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Impacts of Wind Farms on Power System Stability

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Additional information is available at the end of the chapter

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1. Introduction

Power systems are complex systems that evolve over years in response to economic growth and continuously increasing power demand. With growing populations and the industrialization of the developing world, more energy is required to satisfy the basic needs and to attain improved standards of human welfare. In order to make energy economically available with reduced carbon emission using renewable energy sources, the structure of the modern power system has become highly complex [1].

Nowadays, there are many thousands of wind turbines operating with a total nameplate capacity of 238,351 MW. Between 2000 and 2006, world wind generation capacity quadrupled. The United States pioneered wind farms and led the world in installed capacity in the 1980s and 1990s. In 1997 Germany, as for installed capacity, surpassed the U.S. until once again overtaken by the U.S. in 2008. China has been rapidly expanding its wind installations since the late 2000s and passed the U.S. in 2010 to become the world leader [2].

At the end of 2011, worldwide nameplate capacity of wind-powered generators was 238 gigawatts (GW), growing by 41 GW over the preceding year. Data from the World Wind Energy Association, an industry organization, states that wind power now has the capacity to generate 430 TWh annually, which is about 2.5% of worldwide electricity usage. Between 2005 and 2010 the average annual growth in new installations was 27.6 percent. Wind power market penetration is expected to reach 3.35 percent by 2013 and 8 percent by 2018. Several countries have already achieved relatively high levels of penetration, such as 28% of stationary (grid) electricity production in Denmark (2011), 19% in Portugal (2011), 16% in Spain (2011), 14% in Ireland (2010) and 8% in Germany (2011). At the end of 2011, 83 countries around the world were using wind power on a commercial basis [3].

Europe accounted for 48% of the world total wind power generation capacity in 2009. In 2010, Spain became Europe's leading producer of wind energy, achieving 42,976 GWh. Germany

held the top spot in Europe in terms of installed capacity, with a total of 27,215 MW on 31 December 2010 [4].

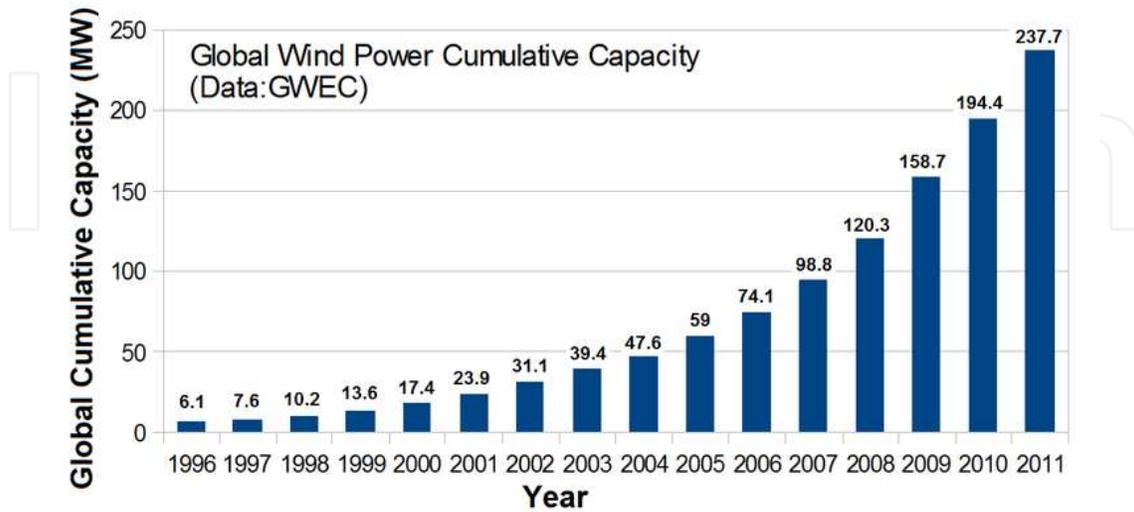


Figure 1. Global Wind Power Cumulative Installed Capacity [2]

The annual energy production of a wind farm is not equal to the sum of the generator nameplate ratings multiplied by the total hours in a year since the wind speed is variable. The capacity factor of a wind farm is the ratio of actual productivity in a year to the theoretical maximum. The range of the capacity factor is between 20 and 40%, with values at the upper end of the range in particularly favorable sites.

The capacity factor is affected by several parameters such as the variability of the wind at the site and the generator size. A small generator would be cheaper and achieve a higher capacity factor but would produce less electricity (and thus less profit) in high winds. On the other hand, large generators would cost more but generate little extra power and may stall out at low wind speed. Thus, the wind farm's optimum capacity factor aimed for would be around 20–35% [6].

Electricity generated from wind power can be highly variable at several different timescales: hourly, daily, or seasonally. However, wind is always in constant supply somewhere, making it a dependable source of energy because it will never expire or become extinct. Annual variation also exists, but is not so significant. Like other electricity sources, wind energy must be scheduled. Wind power forecasting methods are used, but predictability of wind plant output remains low for short-term operation. Because instantaneous electrical generation and consumption must remain in balance to maintain grid stability, this variability can present substantial challenges to incorporating large amounts of wind power into a grid system. Intermittency and the non-dispatchable nature of wind energy production can raise costs for regulation, incremental operating reserve, and (at high penetration levels) could require an increase in the already existing energy demand management, load shedding, storage solutions

or system interconnection with HVDC cables. At low levels of wind penetration, fluctuations in load and allowance for failure of large generating units require reserve capacity that can also compensate for variability of wind generation. Thus, integrating significant amounts of wind generation presents a unique challenge to the power system, requiring additional flexibility while simultaneously imposing a decreased capacity factor on conventional generating units [6].

This work investigates the possible impacts of wind power variability, wind farm control strategy, wind energy penetration level, wind farm location, wind intermittent and variability, and wind power prediction accuracy on the power system stability, reliability and efficiency.

2. Power system connection issues of wind farms

Unlike classical sources of energy, wind farms supply real power variations into the upstream grid, and at the same time, in some types of wind generation systems, the reactive power consumption is related to the real power production. These power variations cause voltage variations with consequences for the electrical power system and the customers. On the other hand, the increasing use of power electronics in wind generation systems introduces voltages and current harmonics into the power system. As wind energy is a non-controllable energy source, it can cause problems with voltage stability and transient stability. Due to the rapid increase in the number of wind farms connected to the grid, the increasing rate of power of single wind farm and the weakness of the upstream power grid, where the wind farm connects, the importance and necessity of the study of wind farms connected to power systems is clear.

The connection of wind farm to electrical power systems influences the system operation point, the load flow of real and reactive power, nodal voltages and power losses. At the same time, wind power generation has characteristics with a wide spectrum of influence [4]:

2.1. Location of the wind farm in the power system

The impact of wind farm on the power system depends on the location of wind power plants relative to the load, and the correlation between wind power production and load consumption. Wind power, like any load or generation, affects the power flow in the network and may even change the power flow direction in parts of the network. The changes in the use of the power lines can bring about power losses or benefits. Increasing wind power production can affect bottleneck situations. Depending on its location, wind power may, at its best, reduce bottlenecks, but at another location result in more frequent bottlenecks. There are a variety of means to maximize the use of existing transmission lines such as the use of online information, FACTS, and wind power-plant output control. However, grid reinforcement may be necessary to maintain transmission adequacy and security. Grid extensions are commonly needed if new generation is installed in weak grids far from load centers to make full use of the wind power. The issue is generally the same for modern wind power plants or any other power plants. The cost of grid reinforcements, due to wind power, is therefore very dependent on where the wind power plants are located relative to the load and grid infrastructure, and one must expect

numbers to vary from country to country. With current technology, wind power plants can be designed to meet industry expectations such as riding through voltage dips, supplying reactive power to the system, controlling terminal voltage, and participating in SCADA (supervision control and data acquisition) system operation with output and ramp rate control [7, 8, 9].

2.2. Impact of different technologies of wind turbine generator systems

There are many different generator types for wind power applications in use today. The main distinction can be made between fixed speed and variable speed wind generator types.

2.2.1. Fixed speed wind turbine generator

In the early stage of wind power development, most wind farms were equipped with fixed speed wind turbines and induction generators. A fixed speed wind generator is usually equipped with a squirrel cage induction generator whose speed variations are limited. Power can only be controlled through pitch angle variations. Because the efficiency of wind turbines depends on the tip-speed ratio, the power of a fixed speed wind generator varies directly with the wind speed. Since induction machines have no reactive power control capabilities, fixed or variable power factor correction systems are usually required for compensating the reactive power demand of the generator. Fig. 2 shows the schematic diagram of the fixed speed induction machine.

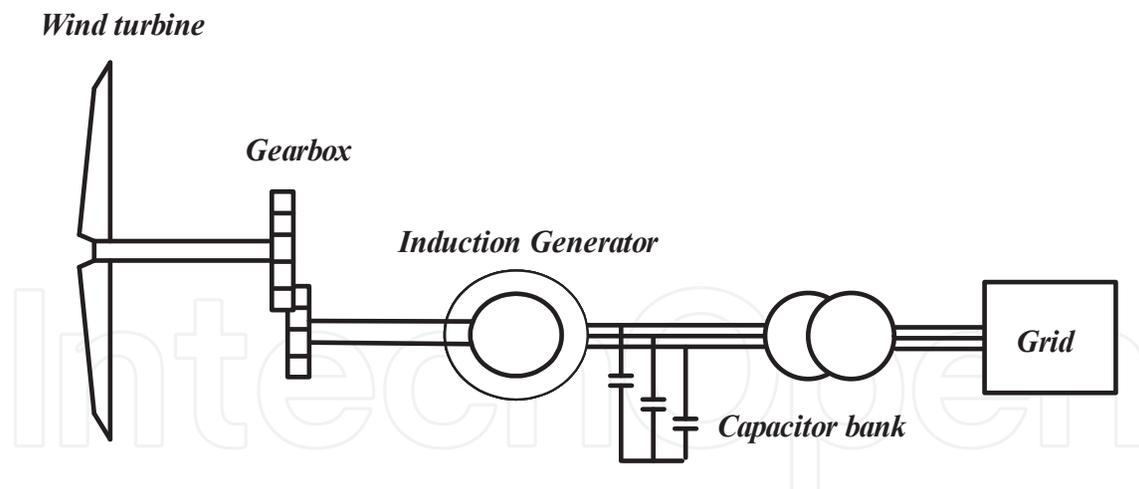


Figure 2. Fixed speed induction generator

2.2.2. Variable speed wind turbine generator

Variable speed concepts allow operating the wind turbine at the optimum tip-speed ratio and hence at the optimum power coefficient for a wide wind speed range. The two most widely used variable speed wind generator concepts are the DFIG and the converter driven synchronous generator.

2.2.2.1. Doubly fed induction generator wind turbine

Due to advantages such as high energy efficiency and controllability, the variable speed wind turbine using DFIG is getting more attention. DFIG is basically a standard, wound rotor induction generator with a voltage source converter connected to the slip-rings of the rotor. The stator winding is coupled directly to the grid and the rotor winding is connected to power converter as shown in Fig. 3.

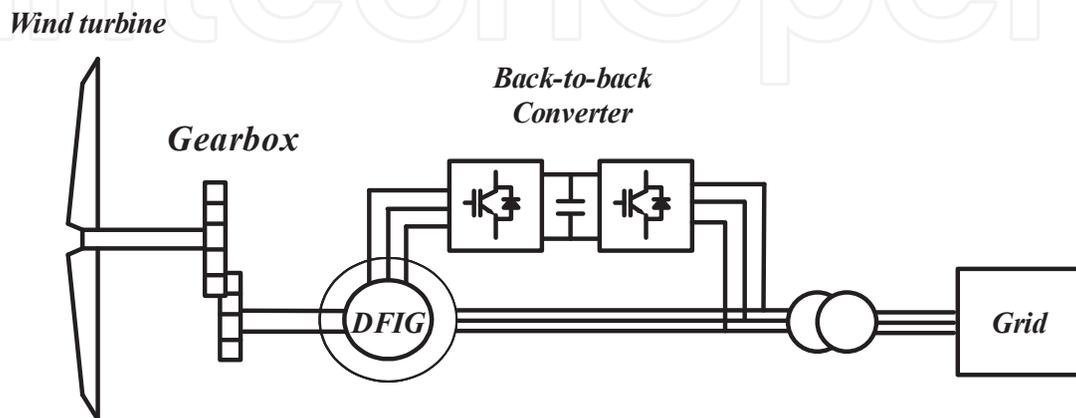


Figure 3. Doubly fed induction generator

The converter system enables two way transfer of power. The grid side converter provides a dc supply to the rotor side converter that produces a variable frequency three phase supply to generator rotor via slip rings. The variable voltage into the rotor at slip frequency enables variable speed operation. Manipulation of the rotor voltage permits the control of the generator operating conditions. In case of low wind speeds, the drop in rotor speed may lead the generator into a sub synchronous operating mode. During this mode, DFIG rotor absorbs power from the grid.

On the other hand, during high wind speed, the DFIG wind turbine running at super synchronous speed will deliver power from the rotor through the converters to the network. Hence, the rotational speed of the DFIG determines whether the power is delivered to the grid through the stator only or through the stator and rotor. Power delivered by the rotor and stator is given by [my papers]:

$$P_R = sP_S \quad (1)$$

$$P_G = (1 \pm s)P_S \quad (2)$$

Where, P_G is the mechanical power delivered by the generator, P_S is the power delivered by the stator, and P_R is the power delivered to the rotor.

However, under all operating situations, the frequency of rotor supply is controlled so that, under steady conditions, the combined speed of the rotor plus the rotational speed of the rotor flux vector matches that of the synchronously rotating stator flux vector fixed by the network frequency. Hence, the power could be supplied to the grid through the stator in all the three modes of operation, namely, sub synchronous, synchronous and super- synchronous modes. This provides DFIG a unique feature beyond the conventional induction generator as the latter can deliver power to the grid during super synchronous speed only.

2.2.2.2. Converter driven synchronous generator

This category of wind turbines uses a synchronous generator that can either be an electrically excited synchronous generator or a permanent magnet machine. To enable variable-speed operation, the synchronous generator is connected to the network through a variable frequency converter, which completely decouples the generator from the network. The electrical frequency of the generator may vary as the wind speed changes, while the network frequency remains unchanged. The rating of the power converter in this wind turbine corresponds to the rated power of the generator plus losses. The schematic diagram of the converter driven synchronous generator is as shown in Fig. 4.

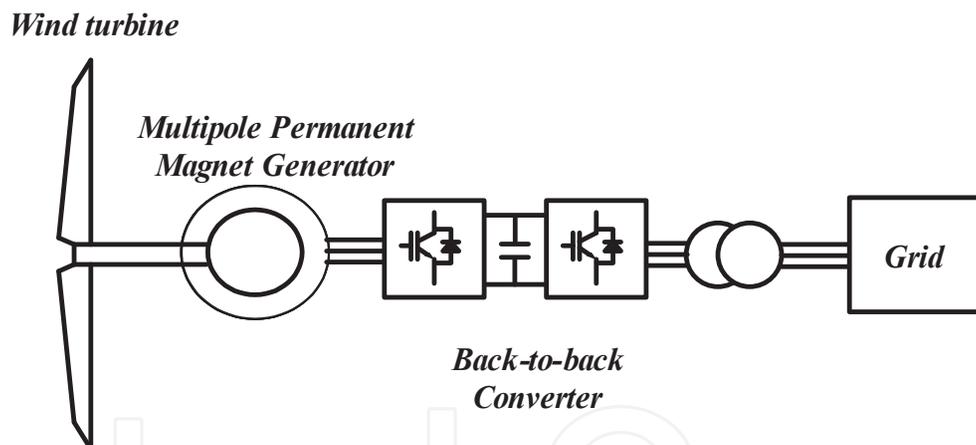


Figure 4. Converter-driven generator

The comparison between the fixed speed and variable speed wind turbines shows that variable speed operation of wind turbines presents certain advantages over constant speed operation. Variable speed wind turbines feature higher energy yields and lower power fluctuations than fixed speed wind turbines. The last feature is particularly important as flicker may become a limitation to wind generation on power systems. Also, variable speed wind turbines produce more reduced loads in the mechanical parts than fixed speed wind turbines. When comparing torque mode control and speed mode control strategies, literature review shows that speed mode control strategy follows wind speed, in order to achieve maximum power coefficient, more accurately, and the higher the speed control loop bandwidth is, the better the tracking is. Nevertheless, as a consequence, it produces more power fluctuations, since speed is rigidly

imposed to the turbine. So, from power quality point of view, torque mode control strategy presents better behavior because speed is not directly imposed to the turbine and this control strategy lets the wind turbine to freely change rotational speed during the transient.

2.3. Impacts of wind intermittent and variability

Uncertainty and variability are characteristics that exist in wind power, aggregate electric demand and supply resources and have always posed challenges for power system operators. Future expansion of the loads cannot be predicted accurately, generator outputs and loads fluctuate strongly in different time frames, and it can also lose energy system equipment at any time and without prior warning. Different amounts and types of operating reserves are secured by power system operators to compensate for uncertainty and variability for load reliable service and to keep the system frequency stable. There are many different terms, definitions, and rules concerning what operating reserves entail. The real power capability that can be given or taken in the operating timeframe to assist in generation and load balance and frequency control is defined as the operating reserves. To provide voltage support systems also require reactive power reserve as well, and require certain targets for installed capacity that is often referred to as planning reserve.

The type of event the operating reserves respond to, the timescale of the response and the direction (upward or downward) of the response can differentiate the types of operating reserves. Unpredictable imbalances between load and generation caused by sudden outages of generating units, errors in load forecasting or unexpected deviations by generating units from their production schedules can be compensated by spinning reserve (SR). It becomes more difficult to predict accurately the total amount of power injected by all generators into the power system, as the proportion of power produced by wind farms increases. This added uncertainty must be taken into account when setting the requirement for SR. The uncertainty on the wind power generation increases the uncertainty on the net demand that must be met by traditional forms of generation if wind power generation is considered as a negative load. Spinning reserve is intended to protect the system against unforeseen events such as generation outages, sudden load changes or a combination of both by taking the increased uncertainty into account when determining the requirements for SR.

It is therefore expected that a large penetration of wind generation might require a significant increase in the requirement for SR. However this is not always the case. The cost of SR is indeed far from being negligible. A large number of conventional generating units will need to be synchronized when large amounts of SR must be scheduled for a higher wind-power penetration. Therefore, the system operating cost would increase to such an extent that it might be economically desirable to curb this increase in the SR requirement. Determining the optimal amount of SR that must be provided as a function of the system conditions is thus an important and timely issue. The optimal amount of SR is defined as the equality of the cost of generating extra MW of reserve to the benefit that this MW provides, where this benefit is determined as a function of the reduction in the expected cost of interruptions. The ideal case is that the energy and SR amounts and repartitions should be optimized simultaneously. The main difficulties in solving such a problem are: the stochastic nature of the net demand due to the demand and

wind forecast errors, and the fact that there are no direct means of incorporating the discrete capacity outage probability distribution in the optimization procedure. The stochastic and highly combinatorial nature of the problem led some researchers to find alternative solutions to the problem [10].

The SR procurement depends on the system as mentioned in [10]. The power system operating cost can increase with the SR provision even though the wind generation reduces the overall net demand. It is also suggested that the extra amounts of MW for reserve can be determined using probabilistic methods combining the uncertain load and wind fluctuations and even including the contingency SR requirements.

2.4. Voltage stability

Power system transient stability is related to the ability to maintain synchronism when subjected to a severe disturbance, such as a short circuit on the bus. System stability is largely associated with power system faults in a network such as tripping of transmission lines, loss of production capacity (generator unit failure) and short circuits. These failures disrupt the balance of power (active and reactive) and change the power flow. Though the capacity of the operating generators may be adequate, large voltage drops may occur suddenly. The unbalance and re-distribution of real and reactive power in the network may force the voltage to vary beyond the boundary of stability. A period of low voltage (brownout) may occur and possibly be followed by a complete loss of power (blackout).

Many of power system faults are cleared by the relay protection of the transmission system either by disconnection or by disconnection and fast reclosure. In all the situations the result is a short period with low or no voltage followed by a period when the voltage returns. A wind farm nearby will see this event. In early days of the development of wind energy, only a few wind turbines were connected to the grid. In this situation, when a fault somewhere in the lines caused the voltage at the wind turbine to drop, the wind turbine was simply disconnected from the grid and was reconnected when the fault was cleared and the voltage returned to normal.

Because the penetration of wind power in the early days was low, the sudden disconnection of a wind turbine or even a wind farm from the grid did not cause a significant impact on the stability of the power system. With the increasing penetration of wind energy, the contribution of power generated by a wind farm can be significant. If the entire wind farm is suddenly disconnected at full generation, the system will lose further production capability. Unless the remaining operating power plants have enough "spinning reserve", to replace the loss within very short time, a large frequency and voltage drop will occur and possibly followed by complete loss of power. Therefore, the new generation of wind turbines is required to be able to "ride through" during disturbances and faults to avoid total disconnection from the grid. In order to keep system stability, it is necessary to ensure that the wind turbine restores normal operation in an appropriate way and within appropriate time. This could have different focuses in different types of wind turbine technologies, and may include supporting the system voltage with reactive power

compensation devices, such as interface power electronics, SVC, STATCOM and keeping the generator at appropriate speed by regulating the power etc. [12], [13].

2.5. Impacts of wind farms on power quality

The Danish Wind Industry Association defines power quality as voltage and frequency stability, together with absence of various forms of electrical noise, such as flicker or harmonic distortion. In a power supply system, voltage and frequency must be maintained near nominal values since electrical appliances are manufactured to work under the given alternate current (AC) specification. Conventional power plants fulfill two main tasks in large-scale electrical power systems: power generation and voltage control. In other words, as well as generating power for electricity consumption, they maintain power quality.

For example, at a diesel plant a voltage drop can be countered by simultaneously raising inductance and the steam input to the synchronous generator. The resulting surge in reactive power restores voltage to the desired level. In fact all voltage control devices are effectively controllable reactive power sources. The flexible operation levels of thermal plants allows for a continuous control of reactive power. Feeding intermittent power into electricity grids can affect power quality. The impact depends primarily on the degree to which the intermittent source contributes to instantaneous load (i.e. on power penetration). At low penetrations, wind farms can be connected to the grid as active power generators, with control tasks concentrated at conventional plants. Many studies agree that penetrations of up to 10–20% can be absorbed in electricity networks without adversely affecting power quality and needing extra reserve capacity. Key problems identified at higher penetrations are: At wind speeds below cut-in or above furl-out, wind turbines are disconnected from the grid and left idle. When the wind speed returns to operating range, the turbines are reconnected. The sudden connection of a large turbine can result in brownout (voltage drop incurred when instantaneous load exceeds generated power) due to the current required to magnetize the generator, often followed by a power peak when active power from the generator is fed to the network. There may be times when wind power output exceeds consumer load, making voltage raise above the grid threshold. Cutting off turbines to avoid the excess is not ideal in view of the reconnection problems, but also because ultimately it implies unnecessary shedding of wind energy.

The short-term wind power variations cause voltage fluctuations in the grid, known as flicker because of their effect on light bulbs. Rapid voltage fluctuations can damage sensitive electrical equipment. In a very weak grid, even a single turbine may produce flicker.

Harmonics produced by consumers' electronic equipment can be magnified by wind turbine operation. And more generally, the response of wind farms to an electrical fault may cause transient instabilities which cannot be countered by the control units in the grid. These problems have been reported mainly with reference to small-scale autonomous systems when significant wind power (>100 kW) is connected to a low voltage grid. Stronger grids, with a larger cross-section, have low impedance and so power variations result in smaller voltage variations. However, a sufficiently large wind farm is likely to disrupt power quality even if connected to a high-voltage transmission line [14].

2.6. Reactive power control and voltage control

It is required as a minimum that the reactive power from a large wind farm can be controlled to a specific interval, which is close to unity power factor. However, most wind turbines are also able to provide more advanced reactive power control, which can be useful as grid support. Depending on the technology and the electrical design, such wind turbines will normally have some additional capacity for reactive power, although the available reactive power normally depends on the active power as it does for any other generating units in the power system. This dependency is expressed in the PQ diagrams. The TSO should have access to the reactive power, and the PQ diagram of the wind farm should be delivered by the owner. The additional reactive power capacity can either be used to control constant reactive power or constant power factor, or it can be used in automatic voltage control. In the latter case, it is essential, that it is the voltage in the wind farm point of common coupling (PCC) which is controlled, and that this is done on the wind farm controller level. If the wind turbines are individually attempting to control the voltage in the individual connection points, there is a risk of instability and/or unnecessarily high flow of reactive power between the wind turbines. The possible voltage control in the PCC is of course limited by the limited reactive power available in the wind turbines or from other compensation equipment in the wind farm [15].

2.7. Impacts of wind farm control strategies

One of the challenges which has gained significant importance within the field of electrical power systems over the last years is reactive power control and voltage support from wind farms. Previously the voltage control in the transmission systems was mainly carried out by adjusting the reactive power production or absorption of central power plants, but as the amount of wind power is growing, the requirements for system services including voltage control delivered by wind turbines, and large wind farms in particular, are rising.

So far reactive power control by wind farms has mainly been carried out by utilizing the reactive power capabilities of the wind turbines, but this strategy may not be the most feasible solution when taking into account the new grid code requirements. The optimal reactive power control strategy is influenced by factors like the reactive power capabilities of the wind farm, the on load tap changers of transformers and possible implementation of compensating devices. From a wind farm operator point of view, reactive power control strategies should be based on economic optimization and hence there is a need for investigation of the implications of the new grid code requirements on the reactive power control strategy [16], [17].

2.8. Inertial response with wind

The inertia of traditional synchronous generators plays a significant role in maintaining the stability of the power system during a transient scenario. The inertia dictates how large the frequency deviations would be due to a sudden change in the generation and load power balance, and influences the eigenvalues and vectors that determine the stability and mode shape of transient response. The larger the inertia, the smaller will be the rate of change in rotor speed of the generator during an imbalance in power. This type of response of the traditional

synchronous generators is called inertial response. This is a synchronous machine's "reaction," inherently dictated by rotational Newton's law, to sudden changes in the balance between applied mechanical shaft power and electrical power extracted at the generator terminals.

The rate of change of frequency depends on the shortfall or the surplus of generation and the power system inertia. For a given generation shortfall, the higher the system inertia, the lower the rate of change of frequency. Consequently, this inertial response is a critical factor that allows enough time for governor primary control to supply sufficient energy to stabilize system frequency. It is relevant to note that interruptible loads are used to arrest the fall in system frequency, in addition to governor primary control. Such interruptible loads and primary control are collectively called instantaneous frequency reserves.

Standard fixed speed induction generators contribute to the inertia of the power system because the stator is directly connected to the power system. Any change in power system frequency manifests as a change in the speed of stator-led rotating flux. Such speed changes are resisted by the rotating mass (generator rotor and the wind turbine rotor) leading to rotational energy transfer to the power system via the stator.

In modern variable-speed wind turbines, its rotational speed is normally decoupled from the grid frequency by the power electronic converter. Therefore variation in grid frequency does not alter the turbine output power. With high wind power penetration there is a risk that the power system inertial effect decreases, thus aggravating the grid frequency stability. The decrease of inertia effect on the grid may be even worse in power system with slow primary frequency response such as those large amount of hydropower, or in small power systems with inherent low inertia system such as islanded systems[18].

As the penetration of wind is expected to grow dramatically in the coming decade, researchers and vendors have sought improved designs to allow these technologies to better contribute to grid frequency regulation and stability. As noted above, most of the solutions proposed to date seek to mimic the inherent inertial response of traditional synchronous generators; i.e., they add a control loop that incrementally feeds or draws active power in response to a decline or rise in the time derivative of frequency. The control power required by this proposed additional loop comes predominantly either by varying the mechanical input power to a wind turbine, through change in its blade pitch or nominal rotational speed, or by drawing/feeding additional active power from/to the grid through the rotor side converter [19].

2.9. Wind probability density distribution

It is essential to assess wind energy potential of a site before any wind energy based system could be set up. Study of wind velocity regime over a period of time in a locality can really help to optimize the design of the wind energy conversion system by ensuring less energy generating costs. Wind velocity is generally recorded in a time-series format, which means wind velocity recorded over hourly basis in a day or over 24 h in a day.

To date, Weibull density function method is widely accepted for evaluating local wind load probabilities and is considered as a standard approach [20]. This method has a great flexibility and simplicity. However, the main limitation of the Weibull density function is its inability to

accurately calculate the probabilities of observing zero or very low wind velocities [21]. Also Weibull two-parameter density function does not address the differences of wind velocity variation during the course of a day. Nevertheless, this statistical method is found to fit a wide collection of recorded wind data [22]. The Weibull wind velocity probability density function can be represented as [23]:

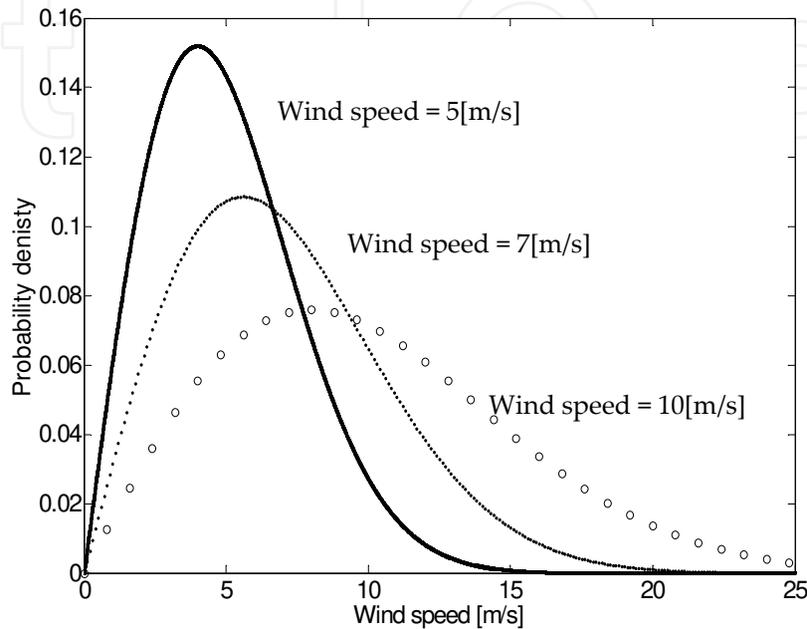


Figure 5. Probability distribution for the wind speed

$$f(v) = \frac{k}{c} \left(\frac{v}{c} \right)^{k-1} \exp \left[- \left(\frac{v}{c} \right)^k \right] \quad (3)$$

Where; $f(v)$ is the probability of observing wind velocity v , c is the Weibull scale parameter and k is the dimensionless Weibull shape parameter. Basically, the scale parameter, c , indicates how 'windy' a wind site under consideration is, whereas the shape parameter, k , indicates how peaked the wind distribution is (that is, if the wind speeds tend to be very close to a certain value, the distribution will have a high k value and be very peaked). The probability distributions for low, medium and high wind speed locations are shown in Fig. 5. The figure demonstrate the difference in the probability distribution between high and low wind speeds.

3. Wind power impacts on the power system

Wind power has impacts on power system operational security, reliability and efficiency. Therefore, it is necessary to know the consequences of dynamic interaction between large scale

wind farms and electrical power systems before incorporation of the wind farms into the grid. The electric power supply undergoes a change from a well-known and developed technology of conventional power plants to a partly unknown technology of wind power. High penetration of wind power could be managed through proper wind power plant interconnection, integration of the generation, transmission planning, and system operations.

Fig. 6 and 7 show impacts of wind power on power systems, divided in different time scales and width of area relevant for the studies. At the time of developing the standard IEC 61400-21: “Measurement and assessment of power quality characteristics of grid connected wind turbines”, the wind turbines were mainly connected to the distribution grid, and the basic concern was their possible impact on the voltage quality and not on power system operation. This has changed with the development of large power rated wind farms that may form a significant part of the power system. In consequence, today’s wind turbines are able to control the power (active and reactive) delivered both in transient and steady state, they can cope with power ramp requirements and they have low voltage ride through(LVRT) capability. They may even contribute to the primary frequency control, but then on the cost of dissipating energy [24]. These impacts can be categorized as follows:

- Short-term: impacts on the operational time scale (minutes to hours).
- Long-term: impacts on planning the transmission network and installed generation capacity for adequacy of power.

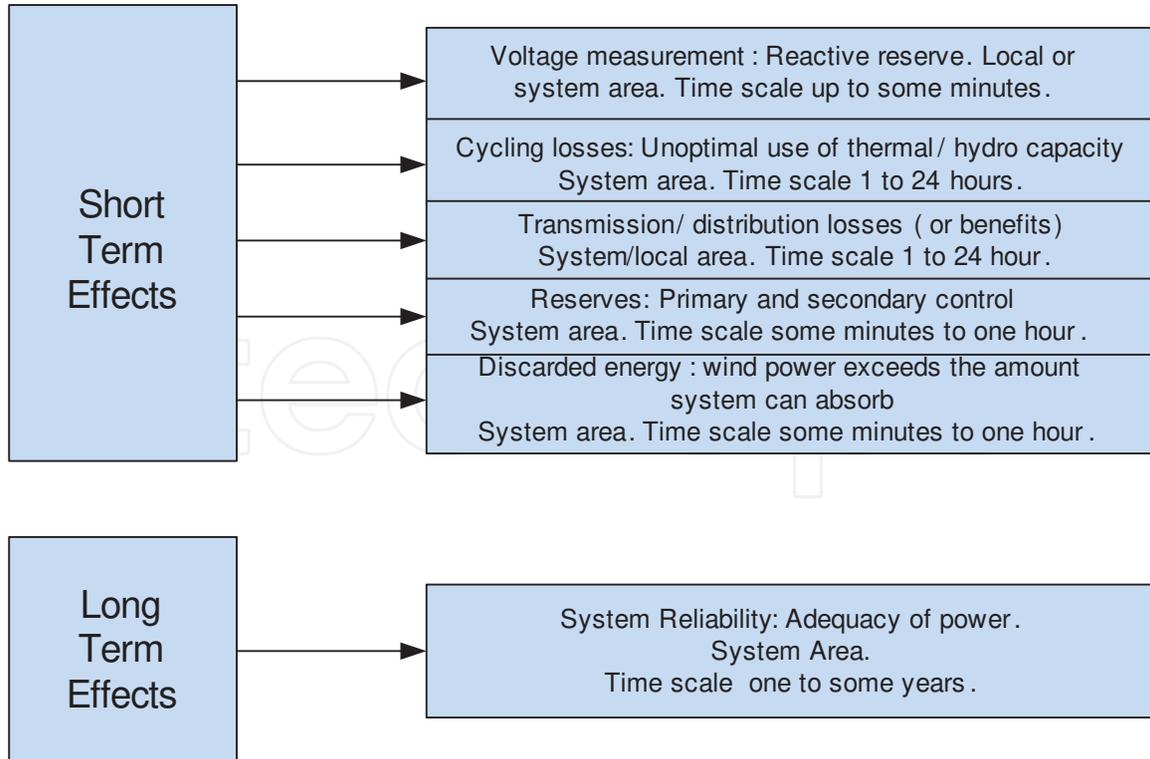


Figure 6. Power system impacts of wind power, causing integration costs [8]

For estimating the impacts, the different timescales involved usually mean different models that used in impact studies. This is why the impacts should be divided into three focus areas [23]:

3.1. Balancing

The first integration of renewable energy sources occurred on a small scale and at medium voltage. No extra measurements were taken for balancing the fluctuating power. However, as electricity grids are facing large scale integration of wind power, imbalances are occurring more frequently and are growing in magnitude. The first way to deal with the variable nature of wind power is to nominate the power day-ahead. Every balance responsible party (BRP) with wind turbines in his portfolio can nominate wind power output day-ahead by forecasting the predicted output. This system is extensively dealt with in the appendix concerning market mechanisms. Thus, the power generation is matched with the expected power demand. After this nomination, prediction errors lead to imbalances in the portfolio of each BRP. A particular BRP has the opportunity to balance its portfolio with different intra-day mechanisms (if available).

Again, the power generated is matched with the expected power demand. After gate closure, it can be expected that all remaining imbalances are dealt by the Transmission System Operator (TSO). Thus, prediction errors of one up to three hours ahead are to be balanced by the TSO. The TSO uses primary, secondary and tertiary reserves to balance the power imbalances as a result of prediction errors.

Wind power imbalances have two origins: prediction errors and inter-prediction deviations because the nominated power amount is for a fixed time period. Inter-prediction errors are related to the variable output of wind. Suppose the power is nominated on a basis of 15 min, wind power varies around the nominated value leading to inter- and intra-minute imbalances. Prediction errors result in positive or negative imbalances on a much longer timescale to even inter-hour imbalances [24].

3.2. Adequacy of power

Total supply available during peak load situations (time scale: several years, and associated with static conditions of the system). The estimation of required generation capacity needs includes the system load demand and maintenance needs of production units (reliability data). The criteria that are used for the adequacy evaluation include the loss of load expectation (LOLE), the loss of load probability (LOLP) and the loss of energy expectation (LOEE), for instance. The issue is the proper assessment of wind power's aggregate capacity credit in the relevant peak load situations – taking into account the effect of geographical dispersion and interconnection [25].

3.3. Grid

The impacts of wind power on transmission depend on the location of wind power plants relative to load, and the correlation between wind power production and electricity consumption. Wind power affects power flow in the network. It may change the power flow direction, and reduce or increase power losses and bottleneck situations. There are a variety of means to

maximize the use of existing transmission lines like use of online information (temperature, loads), FACTS, and wind power-plant output control. However, grid reinforcement may be necessary to maintain transmission adequacy and security. When determining adequacy of the grid, both steady-state load flow and dynamic system-stability analysis are needed. Different wind turbine types have different control characteristics, and consequently, also have different possibilities to support the system in normal and system-fault situations. For system stability reasons, operation and control properties will be required from wind power plants at some stage, depending on wind power penetration and power system robustness [25].

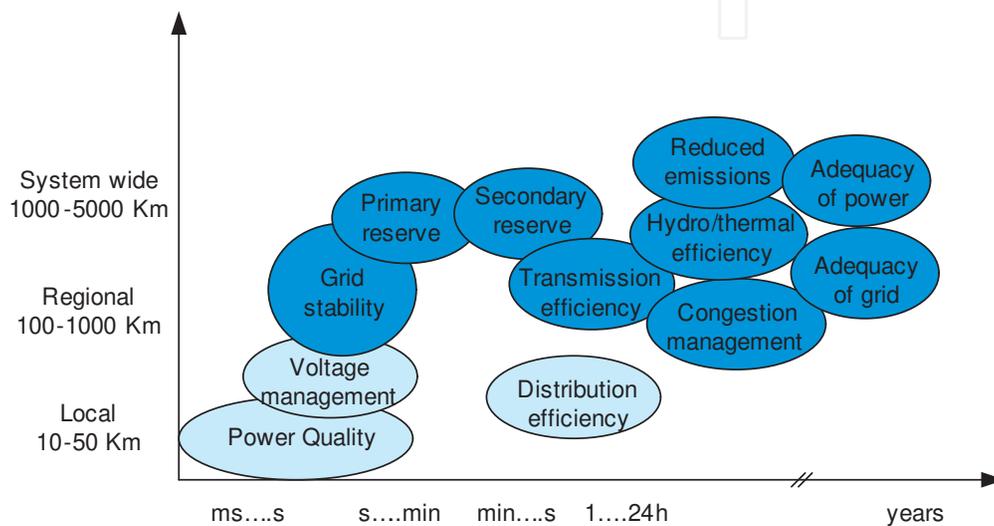


Figure 7. Impacts of wind power on power systems, divided in different time scales and width of area relevant for the studies[19]

4. Wind power integration solutions

Studies show that for an individual wind turbine, the variation in output is small for time-scales of less than a few seconds; for an individual wind farm, the variation in output is small for time scales of tens of seconds, due to the averaging of output of individual turbines across the wind farm; and for a number of wind farms spread out across a large area, such as a national grid system, the variation in output of all wind turbines is small for timescales from minutes to tens of minutes. The power produced from a large number of wind turbines will vary relatively less than the power produced from a single wind turbine due to the cancellation effect from the poor spatial correlation of the wind acting on each wind turbine.

To enhance the security of supply, new transmission and distribution grid codes specify technical requirements such as fault-ride through capability and frequency control of the electrical conversion systems of wind farms. Fault ride-through capability refers to the generators capabilities to remain connected to electricity networks at voltage levels below nominal. Active

power control is closely related to frequency control and the wind farm shall have frequency control capabilities to ramp up and down the wind farm power station's active power output in accordance with the frequency/active power characteristic defined by the grid operator [26], [27].

When a power system is subjected to a sudden increase in reactive power demand following a system disturbance, the additional demand must be met by reactive power reserve carried by generators and compensators. If wind farms or other generation units are unable to withstand voltage drops for a limited time, they will disconnect from the system and then the reactive power supplied by these generators is lost that can entail load shedding or even a blackout, in the worst case [28]. To ensure the voltage recovery the wind-turbine generators must remain connected to the system to provide reactive power support after the fault clearance. For many wind turbine manufacturers these are very costly and challenging requirements. In some cases extensive modifications to the electrical system of the turbines are necessary [29].

Achieving reliable operation at greatly reduced voltage levels is proving problematic. A particular problem regarding power converter-based wind-turbine generators is that conventional controllers for power converters designed for reliable operation around nominal voltage levels will not work as designed during low network voltages that can occur during a fault. A consequence of this is greatly increased converter currents, which may lead to converter failure. New controller design strategies have been proposed for power converter-based wind turbine generators aiming to maintain converter currents within their design limits, even at greatly reduced voltage levels, in order to enhance the wind-turbine generators' fault ride-through capability [30]. With the increasing penetration of power converter-based wind turbine generators the rotational speed of the wind turbines are decoupled from the grid leading to a reduction of inertia in the grid. The lower the inertia of a system, the more and faster the frequency will change with variations in generation or load. In order that a variable-speed wind turbine to contribute to the system inertia and the frequency control as a result it has been proposed in [31] an additional control loop in the power electronic converter which connects the turbine inertia directly to the grid so that the wind turbine will be able to increase its power supplied to the grid during a drop in the grid frequency.

Whilst the wind farms are considered like other generating facilities by some grid operators and as such they are requested to participate in the system frequency and voltage compensation, the wind power sector claims for less strict requirements which imposes unnecessary burden and cost on manufacturers. The wind power sector calls on an overall economically efficient solution where the primary and secondary control should be provided by conventional power plants with the wind farms providing such service only in cases where limits in existing reserves are foreseen, and reactive power compensation provided by FACTS devices directly installed in the transmission network [31].

5. Conclusion

The complexity of power systems has increased in recent years due to the operation of existing transmission lines closer to their limits due to the increased penetration of new types of

generators that have more intermittent characteristics and lower inertial response, such as wind generators. This changing nature of a power system has considerable effect on its dynamic behaviors resulting in power swings, dynamic interactions between different power system devices and less synchronized coupling.

Understanding and quantifying the impacts of wind farms on utility systems is a critical first step in identifying and solving problems. The design and operation of the wind plant, the design and operation of the power system, and the market rules under which the system is operating influence the situation. A number of steps can be taken to improve the ability to integrate increasing amounts of wind capacity on power systems such as improvements in wind-turbine and wind-farm models, improvements in wind-farm operating characteristics, improvements in the flexibility of operation of the balance of the system, carefully evaluating wind-integration operating impacts, incorporating wind-plant output forecasting into utility control-room operations, making better use of physically available transmission capacity, upgrading and expanding transmission systems, developing well-functioning hour-ahead and day-ahead markets and expanding access to those markets, adopting market rules and tariff provisions that are more appropriate to weather-driven resources, and consolidating balancing areas into larger entities or accessing a larger resource base through the use of dynamic scheduling or some form of area control error (ACE) sharing.

As additional integration studies and analyses are conducted around the world, it is expected that more researches will be valuable as wind penetration increases. And with the large increase in installing wind farms, actual practical experience will also contribute strongly in our understanding of the effects that arise from the increasing installation of wind farms on the system as well as on ways that the impacts of wind's variability and uncertainty can be treated in an inexpensive manner.

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References

- [1] M.J. Hossain, H.R. Pota, M.A. Mahmud, and R. A. Ramos, "Impacts of large-scale wind generators penetration on the voltage stability of power systems, " IEEE Power and Energy Society General Meeting, PP: 1-8, July 2011.
- [2] World Wind Energy Association WWEA, "World Wind Energy Report 2010".

- [3] Renewable Energy Policy Network for the 21st Century, "Renewables 2011: Global Status Report," 2011.
- [4] Eolic Energy News, "Spain becomes the first European wind energy producer after overcoming Germany for the first time", Dec. 2010.
- [5] Renewable Energy Research Laboratory, "Wind Power: Capacity Factor, Intermittency," University of Massachusetts, 2008.
- [6] American Wind Energy Association "20% Wind Energy by 2030" 2009.
- [7] H. Holttinen *et al.*, " State-of-the-art of design and operation of power systems with large amounts of wind power summary of IEA wind collaboration EWEC2007," *Proc. European Wind Energy Conf. May 2007*.
- [8] Deutsche Energie-Agentur Dena (DENA), "Planning of the grid integration of wind energy in Germany onshore and offshore up to the year 2020," 2005.
- [9] G. Strbac, A. Shakoor, M. Black, D. Pudjianto, and T. Bopp, "Impact of wind generation on operation and development of the future UK electricity systems," *Electr. Power Syst. Res.*, 2007.
- [10] T. Ackermann, J. R. Abbad, I. M. Dudurych, I. Erlich, H. Holttinen, J. R. Kristoffersen, and P. E. Sorensen, "European balancing act," *IEEE Power Energy Mag.*, vol. 5, no. 6, pp. 90–103, 2007.
- [11] Z. Lubosny, *Wind Turbine Operation in Electric Power Systems*, Springer-Verlag Berlin, ISBN 3-540-40340-X.
- [12] Z. Chen, " Issues of Connecting Wind Farms into Power Systems," *IEEE/PES Transmission and Distribution Conference & Exhibition: Asia and Pacific Dalian, China*, 2005.
- [13] Ö.S. Mutlu, E. Akpınar, and A. Balikci, " Power Quality Analysis of Wind Farm Connected to Alacati Substation in Turkey," *Renewable Energy Journal*, vol. 34 pp. 1312–1318, 2009.
- [14] D. Weissera, and R. S. Garcia " Instantaneous wind energy penetration in isolated electricity grids: concepts and review," Elsevier, *Renewable Energy Journal*, pp. 1299-1308, 2005.
- [15] L. Munteanu, A. L. Bratcu, N.-A. Cutulilis, and E. Ceanga, *Optimal Control of Wind Energy Systems*, Springer, ISBN 978-1-84800-080-3.
- [16] I. de Alegria, J. Andreu, J. Martin, P. Ibanez, J. Villate, and H. Camblong, "Connection requirements for wind farms: A survey on technical requirements and regulation," *Renewable and Sustainable Energy Reviews*, vol. 11, no. 8, pp. 1858–1872, 2007.

- [17] J. Hethey and M. S. Leweson, "Probabilistic Analysis of Reactive Power Control Strategies for Wind Farms," M.Sc. thesis, Technical University of Denmark, 2008.
- [18] G. C. Tarnowski, P. C. Kjaer, P. E. Sorensen, and J. Ostergaard, "Study on variable speed wind turbines capability for frequency response", in *Proc. European Wind energy Conference EWEC*, 16-19 March, Marseille, France, 2009.
- [19] A. Keane, M. Milligan, C. D'Annunzio, C. Dent, K. Dragoon, B. Hasche, H. Holttinen, N. Samaan, L. Söder, M. O'Malley, "Calculating the capacity value of wind," *IEEE Transactions on Power Systems*, vol. 26, no. 2, pp. 564-572, 2011.
- [20] L. Lu, H. Yang H, and J. Burnett, "Investigation on wind power potential on Hong Kong—an analysis of wind power and wind turbine characteristics," *Renewable Energy Journal*, vol. 27, pp.1-12, 2002.
- [21] D. Weisser, "A wind energy analysis of Grenada: an estimation using the Weibull density function," *Renewable Energy Journal*, vol. 28, pp. 1803-1812, 2001.
- [22] I.Y.F Lun and J. C. Lam (2000)," A study of Weibull parameters using long-term wind observations," Elsevier, *Renewable Energy Journal* vol. 20, No. 2, 145-53, 2000.
- [23] C. Justus, W. Hargraves, A. Mikhail, and D. Graber (1978), "Methods for estimating wind speed frequency distributions," *J. Appl. Meteorol.*, vol. 17, 350- 353.
- [24] H. Holttinen et al, "Design and operation of power systems with large amounts of wind power" Final report, IEA WIND Task 25, 2006-2008.
- [25] H. Holttinen, P. Meibom, A. Orths, B. Lange, M. O'Malley, J. O. Tande, A. Estanqueiro, E. Gomez, L. Söder, G. Strbac, J. C. Smith, F. van Hulle, "Impacts of large amounts of wind power on design and operation of power systems, results of IEA collaboration," *Journal of Wind Energy*, 2008.
- [26] R. Leão, T. Degner and F. Antunes, "An overview on the integration of large-scale wind power into the electric power system," Dept. of electrical engineering, Federal University of Ceará, Brazil, 2007.
- [27] M. Dahlgren, H. Frank, M. Leijon, F. Owman, L. Walfridsson, "Windformer™ Wind power goes large-scale", *ABB review*, no. 3, pp. 31-37, 2000.
- [28] Prabha Kundur, *Power system stability and control*, ISBN 0-07-035958-X.
- [29] S. Repo, "On-line Voltage Stability Assessment of Power System- An Approach of Black-box Modelling," PhD Thesis, Aalborg University, 2001.
- [30] A. Mullane et al., "Wind-turbine fault ride-through enhancement," *IEEE Trans. Power Systems*, vol. 20, no. 4, pp. 1929-1937, 2005.
- [31] J. C. Smith, "Winds of change: Issues in utility wind integration," vol. 3, pp. 20-25, Nov. 2005.

