a standard that sets the requirements and imposes limits for the harmonic measurement of different order harmonics and the total harmonic distortion (THD). The limits for system voltage distortion are 5% for THD and 3% for any individual harmonics as stipulated by IEEE 519-1992 [26]. IEC 61400-21 requires harmonic testing and certification of variable speed wind turbines before grid connection since power electronic converters are utilised to achieve grid integration.

3.2. Flickers

Flickers are the periodic voltage frequency variations typically between 0.5 and 25Hz that cause annoyance from the incandescent bulb [29, 32]. Flicker annoyance is severe at a frequency of 8.8Hz [29]. The international electrochemical commission (IEC) standard 61000-4-15 describes the measurement of flicker given the instantaneous flicker level (IFl) as well as the probability short term (Pst) measure for a time span of 10 min, and the probability long term (Plt) measured for an average of 2 hours. For flicker free voltage, Pst = 0. A Pst=1 indicates that the flicker pollution has reached the tolerable limit of an average person. The flicker level for a medium-voltage grid is specified by 0.35(Pst) and 0.25(Plt).

The wind generators sometimes produce oscillatory output power, which could cause flickers in the power system network. The fluctuation caused by the tower shadow and turbulence effect in wind may cause flickers. IEC 61400-21 furnishes the measurement procedure to calculate the flicker impact of wind turbines. According to this standard, the voltage fluctuation by the wind turbine is divided into two components: the continuous operation and the switching operation. Voltage fluctuations due to continuous operations result from the variation of active and reactive power due to the fluctuation in wind speeds (3p effect in fixed speed wind turbines) [29], whereas variable speed wind turbines have the ability to absorb the 3p effect by mean of a small change in their rotor speed. Switching operations are caused by fast changes of power from one level to another which could be due to generator cut-in, cut-out and switching between wind generators.

The effects of flickers are generally not severe in variable speed wind turbines unlike in fixed speed wind turbines. This is because the variable speed wind turbines have the ability to provide speed controls to damp the fluctuations of the aerodynamic torque emanating from switching operations or changes in wind speed therefore mitigating flickers [33]. Both the continuous operation flicker coefficient and the flicker emission due to the switching operations of the wind turbines are provided based on the network impedance phase angle and 10-minute average wind speed [34-36]. This information is based on tests carried out on wind turbines by the manufacturer and will help in ensuring compliance with the acceptable standards before connecting them to the grid.

In power quality campaigns, some of the parameters which characterise power quality are the steady state voltage variations and the flickers present in both continuous and switching operations.

3.3. Voltage Dip

Voltage dip also called voltage sag, is a momentary reduction in the rms voltage value beyond a specified threshold for a short duration of time [25, 31, 37, 38]. Voltage dip is considered according to European standard the EN 50160, as a drop in power voltage to a level below 90 percent of nominal voltage for no longer than a minute. It is a very common and serious type of power quality disturbance due to its effects on sensitive equipment and industrial processes [31, 39, 40]. Voltage dip could occur when there is a large load such as motor start up, transformer energising, capacitor energising, switching of electronic load, momentary overload or a fault in the system network. It can cause the disconnection of wind generators, which could have a negative impact on the stability of the network due to loss of generation. This sometimes discourages the grid connection of WECS.

Voltage dip as a power quality component could extend to stability studies for wind turbines; the limit of voltage dip is given as 70% rms voltage reduction in 1s duration, whereas the limit for many electronic devices is 85% for 40ms [25]. Data mining as well as the characterisation and classification of voltage dips are further explained in [40]. Another problem often experienced as a consequence of voltage dips is the large inrush current during the recovery process after the fault has been cleared. It could damage the equipment components especially the power electronic frequency converters.

3.3.1. Fault Ride through Capability

Fault ride through has come to play a role in strengthening power system security due to the increase in the integration of wind power in recent times. It requires the generators to remain connected in the likelihood of a disturbance on the network. A severe disturbance such as a fault could lead to a voltage dip and if the generators are unable to remain connected it could lead to an excessive loss of generation. This could cause stability problems and may eventually lead to cascaded tripping of other generators. Most wind generators are designed to disconnect following a grid disturbance before the advent of a fault ride through requirement. There is always a fear that large penetrations of wind power could cause a considerable amount of generation loss following the disconnection of wind generators due to disturbances on the grid, causing the system to become unstable in an otherwise harmless disturbance situation. To prevent such situations, newly installed wind turbines are designed to comply with grid connection requirements known as grid codes that demand wind turbines to ride through faults.

Grid codes define the responsibility of wind turbine owners and the technical requirements their wind turbines must meet in order for their turbines to be connected to the power system network. The codes also specify the responsibilities of the owners to protect their machines against damage caused by internal or external impacts, active and reactive power control, frequency control, voltage quality and external control [41]. The grid codes vary from one Transmission System Operator (TSO) to another and it focuses on the testing methods used in the verification of the fault ride through capability of the wind turbines and their behaviour during a grid fault. The Scottish grid code (SB/2 2002) requires a wind turbine with a non-synchronous generator to remain connected to the grid in the event of a zero-voltage grid fault for 140ms. The transmission utility from Germany, E.ON Netz, specifies requirements for wind turbines connected to transmission networks of 110 kV or above. This grid code states that wind turbines must not be disconnected from the network in the event of an 85% voltage dip caused by a three-phase short circuit for 150ms with voltage recovery to 80% within 3 seconds. The Danish system operator specifies grid code requirements separately for wind turbines connected to grids with voltages below 100 kV and above 100 kV which also specifies wind farms' stability in the event of asymmetric grid faults and unsuccessful re-closure. Fig 1 shows the fault ride through requirements of different TSOs [42].

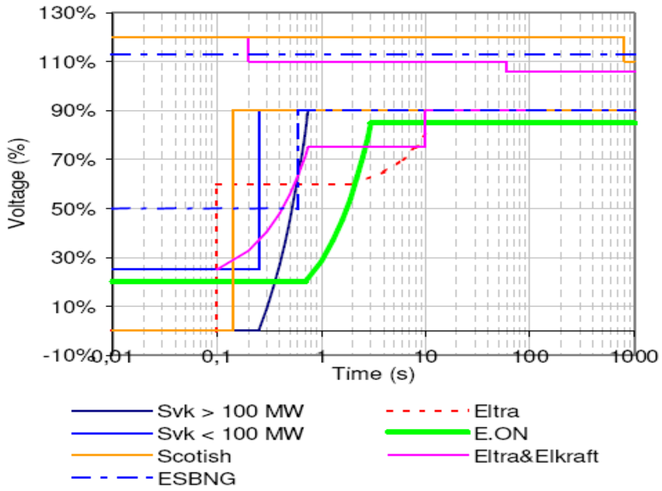

Fig 1. Different operating voltage range for different TSOs [42]

4. Challenges of Wind Power on Power System Stability

Kundur [43] stated that “when a power system maintains a state of equilibrium during normal operating condition or returns to acceptable state of equilibrium after being subjected to a disturbance, then the system is said to be stable”. A disturbance could be disconnection of generators, load, lines, transformers or a fault. The stability where a generator remains in synchronism in order to deliver power is known as angular stability and is governed by the relationship between the generator rotor angle and power angle [43]. The stability that considers large disturbances is referred to as transient stability, and small signal stability is one that considers small system disturbances [44]. Small signal stability problems occur when there is an insufficient damping of system oscillations as a result of changes in the operating parameters of a power system [43].Frequency stability, is related to dynamics that influence system frequency in the range of 10s to 10s of a minute [44]. A typical cause of frequency instability is the loss of generation, which results in an imbalance between the generation and load. Frequency stability could also be related to issues like slow control actions, poor coordination of protection and inadequacy in system equipment. Voltage instability is characterized by a steady decrease of voltage in one or several buses of the power system causing a system collapse as a result of the protective equipment. Voltage collapse results from the inability of a power system to maintain balance between the demand and supply of reactive power within the system network [7].

Before the advent of wind power plants, power systems mainly consisted of synchronous generators for electricity production. The behaviour and control of these generators following a disturbance are well understood by the utility operators due to their experiences thereof over the years. The advent of wind power introduces induction generators into the power system for electricity generation because they are cheap, robust and support variable speed operations. At the earlier stage of wind power integration, there was little concern about its influence on the overall stability of a power system. With the increasing trend of wind power integration, it may begin to have a significant influence on the power system transient stability margin.

The induction generators mostly employed in wind power applications operate asynchronously and are characterized by poor reactive power control capability. A surge in the input torque of a generator and a voltage dip beyond the threshold limit at the point of common connection (PCC) [21, 45] can lead into poor feeder regulation which can eventually cause voltage collapse as a result of reactive power demand from the grid.

Fixed speed induction generators are provided with reactive power compensator to cater for the large reactive power demand from the network. The power electronics devices provide the reactive power to the grid in the case of variable speed generators. Critical clearing method has been widely adopted for transient stability studies [46-48]. Excitation system and voltage source static var compensators such as STATCOM have been used to increase the stability margin thereby improving the ride through capability of the generators [49].

5. The Mitigation Strategies for WECS Integration

An acceptable integration level of wind power has not been definite. No particular definition has been given in the literature. However, by adopting and improving the various mitigating strategies, it is understandable that some of the integration challenges can be alleviated and higher integration level achieved. Gonza’lez et al [50] is of the opinion that the boundary between the low penetration and high penetration depends on the amount that can be integrated without causing problem to the network. The perception of WECS integration depends on the acceptability of individual willingness to accept the operational change in the system which most often goes with additional cost. It is reported in [8] that the integration of WECS has no technical limit but has an economic impact. Some of these mitigation strategies are briefly discussed.

5.1. Geographical Location

One of the mitigating methods includes the use of wide geographical location to smoothening out the oscillations in the output of the intermittent energy sources. Different studies have shown that the correlation between the fluctuating primary resources of different site decreases with the distance between the site [23].

A study also reviewed that ten or more geographically separated wind farms connected together have a reliability of about 33-47% of their average output compared to a concentrated located wind farms [24]. This is better explain in Fig 2 [23] where the power output of a geographically distributed wind farms (GDWF) is compared to the same capacity (1000MW) of a single wind farm in western Denmark. The result shows that GDWF gives a better smoothening output power. Fig 3 explains the decreasing correlation between the wind turbine output power in respect to the distance between the site [51].This is extensively explained by Holttinen in [51].

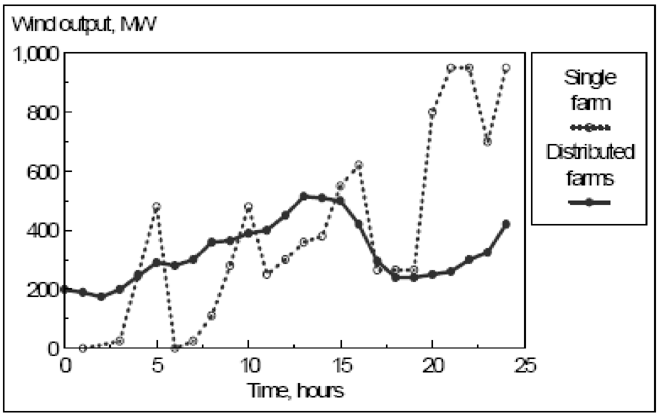

Fig 2. Smoothening impact comparison between a single farm and a geographically separated farm (both farm have 1000mw capacity) [23].

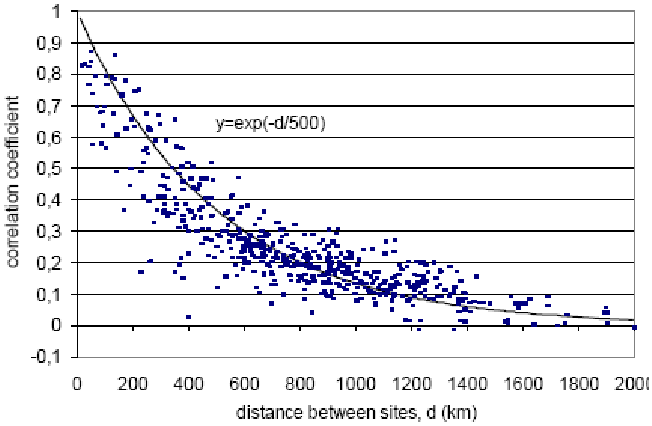

Fig 3. The correlation of wind turbine output power and distance between them for site 200-400km apart from the Nordic countries [51]

5.2. *The Use of Smart and Super Grid*

References [31, 52] described smart grid as an ICT-based network that would allow bi-directional flow of power and information. According to [53], IEC defines smart grid as "a concept of integrating the electrical and information technologies in between any point of generation and any point of consumption". Smart grid involves the modernization of the electric grid in such a way that it would encourage active users, participation at all levels. It would be accessible to the distributed generators such as wind turbines without threatening the network integrity; it would enhance power quality and system stability; it would enable market competition with pricing flexibility control.

For this to be fully realized, improvement must be made in the area of smart technologies. This will include smart meters that will be able to quantify the energy consumption and the power quality of each electrical equipment connected to it and allow the user to take a decision on the best way to consume power and what equipment to consider as regard to power quality. Smart technologies also include artificial intelligent monitoring equipment that has the ability to pre-detect fault and monitor power quality on the network. Included also are real- time transmission power flow monitoring equipments and power electronics that can limit the waveform distortion either from the generator or the load and correct the waveform deformity.

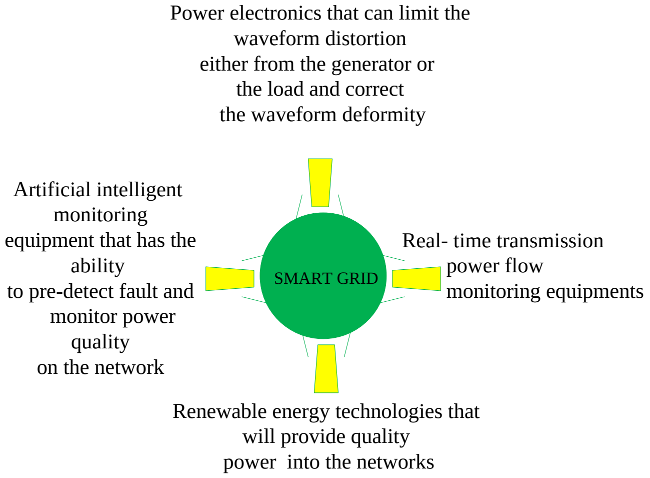

Fig 4. Components of smart grid

Super grid allows the transmission of wind power from a site of favourable generation to places of high demand over a long distance [54]; this is mostly practiced with the high voltage direct current lines (HVDC). It allows the possibility of smoothing out the intermittent output power by geographical location, where wind power is transmitted from variety of large generation sites scattered over wide area with the ability to manage both fluctuation supply and load.

5.3. *Improved Energy Storage Technology*

Power schedule and dispatch can be made possible with the adoption of energy storage. It allows intermittent power to be harvested at the time of excess and redistributed during scarcity. With this technology, degree of intermittency can be reduced and integration flexibility is enhanced, therefore the contribution from WECS can be increased. Hydrogen storage proves to be a promising storage technology compared to other technologies limited by expensive cost of storage. [50] Suggested the generation of hydrogen from the excess wind power. In Pump-hydro, water is stored when the cost of electricity is low and then released during the peak hours for electricity generation. The use of electric vehicles (EV) as a storage technique will increase the integration level of wind power. The battery of EV is charged at night when the cost of power is low and there is excess power from wind generators.

5.4. *Improved Forecasting Techniques*

Reliable estimation of wind speed will allow improved schedule and dispatch of wind power. This can be advantageous in term of reduction in the upset that can be generated on the grid due to intermittent power supply. With accurate prediction techniques, optimization of the spinning reserve can be reliably estimated and the ancillary service cost reduced, the market value of wind power can consequently be increased. In recent time, software packages that allow 1hour to 48hour prediction are available.

5.5. Regulatory Improvement

Although the regulations that ensure smooth integration of wind power exist in form of grid code such as IEC 61400-21, IEE519-1992, revisiting these regulations from time to time based on the experience gain from the previous regulatory frame work can help improve the quality of power from WECS.

5.6. Grid Reinforcement

Most wind resources are found very far from the city where access to strong grid is limited. The grid in this area is initially planned for unidirectional power flow. Wind power integration can have a negative impact on the steady state operation of these kinds of grids. Voltage fluctuation due to load fluctuation in weak grid can be magnified; this in turn can aggravate the power quality problem. Construction of new grid is capital intensive but may be unavoidable if required.

6. Conclusion

In response to the energy needs and environmental concerns, electricity from wind generators is considered as one of the future solutions. However, the variability and the diffuse nature of the wind power can be challenging to the operation of a power system. The various issues regarding the impact of wind power on the power system grid integrity has been discussed which include security of the power system, power quality and the power system stability. At low penetration level, the impacts can be minimal but increase with the increase in penetration. Different strategies that can reduce these challenges were pointed out which can consequently improve the flexibility of the power system and increase the integration of wind power to the grid.

References

[1] Z. O. Olaofe and K. A. Folly, "Statistical Analysis of Wind Resources at Darling for Energy Production," International Journal of Renewable energy Research, vol. 2, no 2, pp. 250-261, 2012.

[2] G. M. J. Herbert, S. Iniyan, E. Sreevalsan, and S. Rajapandian, "A Review of Wind Energy Technologies," Renewable and Sustainable Energy Reviews, vol. 11, pp. 1117-1145, 2007.

[3] M. A. El-Sayed, "Integrating Wind Energy into Weak Power Grid Using Fuzzy Controlled TSC Compensator," in International Conference on Renewable Energies and Power Quality (ICREPQ,2010), Granada, Spain, 2010.

[4] I. El-Amin, J. Bakhashwain, and M. Abido, "Power System Stability in the Deregulated Environment," 15th GCC-CIGRE Symposium, Abu-Dhabi, UAE., 2006, pp. 147-152.

[5] H. Outhred, S. R. Bull, and S. Kelly, "Meeting the Challenges of Integrating Renewable Energy into Competitive Electricity Industries," http://www.reilproject.org/documents/GridIntegrationFinal.pdf Accessed 28th October 2009.

[6] P. Gipe, "Grid integration of wind energy," in http//www.wind-works.org/articles/GridIntergrationofWind Energy.html, 2009.

[7] P. S. Georgilakis, "Technical Challenges Associated with The Integration of Wind Power into Power Systems," Renewable and Sustainable Energy Reviews, vol. 12, pp. 852-863, 2008.

[8] D. Weisser and R. S. Garcia, "Instantaneous Wind Penetration in Isolated Electricity Grids:Concepts and Review," Renewable Energy vol. 30, pp. 1299-1308, 2005.

[9] J. C. Smith, E. A. DeMeo, B. Parsons, and M. Milligan, "Wind Power Impacts on Electric Power System Operating Costs: Summary and Perspective on Work to Date," American Wind Energy Association Global WindPower Conference Chicago, Illinois, 2004.

[10] B. W. Kennedy, "Integrating wind power: Transmission and operational impacts," Refocus, vol. 5, pp. 36-37, 2004/2// 2004.

[11] R. Pacudan, "The Challenge of Renewable Energies Intergration in Energy Distribution Systems," Science Forum of the Renewable, pp. 51-54, 2004.

[12] A. S. Chuang and C. Schwaegerl, "Ancillary services for renewable integration," Integration of Wide-Scale Renewable Resources Into the Power Delivery System, 2009 CIGRE/IEEE PES Joint Symposium, 2009, pp. 1-1.

[13] R. Billinton and Bagen, "Reliability Consideration in Utilization of Wind Energy, Solar Energy and Energy Storage in Electric Power Systems," 9th International Conference on Probabilistic Methods Applied to Power Systems, KTH,Stockhlm, Sweeden, 2006, pp. 1-6.

[14] R. Billinton and D. Huang, "Wind Power Modelling and determination of Capacity Credit in an Electric Power System," Proceeding of the Institution of Mechanical Engineers,Part O: Journal of Risk and Reliability, vol. 224, pp. 1-9, 2010.

[15] M. F. Conlon and W. Carr, "Generation adequacy assessment incorporating wind energy capacity," 39th International Universities Power Engineering Conference, (UPEC 2004). , Bristol, UK, 2004, pp. 1014-1018 vol. 2.

[16] R. Billinton and G. Bai, "Generating Capacity Adequacy Associated with Wind Energy," IEEE

Transaction on Energy Conversion, vol. 19, pp. 641-646, 2004.

[17] R. Billinton and Y. Gao, "Multi State Energy Conversion System Models for Adequacy Assessment of Generating Systems Incorporating Wind Energy," IEEE Transaction on Energy Conversion, vol. 23, pp. 163-170, 2008.

[18] R. Billinton, Y. Gao, and R. Karki, "Composite System Adequacy Assessment Incorporating Large - Scale Wind Energy Conversion Systems Consisting Wind Speed Correlation," IEEE Transaction on Power Systems, vol. 24, pp. 1375-1382, 2009.

[19] C. Ensslin, M. Milligan, H. Holttinen, M. O'Malley, and A. Keane, "Current methods to calculate capacity credit of wind power, IEA collaboration," Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, 2008, pp. 1-3.

[20] Y. Gao and R. Billinton, "Adequacy Assessment of Generating Systems Containing Wind Power Considering Wind Speed Correlation," IET Renewable Power Generation, vol. 3, pp. 217-226, 2009.

[21] C. Veganzones, S. Martinez, and F. Blazquez, "Large Scale Integration of Wind Energy into Power Systems," Electrical Power Quality and Utilisation, Magazine. vol. 1 Spain, 2005, pp. 15-22.

[22] J. A. P. Lopes, N. Hatziargyrious, J. Mutale, P.Djapic, and N. Jenkins, "Intergrating Distributed Generation into Electric Power Systems:A reviw of Drivers,Challenges and Opportunities," Electric Power System Research, vol. 77, pp. 1187-1203, 2007.

[23] R. Ford and D. Milborrow, "Integrating Renewables," http:/w.bwea.com/pdf/RAEInternational.pdf, 2005.

[24] Wikipedia, "Intermittent Energy Sources." vol. 2009, 2009.

[25] M. H. J. Boolen, "What is Power Quality?," Electric Power and Energy Systems Research, vol. 66, pp. 5-14, 2003.

[26] M. Patsalides, A. Stavrou, G. Makrides, V. Efthimiou, and G. E. Georghiou, "Harmonic Response of Distributed Grid Connected PhotoVotaic Systems," http:/www.pvtechnology.ucy.ac/pvtechnology/publication/DEMSEE08_pq.paper.pdf, 2008.

[27] EURAMET, "Metrology for Smart Electrical Grids," European Association of National Metrology Institute 2009.

[28] T. Ackermann and L. SoEder, "Wind Energy Technology and Current Status: a Review," Renewable and Sustainable Energy Reviews, vol. 4, pp. 315-374, 2000.

[29] P. Sorensen, N. A. Cutululis, T. Lund, A. D. Hansen, T. Sorensen, J. Hjerrild, M. H. Donovan, L. Christensen, and H. K. Nielsen, "Power Quality Issues on Wind Power Installations in Denmark," IEE Power Engineering Society General Meeting, 2007. , 2007, pp. 1-6.

[30] R. Jacobson and B. Gregory, "Wind Power Quality Test for Comparison of Power Quality Standards," Windpower 99, Burlington, Vermont, 1999, pp. 1-11.

[31] NETL, "Provides Power Quality for 21st Century Needs," Apendix A4, NETL, Ed. USA: Office of Electricity Delivery and Energy Reliability, 2007.

[32] C. Kocatepe, A.Inan, O. Arikan, R. Yumurtaci, B.Kekezoglu, M. Baysal, A. Bozkurt, and Y. Akkaya, "Power Quality Assessment of Grid-Connected Wind Farms Considering Regulation in Turkey," Renewable and Sustainable Energy Reviews, vol. 13, pp. 2553-2561, 2009.

[33] E. Ghiani, F. Pilo, G. G. Soma, and G. Celli, "Power Quality Measurements Performed on a Large Wind Park at Low an Medium Voltage Level," International Conference on Power Systems Transient, Lyon, France, 2007.

[34] D. Dragomir, N. Golovanov, and P. Postolache, "Overview on the Grid Code Requirements Related to the Connection of Wind Power Plants," 2nd International Comference on Modern Power System MPS. , CLUJ-NAPOCA, Romania, 2008.

[35] H. Emanuel, M. Schellschmidt, S. Wachtel, and S. Adloff, "Power quality measurements of wind energy converters with full-scale converter according to IEC 61400-21," 10th International Conference on Electrical Power Quality and Utilisation, 2009. EPQU 2009. , 2009, pp. 1-7.

[36] N. Golovanov, G. C. Lazaroiu, M. Roscia, and D. Zaninelli, "Integrating RES into the Romanian transport system," IEEE PowerTech Bucharest, 2009, pp. 1-6.

[37] C. D. Dumitru and A. Gligor, "Power Quality Analysis of a System Based on Renewable Energy Supplying a Local Distribution Network," 2nd International Conference on Modern Power System MPS, Cluj-Napoca, Romania, 2008, pp. 224-226.

[38] N. Jenkins, "Battery Storage for Power Quality Improvement," Final Report of EPSRC: http:/www.eee.manchester.ac.uk, 2002.

[39] H. Fechner, R. Brundlinger, and B. Bletterie, "Power Quality and Safety Aspects for Grid Connection of Photovoltaic System," Arsenal Research,Vienna, 1998.

[40] V. B. Nunez, J. M. Frigola, and S. H. Jaramillo, "A Survey on Voltage Dip Events in Power Systems," International Conference on Renewable Energies and Power Quality (ICREPQ,2008), Santander, 2008.

[41] S. Seman, " Transient Performance Analysis of Wind-Power Induction Generators," Laboratory of Electromechanics, Department of Electrical and Communications Engineering,. vol. Phd Helsinki: Helsinki University of Technology, 2006, p. 60.

[42] J. Matevosyan, T. Ackermann, S. Bolik, and L. Sder, "Comparison of international regulations for connection of wind turbines to the network," Nordic wind power conference, Goteborg, 2004.

[43] P. Kundur, Power System Stability and Control,The EPRI Power System Engineering Series vol. 1: McGraw-Hill,Inc, New York, 1994.

[44] I. Norheim, E. Lindgren, S. Uski, P. Sørensen, and C. Jauch, "Work Package 5 (WP5), the EU Supported Project Wind Power Integration in Liberalized Electricity Markets (WILMAR)." SINTEF, KTH,VTT,Risø 2005.

[45] B. Venkatesh, R. Alex, and L. C., "Dynamic Voltage Collapse Index -Wind Generator Application," IEEE Transaction on Power Delivery, vol. 22, 2007.

[46] [46] H. Li and Z. Chen, "Transient Stability Analysis of Wind Turbines with Induction Generators Considering Blades and Shaft Flexibility," IEEE Industrial Electronics Society, 2007. IECON 2007. 33rd Annual Conference of the 2007, pp. 1604-1609.

[47] T. Miki, D. Okitsu, E. Takashima, Y. Abe, and M. Tano, "Power system transient stability assessment using critical fault clearing time functions," IEEE/PES Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. , 2002, pp. 1514-1517 vol.3.

[48] E. Muljadi, T. B. Nguyen, and M. A. Pai, "Transient stability of the grid with a wind power plant," Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES, 2009, pp. 1-7.

[49] M. Molinas, J. A. Suul, and T. Undeland, "Wind farms with increased transient stability margin provided by a STATCOM," CES/IEEE 5th International Power Electronics and Motion Control Conference, 2006. IPEMC 2006. , 2006, pp. 1-7.

[50] A. Gonza´lez, E. McKeogh, and B. O. Gallachoir, "The role of hydrogen in high wind energy penetration electricity systems: The Irish case," Renewable Energy, vol. 29, pp. 471-489, 2003.

[51] H. Holttinen, "A Multi-Turbine Power Curve Approach," Nordic Wind Power Conference NWPC,04, Gothenburg, Sweden, 2004.

[52] T. J. Hammons, "Integrating Renewable Energy Sources into European Grids," Electric Power and Energy Systems vol. 30, pp. 462-475, 2008.

[53] M. Olofsson, "Power Quality and EMC in Smart Grid," 10th International Conference on Electrical Power Quality and Utilisation, 2009. EPQU 2009. , 2009, pp. 1-6.

[54] A. Battaglini, J. Lilliestam, C. Bals, and A. Haas, "The SuperSmart Grid," European Climate Forum (ECF), Postdam Institute for Climate Impact Research, 2008.