Introduction to FACTS Controllers in Wind Power Farms: A Technological Review

Bindeshwar Singh*

*Research Scholar, Kamla Nehru Institute of Technology (KNIT), Sultanpur-228118, U.P., India

bindeshwar.singh2025@gmail.com

Abstract-This paper presents a state-of-the-art on enhancement of different performance parameters of power systems such as voltage profile, damping of oscillations, loadability, reduce the active and reactive power losses, sub-synchronous resonance (SSR) problems, transient stability, and dynamic performance, by optimally placed of FACTS controllers such as TCSC, SVC, STATCOM, SSSC, UPFC, IPFC, HPFC in wind power Systems. Also this paper presents the current status on enhancement of different performance parameters of power systems by optimally placed of FACTS controllers in wind power Systems. Authors strongly believe that this survey article will be very much useful to the researchers for finding out the relevant references in the field of the enhancement of different performance parameters of power systems such as voltage profile, damping of oscillations, loadability, reduce the active and reactive power losses, sub-synchronous resonance (SSR) problems, transient stability, and dynamic performance, by optimally placed of FACTS controllers in wind power Systems.

Keywords-Wind Power Systems, Flexible AC Transmission Systems (FACTS), FACTS Controllers, Static Var Compensator (SVC), Thristor Controlled Series Capacitor (TCSC), Thristor Controlled Phase Angle Regulator (TCPAR), Sub-synchronous Series Compensator (SSSC),Static Synchronous Compensator (STATCOM), Unified Power Flow Controller (UPFC), Inter-link Power Flow Controller (IPFC),and Hybrid Power Flow Controller (HPFC).

1. Introduction

The worldwide concern about environmental pollution and a possible energy shortage has led to increasing interest in technologies for the generation of renewable electrical energy. Among various renewable energy sources, wind power is the most rapidly growing one in Europe and the United States. With the recent progress in modern power electronics, the concept of a variable-speed wind turbine (VSWT) equipped with a doubly fed induction generator (DFIG) is receiving increasing attention because of its advantages over other wind turbine generator concepts. In the DFIG concept, the induction generator is grid-connected at the stator terminals; the rotor is connected to the utility grid via a partially rated variable frequency ac/dc/ac converter (VFC), which only needs to handle a fraction (25%–30%) of the total DFIG power to achieve full control of the generator. The VFC consists of a rotor-side converter (RSC) and a grid-side converter (GSC) connected back-to-back by a dc-link capacitor. When connected to the grid and during a grid fault, the RSC of the DFIG may be blocked to protect it from over current in the rotor circuit. The wind turbine typically trips shortly after the converter has blocked and automatically reconnects to the power network after the fault has cleared and the normal operation has been restored. The author proposed an uninterrupted operation feature of a DFIG wind turbine during grid faults. In this feature, the RSC is blocked, and the rotor circuit is short-circuited through a crowbar circuit (an external resistor); the DFIG becomes a conventional induction generator and starts to absorb reactive power. The wind turbine continues its operation to produce some active power, and the GSC can be set to control the reactive power and voltage at the grid connection. The pitch angle controller might be activated to prevent the wind turbine from fatal over speeding. When the fault has cleared and when the voltage and the frequency in the utility grid have been reestablished, the RSC will restart, and the wind turbine will return to normal operation. However, in the case of a weak power network and during a grid fault, the GSC cannot provide sufficient reactive power and voltage support due to its small power capacity, and there can be a risk of voltage instability. As a result, utilities, typically, immediately disconnect the wind turbines from the grid to prevent such a contingency and reconnect them when normal operation has been restored. Therefore, voltage stability is the crucial issue in maintaining uninterrupted

operation of wind turbines equipped with DFIGs. With the rapid increase in penetration of wind power in power systems, tripping of many wind turbines in a large wind farm during grid faults may begin to influence the overall power system stability. It has been reported recently that integration of wind farms into the East Danish power system could cause severe voltage recovery problems following a three-phase fault on that network.

The problem of voltage instability can be solved by using dynamic reactive compensation. Shunt flexible ac transmission system (FACTS) devices, such as the SVC, TCPAR, TCSC, SSSC, UPFC, IFPC, GUPFC, HPFC, and the STATCOM, have been widely used to provide high-performance steady state and transient voltage control at the point of common coupling (PCC). The application of an SVC or a STATCOM to a wind farm equipped with fixed-speed wind turbines (FSWTs) and squirrel-cage induction generators (SCIGs) has been reported in open literatures for steady-state voltage regulation and in [1] and [8] for short-term transient voltage stability. However, compared with the FSWT with a SCIG, the operation of the VSWT with a DIFG, particularly during grid faults, is more complicated due to the use of power electronic converters, and it has not yet been studied with the use of dynamic reactive compensation. Nowadays wind as a significant proportion of non-pollutant energy generation, is widely used. If a large wind farm, which electrically is far away from its connection point to power system, is not fed by adequate reactive power, it present major instability problem. Various methods to analyze and improve wind farm stability have been discussed in open literatures. The increasing power demand has led to the growth of new technologies that play an integral role in shaping the future energy market. Keeping in view the environmental constraints, grid connected wind parks are a promising aspect in increasing system reliability and congestion relief. Wind farms are either connected to the grids or a stand-alone operation. With the ever changing wind patterns, it is not feasible to connect wind farms directly to the grids. Certain conditions have to be met before wind farms start operating in conjunction with the main power network. The succeeding sections of this paper present the problems related with the reliable and secure operation of Wind Energy Conversion Systems (WECS) and the possible solutions. Though Doubly-Fed Induction Generators (DFIGs), which have the feature of regulating the reactive power demand, have emerged but most of the wind farms worldwide employ either squirrel-cage induction generators or rotor wound induction generators. These induction generators draw reactive power from the main power grid and hence might result in voltage drops at the Point of Common Coupling (PCC). Moreover, the input power to these induction machines is variable in nature and hence the output voltages are unacceptably fluctuating. To address these problems FACTS Controllers are being encouraged. FACTS Controllers provide the necessary dynamic reactive power support and the voltage regulation. Herein these Controllers and their applications to wind farms is discussed. On the other hand there exist instruments like Flexible AC Transmission Systems (FACTS), which were developed in order to dynamically control and enhance power system performance. Stability is the key aspect for introducing FACTS devices. Therefore, is seems quite natural, that one of the today's research topics is employment of FACTS devices for enhancing wind farm performance with respect to the grid codes and power system stability. FACTs are an acronym which stands for Flexible AC Transmission System. FACTS is an evolving technology based solution envisioned to help the utility industry to deal with changes in the power delivery business. The potential benefits of FACTs equipment are now widely recognized by the power systems engineering and T&D communities. The philosophy of FACTs is to use power electronic controlled devices to control power flows in a transmission network, thereby allowing transmission line plant to be loaded to its full capability. FACT devices are broadly classified in to two categories based on the type of power switches employed.

They can be

1. Thyristor-Based FACTs Controllers

2. GTO-Based FACTS

Developments in the field of high voltage power electronics have made possible the practical realization of FACTs controllers. By the 1970s, the voltage and current rating of GTOs had been increased significantly making them suitable for applications in high voltage power systems. This made construction of modern SVC, TCSC, TCPAR, and many other FACTS controllers possible. A fundamental feature of the thyristor based switching controllers is that the speed of response of passive power system components such as a capacitor or a reactor is enhanced, but their compensation capacity is still solely determined by the size of the reactive component. Series capacitors are connected in series with transmission lines to compensate for the inductive reactance of the line, increasing the maximum transmittable power and reducing the effective reactive power loss. Power transfer control can be done continuously and rather fast using the TCSC, making it very useful to dynamically control power oscillations in power systems. A normal thyristor, which is basically a one-way switch, can block high voltages in the off-state and carry large currents in the on-state with only small on-state voltage drop. The thyristor, having no current interruption capability, changes from onstate to off-state when the current drops below the holding current and, therefore, has a serious deficiency that prevents its use in switched mode applications.

With the development of the high voltage, high current Gate Turn-Off thyristors (GTOs), it became possible to overcome this deficiency. Like the normal thyristor, a gate current pulse can turn on the GTO thyristor, while to turn it off, a negative gate-cathode voltage can be applied at any time. This feature and the improved ratings of GTOs made possible the use of Voltage-Sourced Converters (VSC) in power system applications. If a VSC is connected to the transmission system via a shunt transformer, it can generate or absorb reactive power from the bus to which it is connected. Such a controller is called Synchronous Static Compensator or STATCOM and is used for voltage control in transmission systems. The major advantage of a STATCOM, as compared to a SVC, is its reduced size,

sometimes even to less than 50 %, and a potential cost reduction achieved from the elimination of capacitor and reactor banks as well as other passive components required by the SVC. If a VSC is employed as a series device by connecting it to the transmission line via a series transformer, it is called a Static Synchronous Series Compensator or simply SSSC. This controller can also generate or absorb reactive power from the line to which is connected and in that way change the series impedance of the line. It is convenient to think of the SSSC as being comparable to a continuously variable series capacitor or inductor, and, therefore, can be used to control the power flow in the transmission line.

A UPFC can control transmission line impedance, voltage and phase angle. It has the capability of controlling with two-degrees of freedom, i.e. it can control inverter output voltage magnitude and phase angle and only the current rating of the device limits its output capabilities. This new device offers utilities the ability to control voltage magnitude in the system, control power flows, both steady-state and dynamic, on predefined corridors, allowing secure loading of transmission lines up to their full thermal capability. A summary of different FACTs controllers is given in Fig.1

The various FACTS controllers employed at wind power farms sites are listed below.
- Static Var Compensators (SVC)
- Thyristor controlled Series Capacitor (TCSC or FC-TCR)
- Thyristor controlled Phase angle Regulator (TC-PAR)
- Sub synchronous Series Capacitor (SSSC)
- Static Compensators (STATCOM)
- Unified Power Flow Controller (UPFC)
- Interlink Power Flow Controllers (IPFC)
- Generalized Power Flow Controllers (GUPFC)
- Hybrid Power Flow Controllers (HPFC)

The different type of FACTS controllers are discussed in fig.1

Off-Shore wind farms have emerged as major contributor of power generation in the European countries. This power is being generated far from the point of consumption. In the past, wind energy used to contribute a very small fraction of the electrical power system network. Today, this has changed dramatically with more wind energy penetrating the conventional power network. The amount of electricity being generated by wind turbines is increasing continuously. In next 10 years, the wind energy is expected to be in a proportion comparable to energy produced from the conventional steam, hydro and nuclear systems so that any adverse effect of wind generation integration would jeopardize the stability of the system. With the current integration and control schemes, the impact of wind energy integration has adverse effects on the dynamics of the already stressed power system in USA [1].
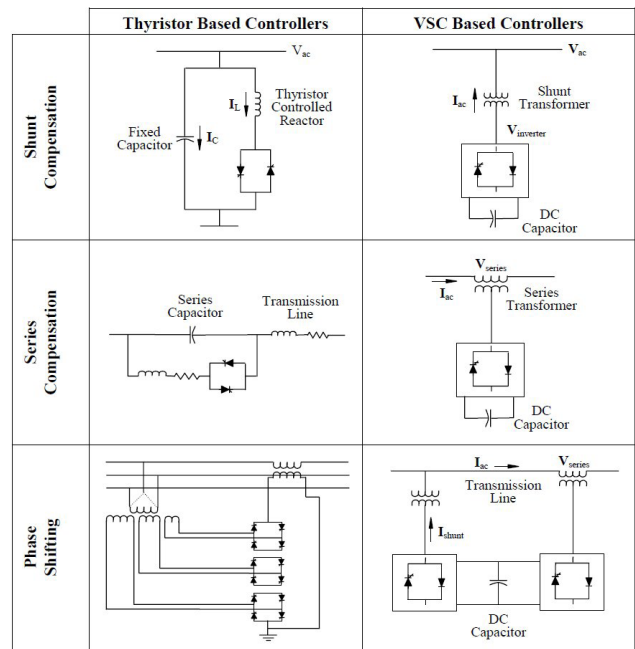

Fig. 1. Summary of different FACT controllers

The main motivation behind this work is to utilize thyristor-based FACTS devices for mitigation of SSR. The FACTS devices may be already installed for achieving other objectives and SSR damping function can be additionally included, or the FACTS devices can be exclusively connected for mitigating SSR. For instance, an SVC may be already located at the wind farm for dynamic reactive power support or for other power-quality (PQ) improvement purposes. Similarly, a TCSC may already be inserted in the transmission network to increase the power transfer capability, and the large capacity wind farm may now need to evacuate power through this series-compensated network. The earlier fixed speed generators with variable gear mechanical couplings used to generate electricity with a low efficiency. In the recent years, variable speed wind generatorshave been incorporated using power electronic converters to decouple mechanical frequency and electric grid frequency. The power electronic components are very sensitive to over currents because of their very short thermal time constants [2]. They sense a small voltage drop in the terminal voltage instantly and the wind turbine is quickly disconnected from the grid to protect the converter. This can lead to instability even a wide-spread blackout when a power system with high wind penetration is disconnected as a result of a small drop in the voltage. For the integration of wind generation to the utility grid, the voltage profile of the bus at the PCC is critical. Thus, it is necessary to maintain and control the bus voltage at the PCC under different operating conditions. FACTS) devices such as SVCs and STATCOM are power electronic switches used to control the reactive power injection at the PCC, thereby regulating the bus voltages. Various papers have suggested methods to control the bus voltage with SVCs on the system. It has been shown in [3], [4] and [5] that the voltage profile of the power system can be improved with SVCs and STATCOMs. Coordination among the voltage compensating devices leads to better performance and improves stability in the system. Linear

control techniques use PI controllers which are tuned for nominal operating condition to achieve acceptable performances. The drawback of such PI controllers is that their performance degrades as the system operating conditions change. Thus, nonlinear controllers can provide good control capability over a wide range of operating conditions [6]. They can compensate for the dynamics of wind farms through adaptation of the controller parameters. Wind power is the most rapidly growing technology for renewable power generation [7]. It is being predicted that 12% of the total energy demand all over the world will come from wind power at the end of 2020 [8]. With this rapid growth of installed capacity of the wind farms, it is also necessary to transmit the generated power to the grid through the transmission networks. It is a well known fact that series compensation is an effective means of increasing power transfer capability of an existing transmission network. However, in case of series compensated networks supplied by steam turbine driven synchronous generators sub-synchronous resonance may become a potential problem [9-10]. FACTS can provide an effective solution to mitigate SSR [11]-[13]. SSR may comprise both torsional interactions and induction machine self excitation effect. Self excitation effect may arise when an Induction Generator employed in a wind farm is supplying power to the grid through a series connected transmission line [14]. Also, wind turbine generators exhibit natural mechanical oscillation modes for both tower structure and the turbine [14]. These torsional oscillations are caused by various mechanical masses mounted on the same shaft of the wind turbine such as gear train and turbine modes or sideways oscillations of the tower [15]. Wind turbine torsional systems had been modeled in detail in the past and mechanical oscillations due to those torsional masses were damped using pitch angle controller as well as power system stabilizer (PSS) [16].

The references discussed in regarding with the sub-synchronous resonance (SSR) problems in wind power system viewpoint [17]-[31], voltage stability of wind power systems viewpoint [32]-[126], power oscillation damping of wind power systems viewpoint [127]-[136], wind power transfer capability viewpoint [137]-[138], transient stability of wind power systems viewpoint [139]-[141], loadability of wind power system viewpoint [142]-[143], voltage security viewpoint [144], reduce active power and energy losses viewpoint [145]-[148], dynamic performance of wind power system viewpoint [149]-[150], mitigations of harmonics parameters of wind power systems viewpoints [151]-[157], reliability of wind power systems viewpoints [158]-[172], operations of flexibility of wind power systems viewpoints [173]-[224], operation of wind power systems viewpoints [225]-[252], control of wind power systems viewpoints [253]-[275], planning of wind power systems viewpoint [276]-[278], protection of wind power systems viewpoint [279]-[299], steady-state and dynamic stability by svc and STATCOM in wind power systems viewpoints [300]-[321], low-voltage-ride-through (LVRT) capability in wind power systems viewpoints [322]-[348], others parameters of wind power systems viewpoints [349]-[378].

This paper is organized as follows: Section II discusses the overview of facts controllers for an integrated wind

power farms technology. Section III presents the a survey on enhancement of performance parameters of wind power farms by facts controllers. Section IV presents the summary of the paper. Section V presents the results and discussions. Section VI presents the conclusions of the paper.

2. Overview Of Facts Controllers For An Integrated Wind Power Farms Technology

2.1. Background and Motivation in Wind Power

Over the last 30 years, wind power has emerged as the most promising renewable re-source for its rapid developments in disciplines such as aerodynamics, structural dynamics, mechanics as well as power electronics. In spite of the phenomenal growth and development in the last decades, the WT industry keeps moving forward in order to increase the efficiency and controllability of the wind turbines and to improve the integration to the power grid [1].

The present wind power share of the world's electricity generation is of 1.6%, but a bigger share up to 8.4% in 2019 was indicated by the forecasts and the predictions presented in [2]. The European Wind Energy Association scenario shows that over the next ten years, wind energy could meet one fifth of the EU's electricity demand in 2020, one third in 2030, and half by 2050 (Figure 2) [3].

Fig. 2. Expected increase in EU`s share of electricity provided by wind power

As a result of this scenario, high level of wind power (>30%) should be integrated into large inter-connected power systems and major issues can appear if the existing power systems are not properly redesign. Penetration levels in the electricity sector have already reached 21% in Denmark, 7% in Germany and about 12% in Spain. Achievements are even more impressive at the regional level. For example in the north German state of Schleswig-Holstein the installed wind capacity has over 2500 MW enough to meet 36% of the region's total electricity demand, while in Navarra, Spain, 70% of consumption is met by wind power [4]. The figure 3 show that the global wind power projections.
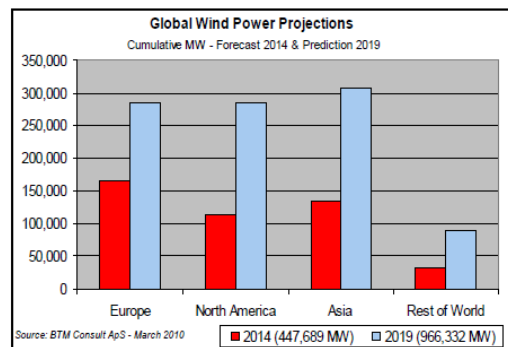

Fig. 3. Global wind power projections

From Figure 3 it can be observed that in future, many countries around the world are likely to experience similar penetration levels, as wind power is an interesting economic alternative in areas with appropriate wind speeds.

Today, modern energy industry faces a growing awareness regarding the impact of conventional power generation on the environment. An issue such as limited fossil fuel reserves, climate change due to CO2 emissions, brings to attention alternative technologies to generate electricity in a more sustainable manner [4]. As global energy demand is constantly rising, there is a great responsibility for society to develop the green technologies for reducing its impact on the environment. In the trend of diversifying the energy market, wind power is the most rapidly growing sector. After the oil crisis from three decades ago, wind power industry started to flourish. Since then wind turbine technology improved rapidly and it soon took the title of champion from all renewable sources of energy. According to Global Wind Energy Council more than 160 GW of installed capacity has been achieved by the end of 2009 around the world. Also a total power increase of 35% is accomplished in the year 2009 in the world. Thus a new record per annum of installed wind power capacity has been reached, summing up in 38 GW around the world. Europe accounts for 50% of the total amount of installed Wind Power around the world [5]. Figure 4 shows the continuously growing trend of wind power installations inside European Union. This reference scenario shows that with installations of up to 300 GW by the year 2030, EU will have a 21% to 28% wind market penetration [2].
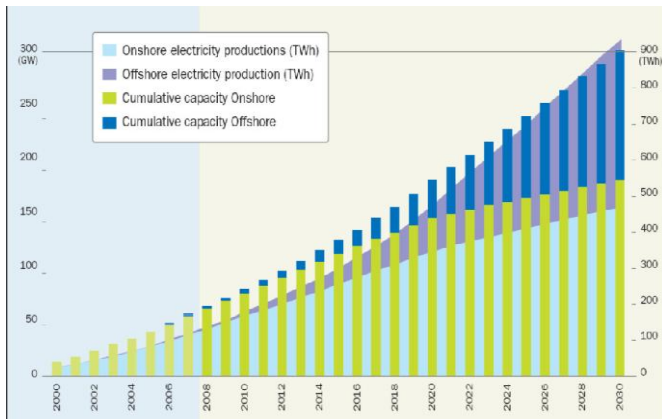

Fig. 4. EU Wind Power Forecast for 2030

Along with the increasing demands for wind power, the turbine technologies are improving and thus equipment costs are reducing. Because the wind industry is a well established powerhouse on the renewable market, its prices per kWh are comparable with prices of the conventional energy generations. Unlike gas, coal and oil resources which in future will become scarce, and for which the technologies became mature decades ago, the wind energy is abundant and new improvements on aerodynamics and power electronic devices are still to come. Therefore by 2030 electricity production from wind will inevitably become cheaper than any other source of energy, currently having a high market share [2]. There is a good correlation between wind turbines costs and their sizes. Unlike solar panels, which remain at the

same price regardless of array size, wind turbines become cheaper with increased system size. The practical explanation is that the power delivered by the wind turbine depends on the square of the rotor diameter.

Figure 5 shows the evolution of wind turbine size with respect to year of production. It is seen that in the last 20 years the rotor diameter has increased by a factor of 10. Today state-of-the-art wind turbines, with 126 m for rotor diameter, produce 5 to 6 MW of power (from RE Power and Enercon manufacturers [6]).
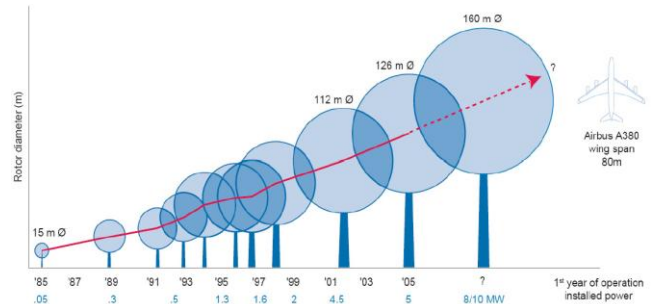

Fig. 5. Increase of wind turbine size over the years

In order to better control more and more wind power fed into the network, these MW range wind turbines are usually connected together either onshore or offshore to form a wind farm. However, including larger (hundreds of MW) wind farms into the grid, will rise the wind power penetration to a point at which it will have a significant impact on power system operation. Already some regulatory tasks needed for system stability, are being performed by wind power plants. With the ever increasing of wind power in the energy mix, Transmission System Operators (TSO) are forced to impose new requirements on the wind farms for the well-functioning of the power system network.

2.2. Wind Turbine Control Scheme

Basic Structure of the DFIG Wind Power Generation System:

The term 'doubly fed' refers to the fact that the voltage on the stator is applied from the grid and the voltage on the rotor is induced by the rotor-side converter. This system allows a variable-speed operation over a large, but restricted, range. The converter compensates the difference between the mechanical and electrical frequency by injecting a rotor current with a variable frequency. The behavior of the DFIG is controlled by the converter and its controller in both normal and fault condition operation. Figure 6 shows the basic structure of the DFIG wind power generation system. Back-to-back PWM converters consist of two converters, the stator-side converter and rotor-side converter, which are controlled independently of each other. The main idea is that the rotor-side converter controls the active and reactive power by controlling the rotor current components, while the stator-side converter controls the DC-link voltages and ensures a converter operation at unity power factor (zero reactive power). Depending on the operating condition of the rotor, the power is fed into or out of the rotor. In an over synchronous condition, power flows from the rotor via the

converter to the grid, whereas power flows in the opposite direction in a sub-synchronous condition. In both cases, the stator feeds power into the grid.
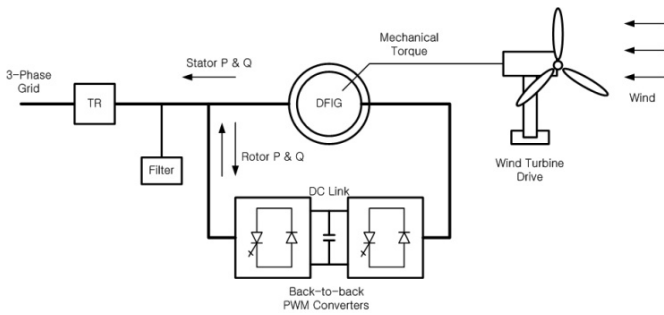

Fig.6. Structure of DFIG wind power generation system

The theoretical power generated by the WTG is expressed as:

$$P = \frac{1}{2} C_p \rho V^3 A$$

Where,

P: power [W]
Cp: power coefficient
ρ: air density (1.225 kg/m3)
V: wind velocity (m/sec)
A: swept area of rotor disc (m2)

The project deals with a variable speed, variable pitch FSPC WT. The main circuit and control block diagrams for the chosen WT topology, are presented in Figure 7. For variable speed operation, the WT uses a full scale back-to-back converter.
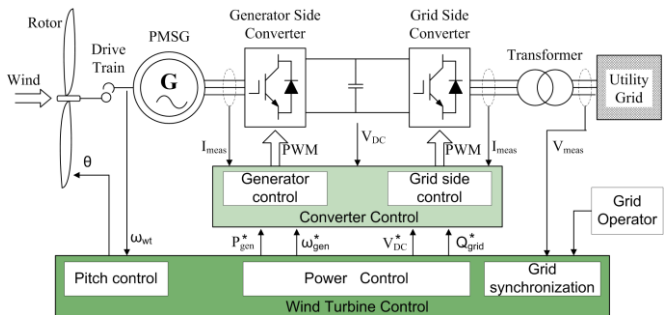

Fig. 7. Control scheme of WT

The generator side converter is controlling the speed of the generator for maximum power extraction. The grid side converter controls the voltage on the DC-link and also the reactive power flow between the WT and grid. Another control for the WT is the pitch control. It is applied to the rotor blades and modifies the angle of attack of the blades so that the output power can be controlled during high wind speeds.

2.3. Problem Statement

To ensure the stability of the system, regarding power quality and voltage level, all the grid codes demand that the Wind Power Plant (WPP) must be able to produce reactive power at the PCC. When dealing with WPP, adding the reactive power capability of each individual WT may not be sufficient to comply with the grid codes. This is due to the losses in connection cables and line losses between WPP and PCC. One solution is to use external reactive power compensation, for example installing STATCOM at the PCC. The main objective of this project is to develop a reliable control strategy for WPP and STATCOM and investigation of the impact of the connection cable length on reactive power losses during steady state.

2.4. Fundamentals of FACTS Controllers in an Integrated Wind Power Farms

In recent years, severe requirements have been placed on the transmission network, and these requirements will continue to increase because of the increasing number of non-conventional generator plants. Several factors such as increased demands on transmission and the need to provide open access to generating companies and customers have reduced the security of the system and the quality of supply. The cost of transmission lines and losses, as well as difficulties encountered in building new transmission lines, would often limit the available transmission capacity. These problems have necessitated a change in the traditional concepts and practices of power systems. There are emerging technologies available, which can help system operators to deal with above problems [28]. FACTS is one aspect of the power electronics revolution that happened in all areas of electric energy. These controllers provide a better adaptation to varying operational conditions and improve the usage of existing installations. FACTS controller is defined as a power electronic-based system that provide control of one or more AC transmission system parameters (series impedance, shunt impedance, current, voltage, phase angle).

The FACTS controllers are mainly used for the following applications:

- Power flow control,
- Increase of transmission capacity,
- Voltage control,
- Reactive power compensation,
- Stability improvement,
- Power quality improvement,
- Power conditioning,
- Flicker mitigation,
- Interconnection of renewable and distributed generation and storage

Using the advantages offered by the power electronic devices the FACTS controller provides a smoother operation and an increased lifetime of the system(less maintenance), compared to the conventional devices which are mechanical switched [28]. In general, FACTS controllers can be divided into four categories:

- Series FACTS Controllers
- Shunt FACTS Controllers
- Combined series-series FACTS Controllers
- Combined series-shunt FACTS Controllers

The basic limitations in power system transmission such as distance, stability, effective power flow and cable loading limits led to the investigation of power electronic devices into power systems and their impact on reactive power compensation. Thus FACTS devices were introduced as a solution for ameliorating the power system performance. Development of this technology was based on the same principle as in traditional power system controllers (i.e. phase shifting transformers, passive reactive compensation, synchronous condensers etc.)[7]. Growing capabilities of power electronic components resulted in creation of controllers with much faster response times, due to their lack of mechanical switch inertias. Lower transient over voltages are accomplished when using semiconductor devices, also a smooth, gradual change in var output is made, compared to the large discrete steps that arise from mechanically switching in capacitor and/or reactor banks. FACTS controllers using semiconductor devices are the fastest option for obtaining maximum system benefits. Also the usage of semiconductor switches instead of mechanical switches, led to an increased life-time of the system by less maintenance. The drawback of this technology is that it is more expensive than the traditional methods. As can be seen in Fig. 3.1 FACTS devices can be divided into two subgroups. Old generation was based in thyristor valve idea and the new generation focuses on using the voltage source converter. In both cases corresponding solutions provide similar services. The main difference between those two categories is that VSC technology is much faster and has a bigger range of control [8].

A more detailed classification of the FACTS controllers is presented in Figure 8.
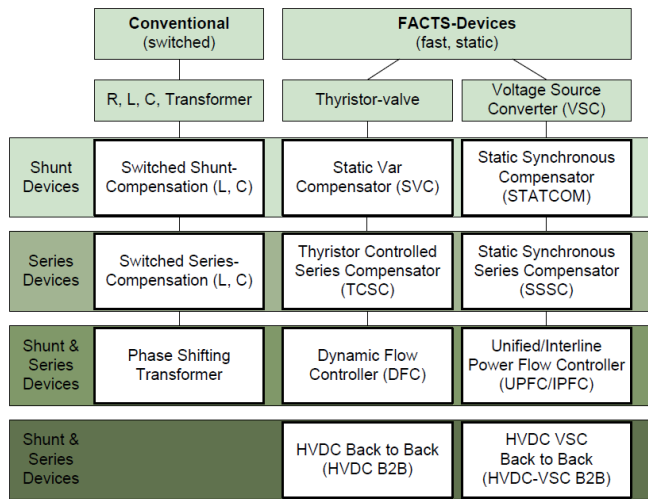

Fig. 8. Overview of major FACTS controllers

The first column in Figure 8 contains the conventional devices build out of fixed or me-chanically switchable components. From this figure it can be also observed that the FACTS controllers are divided in two categories. While the first category is represented by the old generation of controllers based on the well proven thyristor valve technology, the second category is represented by the new Voltage Source Converter technology based mainly on the Insulated Gate Bipolar Transistors (IGBT) [29]. For a WPP

one of the requirements imposed by the TSO, through the new grid codes, is the reactive power compensation at the PCC during normal or abnormal conditions operation. Since the purpose of the application is to control the voltage at and around the point of connection by injecting reactive current (leading or lagging), the Shunt devices proved to be the most suitable solution [28]. Eventually FACTS devices found applicability in the wind power industry. It was found that providing earlier WPP's with some external reactive compensation devices such as SVC or STATCOM, the grid compliance can be met, and thus the WPP's could remain connected to the power system without stability risks. Different way to categorize the FACTS controllers is to group them in a way that they are connected to the power system: shunt, series or shunt-series connection. This project focuses on FACTS device applicable for Wind Power (WP) technology. In the following section the shunt FACTS controllers used for Wind Turbines are presented.

a. Static Var Compensator(SVC)

SVC's being dated from early 70's, have the largest share among FACTS devices. They consist of conventional thyristors which have a faster control over the bus voltage and require more sophisticated controllers compared to the mechanical switched conventional devices. SVC's are shunt connected devices capable of generating or absorbing reactive power. By having a controlled output of capacitive or inductive current, they can maintain voltage stability at the connected bus. Figure 9 shows these configurations: the Thyristor Controlled Reactor (TCR), the Thyristor Switched Reactor (TSR) and the Thyristor Switched Capacitor (TSC) or a combination of all three in parallel configurations. The TCR uses firing angle control to continuously increase/decrease the inductive current whereas in the TSR the inductors connected are switched in and out stepwise, thus with no continuous control of firing angle. Usually SVC's are connected to the transmission lines, thus having high voltage ratings. Therefore the SVC systems have a modular design with more thyristor valves connected in series/ parallel for extended voltage level capability.
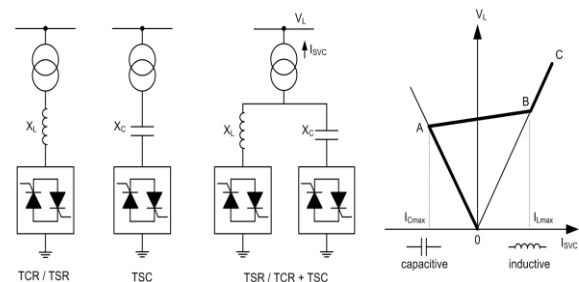

Fig. 9. Basic structures of Thyristor Controlled Reactor (TCR) and its characterizes

To provide the needed reactive power generation/consumption in the network SVC's adjust the conduction periods of each thyristor valve. For an SVC consisting of one TCR and one TSC, assuming that both reactor and capacitor have same pu. ratings then the following scenarios can occur:

- Reactive power is absorbed when the thyristor valve on the reactor leg is partially or fully conducting and the capacitor leg switch is off.
- Reactive power is generated when the thyristor valve on the reactor leg is in partial or no conduction mode and the capacitor leg switch is on.
- No reactive power is generated/absorbed if both the thyristor valve is not conducting and the capacitor switch is off.

The voltage-current (V-I) characteristic of an SVC with the two operating zones is shown in Figure 3.2. A slope around the nominal voltage is also indicated on the V-I characteristic, showing a voltage deviation during normal operation, which can be balanced with maximum capacitive or inductive currents. As the bus voltage drops, so does the current injection capability. This linear dependence is a significant drawback in case of grid faults, when large amount of capacitive current is needed to bring back the bus nominal voltage. The technology of SVC with thyristor valves is becoming outdated mainly due to the slow time responses, of injected current dependence on bus voltage and low dynamic performance. Their replacements are called Static Synchronous Compensator's (STATCOM) and will be discussed in the following section.

b. Static Synchronous Compensation(STATCOM)

Another way to enhance a Wind Power Plant with ability to deliver or absorb reactive power from the grid is to use Static Synchronous Compensation. STATCOM can be treated as a solid state synchronous condenser connected in shunt with the AC system. The output current of this controller is adjusted to control either the nodal voltage magnitude or reactive power injected at the bus. STATCOM is a new breed of reactive power compensators based on VSC. It has a characteristic similar to a synchronous condenser, but because it is an electrical device it has no inertia and it is superior to the synchronous condenser in several ways. Lower investment cost, lower operating and maintenance costs and better dynamics are big advantages of this technology [8].

STATCOM consists of one VSC with a capacitor on a DC side of the converter and one shunt connected transformer. Voltage Source Converter is usually built with Thyristors with turn-off capability like Gate Turn-Off (GTO) or today Integrated Gate Commutated Thyristors (IGCT) or with Insulated Gate Bipolar Transistors (IGBT) based converter. Configuration of the STATCOM circuit is presented on Fig. 10.
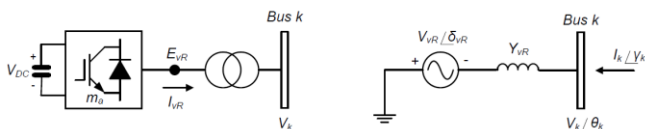

Fig. 10. STATCOM scheme with equivalent circuit representation.

As it was mentioned before STATCOM can be treated as a synchronous voltage source, because its output voltage can be controlled as desired (Fig. 3.3). Assuming that no active power is exchanged between STATCOM and the grid

(lossless operation) the voltage of the controller is in phase with the grid voltage. If the compensator voltage magnitude is smaller than the voltage at the connection node current will flow from the grid to STATCOM. In this case the reactive power will be consumed. If the situation is opposite the reactive power will be delivered to the grid. Schematic representation of this principle is presented using phasor diagrams on Fig. 11.
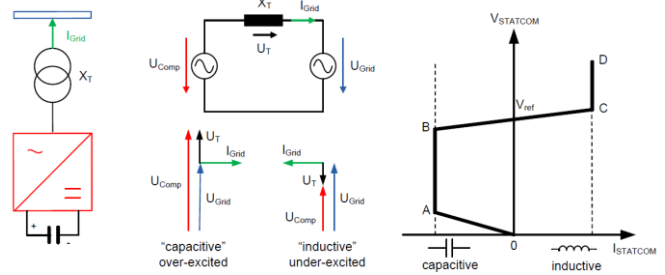

Fig. 11. Schematic representation of working principle of STATCOM

Figure 12 show that the comparison between SVC and STATCOM

Fig. 12. Comparison between SVC and STATCOM

	SVC		STATCOM
	TCR	TSR (+TCR)	
Compensation Accuracy	Very Good	Good (very good with TCR)	Excellent
Control Flexibility	Very Good	Good (very good with TCR)	Excellent
Reactive Power Capability	Lagging/Leading indirect	Leading/Lagging indirect	Leading/Lagging
Control	Continuous	Discontinuous (cont. with TCR)	Continuous
Response Time	Fast, 0.5 to 2 cycles	Fast, 0.5 to 2 cycles	Very Fast
Harmonics	Very high (large size filters are needed)	Good (filters are necessary with TCR)	Good, but depends on switching pattern
Losses	Good, but increase in lagging mode	Good, but increase in leading mode	Very good, but increase with switching frequency
Phase Balancing Ability	Good	Limited	Very good with 1-f units, limited with 3-f units
Cost	Moderate	Moderate	Low to moderate

A STATCOM injecting reactive current is supporting the grid voltage. Comparably when STATCOM is absorbing reactive current it is decreasing the grid voltage. In the first case controller behaves as an overexcited generator or capacitor and in the second case STATCOM behaves as an under excited generator or inductor. According to [8] the power flow constraints of STATCOM are:

Control modes:

The control of reactive power flow provided by STATCOM can be realized in one of the following control modes.

Reactive power:

This type of control strategy focuses on reactive power injection to the local bus, to which the STATCOM is connected, according to a reference from the wind park controller.

Voltages droop characteristic:

In this type of operation STATCOM works in a way to fulfill a voltage/reactive power slope characteristics. This is done by setting a target voltage accepted from wind park controller at the PCC.

Power factor:

The following table summarizes the main characteristics of the most important shunt Var compensators. The significant improvements observed in the STATCOM devices, makes them a first choice for improving the performances in AC power systems.

2.5. Reactive Power Distribution Algorithm With And With STATCOM

Having the ability for providing the reactive power by WPP is not always enough. For WPP with long connection cables the line losses can significantly influence the availability of reactive power at PCC. One of the possible solutions is to use STATCOM at the PCC. The challenge lies in building a good communication and distribution algorithm, for both WPP and STATCOM. This section proposes a simple solution. Figure 13 presents the idea:
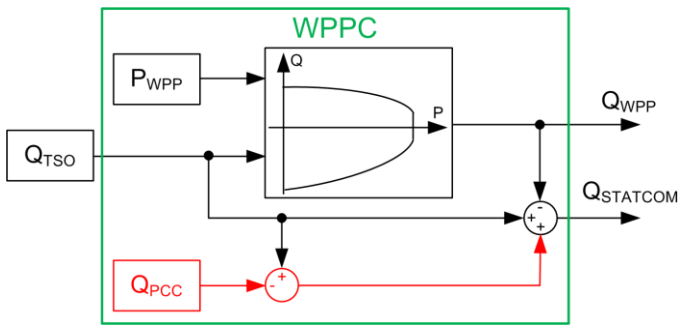

Fig. 13. Simple reactive power distribution algorithm for WPP with STATCOM.

The algorithm works as follows: first the Wind Power Plan Controller (WPPC) gets the reactive power reference signal from TSO. Then depending on the produced active power WPPC gets the available reactive power from WPP. If the TSO requirement is not fulfilled a reactive power reference signal is send to STATCOM controller. This signal is built as a difference between the required reactive power at PCC and reactive power produced by WPP. In case of having a connection line between the WPP and the PCC additional reference signal component for STATCOM is defined. This

signal is built as a difference between required reactive power at PCC and actual measured reactive power at PCC.

2.6. Technical and Economic Analysis Assumptions

As presented above, reactive power devices can be characterized as dynamic or static depending on their location and functionality. Static reactive power supply is most commonly found in the WF PCC and it is provided by capacitors, load tap changers on transformers, and reactors. In the following analysis only capacitor banks were considered while load tap changers for transformers are proposed as one of the objectives for the further work. However, static reactive power supply cannot respond to load changes rapidly. Therefore due to this primary disadvantage of static reactive reserves, the interest for the dynamic reactive reserves increased rapidly in the past years [30]. Moreover, in this project the following devices were considered for dynamic reactive power capability:

- Pure Reactive Power Compensator (STATCOM) in the WF PCC
- Oversized WTs Grid Side Converter

An inverter that is connected with a distributed energy device such as a WT can provide dynamic control of real and reactive power. Although conventionally the range of the reactive power supply from such devices is limited, it is possible to upgrade the inverters to supply reactive power in a much larger range. Over sizing of the inverter will significantly increase the range of reactive power supply but the main disadvantage is that cost increases as the reactive power ability is increased. It can be concluded that the optimal allocation of reactive power capability for a given WF will be defined by 3 devices:

- WTs grid side converter
- STATCOM
- Capacitor banks in PCC

Since the economical scope of this analysis is to minimize the capital costs for the above devices the range of prices per kVAr where considered based on Figure 14 and [31-32].
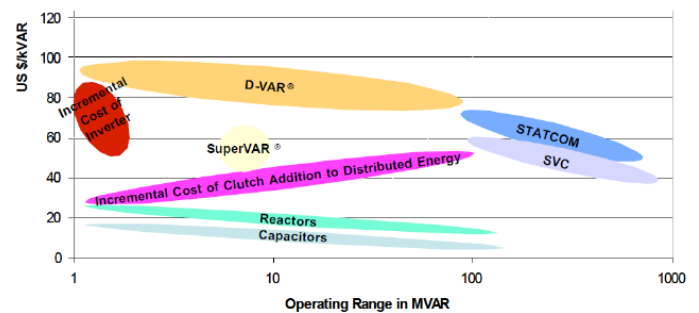

Fig. 14. Average Costs of Reactive Power Technologies

Moreover two types of study cases are presented. While for the first study case, the fulfillment ratio (FFR) of the WF based on TSO Q requests is less than 100%, for the second study case the optimal Q ratings for the WF compensators will always be capable of fulfilling all TSO request.

3. A Survey On Enhancement of Performance Parameters Of Wind Power Farms By Facts Controllers

3.1. Sub-synchronous Resonance (SSR) Problems in Wind Power System Viewpoint:

Hence with the rapid growth of installed capacity of wind farms, the large wind turbine generators (WTGs) are integrated into electric power grids. The generated power by this way should be transmitted through the transmission system that can sustain large power flow. For an existing transmission network, the series compensation is known as an effective mean of increasing the total and available transfer capability (TTC and ATC) [17]. However, in such compensated networks, a serious destructive phenomenon referred to as sub-synchronous resonance (SSR) might appear which could be a potential origin for the turbine-generator shaft failure and instability of the power system [18]-[19]. SSR could comprise either torsional interactions (TI) or induction generator (IG) effect [20]. A radial connected wind farm operating on the end of a series compensated transmission line is highly susceptible to the SSR which is generated due to the induction generator effect [21]. It is widely accepted that flexible ac transmission systems (FACTS) can provide an effective solution to relieve the SSR [22]-[29]. Quite few papers attempted the application of various FACTS devices to attenuate SSR in series compensated wind farm connections. In [26], [27], and [30], SSR mitigation in a series compensated wind farm was examined utilizing SVC as well as TCSC. Reference [31] has proposed a novel STATCOM controller for mitigating SSR. The main concentration of this reference is to design a novel controller and examine its performance. Hence, a detailed review and study on STATCOM performance in alleviating SSR is still essential in order to provide a comprehensive understanding of the issue. The growing penetration of produced wind power (size growth of wind farms) forced the TSO and DSO to develop more strict and detailed grid codes for wind turbines. The new grid codes specify new requirements for WPP regarding such issues as frequency control, voltage control and fault ride-through behavior. This thesis deals with reactive power compensation, which in practice influences the voltage control. Besides its main role, which is voltage regulation, STATCOM applications include the following:

- stabilization of weak system voltage
- reduced transmission losses
- enhance transmission capacity
- power oscillation damping
- improve power factor
- reduce harmonics
- flicker mitigation
- assist voltage after grid faults

3.2. Voltage Stability of Wind Power Systems Viewpoint:

In [32], the swing equations for renewable generators are formulated as a natural Hamiltonian system with externally applied non-conservative forces. A two-step process referred to as Hamiltonian Surface Shaping and Power Flow Control (HSSPFC) is used to analyze and design feedback controllers for the renewable generator system. This formulation extends previous results on the analytical verification of the Potential Energy Boundary Surface (PEBS) method to nonlinear control analysis and design and justifies the decomposition of the system into conservative and non conservative systems to enable a two-step, serial analysis and design procedure. In particular, this approach extends the work done by developing a formulation which applies to a larger set of Hamiltonian Systems that has Nearly Hamiltonian Systems as a subset. The results of this research include the determination of the required performance of a proposed Flexible AC Transmission System (FACTS)/storage device to enable the maximum power output of a wind turbine while meeting the power system constraints on frequency and phase.

In [33], like conventional power plants, wind power plants must provide the power quality required to ensure the stability & reliability of the power system. Increasing amount of wind turbine are connected to electrical power system in order to mitigate the negative environmental consequence of conventional electricity generation. While connecting wind turbine to grid it is important to understand source of disturbance that affect the power quality. In general voltage & frequency must be kept as stable as possible. This stability can be obtained by using FACTS devices. Recently voltage-source or current-source inverter based various FACTS devices have been used for flexible power flow control, secure loading and damping of power system oscillation. Some of those are used also to improve transient & dynamic stability of wind power generation system (WPGS). In this paper, we propose the STATCOM based on voltage source converter (VSC) PWM technique to stabilize grid connected squirrel cage wind generator system. In [34], voltage control and reactive power compensation in a distribution network with embedded wind energy conversion system (WECS) represented in this literature. The WECS is of a fixed speed constant frequency type that is equipped with an induction generator driven by an unregulated wind turbine. The problem is viewed from short term (10 seconds) and mid-term (10 minutes) time domain responses of the system to different wind speed changes. Being disturbed by a variable wind speed, the WECS injects variable active and reactive power into the distribution network exposing nearby consumers to excessive voltage changes. In the FACTS based solution approach, the UPFC is used at the point of the WECS network connection to help solve technical issues related to voltage support and series reactive power flow control. Further on, continuous voltage control and reactive power compensation at the point of the WECS network connection is provided by using FACTS-based device. Among FACTS devices, the UPFC is chosen due to its versatile regulating capabilities [35]. The UPFC consists of shunt and series branches, which could be interchangeably used. Being located at the point of the WECS connection to the distribution network, it is made possible to simultaneously control the WECS bus voltage magnitude and/or series reactive power flow that WECS exchanges with the network. Wind energy is a promising renewable energy

source. In particular in Europe the installed capacity is growing at a considerable rate, approximately 20% annual growth rate for the past five years [36]. Today, the focus regarding the interaction between the electric network and wind energy installation has been shifted, since the loss of such a considerable part of the power production (as wind energy constitute in some regions) due to network disturbances cannot be accepted any more [37]. Accordingly the important issue is to avoid a disconnection of a wind energy installation during a network disturbance. Moreover, it is of course also of great importance to be familiar with how a wind energy installation reacts to network disturbances. Induction generator (IG) is widely used as wind generator due to its simple, rugged and maintenance free construction. But as it has some stability problem, it is necessary to investigate the stability aspect of induction generator while connected to the power grid [38]. The voltage recovery after the network disturbance can be assisted by dynamic slip control and pitch control in a wound rotor induction generator based WPP [39]. Recently voltage-source or current-source inverters based FACTS devices such as static var compensator (SVC), static reactive compensator (STATCOM), dynamic voltage restorer (DVR), solid state transfer switch (SSTS) and UPFC have been used for flexible power flow control, secure loading and damping of power system oscillation [40].

Some of those are used also to improve transient and dynamic stability of wind power generation system. SVC is reported to improve the terminal voltage of induction generator by compensating the reactive power [41]. But STATCOM has somewhat better performance compared to SVC for reactive power compensation, which is reported clearly in [42]. it is reported that STATCOM can recover terminal voltage of wound rotor induction generator after the fault clearance. But as only induction generator is connected to the network, the Effect of STATCOM on the rest of the system is not presented there clearly. Due to clean and economical energy generation, a huge number of wind farms are going to be connected with the existing network in the near future. Induction generator (IG) is widely used as wind generator due to its simple, rugged and maintenance free construction. But as it has some stability problems [43], it is necessary to investigate the stability aspect of induction generator when connected to the power grid. Since a few years ago, voltage-source or current-source inverter based FACTS devices have been being used to improve transient and dynamic stabilities of wind generator. Some authors have reported valuable studies on STATCOM connected with wind turbine generator system (WTGS) [44]-[48]. In [44], steady state reactive power control and islanding performance of induction generator are discussed. Flicker mitigation of wind generator by using STATCOM is discussed in [45]. Though a lot of works with STATCOM have been reported so far, stability enhancement of WTGS by using STATCOM is not sufficient enough. In [46], it is reported that STATCOM can recover terminal voltage of wound rotor induction generator after a fault clearance. But as only induction generator is considered in the model network, the effect of STATCOM on the rest of the system is not clarified there. In our previous work [47], stability of

fixed speed WTGS connected to a grid was discussed with considering a two-level VSC based STATCOM. But in high voltage applications, three-level inverter is better for VSC based STATCOM. Therefore, in [48], we considered three-level STATCOM based on PWM technique to enhance the stability of wind generator in the simple model system with a synchronous generator and infinite bus. A three-level PWM based STATCOM is connected with each wind farm terminal. Fuzzy logic controller (FLC) is used as the control methodology of the STATCOM. Since shaft system modeling has significant effect on the transient stability of WTGS [49]-[50], two-mass shaft model is adopted in this study. The capacitor bank capacity of wind generator is reduced by 15 percentages when STATCOM is installed at wind farm. As wind speed is intermittent and stochastic in nature, the terminal voltage of wind generator fluctuates randomly, which has an adverse effect on the rest of the power system. In this study, it is reported that the STATCOM with reduced capacitor bank can decrease the voltage fluctuations of multi-machine power system as well as wind generator terminals. Moreover, it is shown that the STATCOM can also enhance the transient stability of induction and synchronous generators when a network disturbance occurs in the power system. In [48], only the symmetrical fault is considered. In this study, both of the symmetrical and the unsymmetrical faults are considered. A wind farm including multiple wind generators is also considered in this study for the sake of precise analysis, which is not considered in [48]. In [51], has been presented a state of art on voltage and frequency controllers (VFCs) for isolated asynchronous generators (IAGs) for standalone wind energy conversion systems. In wind turbine-driven IAG, magnitude and frequency of the generated voltage vary because of varying consumer loads and wide fluctuation in wind speeds. Therefore, new types of VF controllers based on a voltage source converter along with a battery energy storage system are proposed to maintain the voltage and frequency of IAG constant at varying wind speeds and varying consumer loads. STATCOMs serve the same purpose as the Static Var Compensators but their response to the faults is faster as compared to its thyristor based counterparts. STATCOM may have a power supply of their own and hence help in controlling the sudden voltage outbursts during the islanding situations. STATCOMs find application in flicker mitigation at the point of common coupling (PCC) during continuous operation and providing reactive power support to the Wind Energy Conversion Systems (WECS) [52]-[61]. STATCOM is a relatively new technology as compared to and being expensive is not being used extensively but STATCOMs have been brought into operation at few sites. UPFC is an upcoming device in FACTS technology. It hasn't been used in wind farm technology but a few proposals [62]-[64] showing them as replacements for SVC and TCSC have come up. Fuzzy Logic Control for UPFC employed in wind farm applications has been discussed by A. Papantonniou [65]. Part of the reactive power requirement is supplied by Fixed Capacitors (FC) connected at the terminals of each turbine. As most of the wind turbines operate from remote areas, therefore, effect of real power and reactive power flow on the voltage quality is prominent. A SVC is installed to provide dynamic reactive

power support required [66]-[83]. To initiate the proper operation of the SVC various mathematical models for control have been developed. Studies have been performed addressing the steady state and transient state problems on a number of simulation platforms. Regarding wind power conversion units, several studies have investigated the impact on power system oscillations of wind power plants (WPP) based on primarily the fixed speed induction generator (FSIG) and the doubly-fed induction generator (DFIG) [84]-[87]. With expanding penetration of wind power it must be expected that power plants based on synchronous generators at some point start being displaced.

This is to be expected due to multiple reasons; it is first of all important to keep the power balance in the system, and secondly, it may be economically and energy inefficient to keep a large number of partially loaded synchronous generators on-line. Synchronous machines equipped with power system stabilizers (PSS) are today the most cost-effective method of improving the small signal stability [88]. Besides synchronous generators equipped with PSSs, also FACTS devices, e.g. SVCs or STATCOMs [89]-[91], and HVDC stations [92], [93] are used to deliver the required damping torque. Variable-speed WTs interfaced to the grid with voltage source converters offer decoupled control of active and reactive power [94], and these control capabilities are used for active, e.g. [95], [96], and reactive power control, e.g. [96], [97]. In [98]-[101] it has been proposed to actively damp selected system modes using variable speed WTs, and in [102], [103] robust controller tuning is presented for a WPP power oscillation damping controller (POD). In [104], the STATCOM application for efficient operations of wind farm is described. The wind farm connected with the electric power network is one of good alternative energy sources. However, it would be also highly possible that interconnection of wind farm causes unwanted influences on distribution system operation, protection and control. This paper proposes the STATCOM application for reducing the negative effects from interconnection of wind farm with distribution networks. The simulation results show that STATCOM would be and effective and useful device to resolve the bad influences from wind farm on distribution networks and improve the operational efficiency of wind farm. In [105], the wind power is known as the most promising future energy source to obtain the electricity. Induction generator is a simple energy conversion unit in the wind power generation system but it consumes the reactive power from the interconnected power system. Switched capacitor banks are normally used to compensate the reactive power, which bring about the transient overvoltage. This paper proposes a method for compensating the reactive power with STATCOM. A detail simulation model for analyzing the interaction between the wind power system and the commercial power system was developed using EMTDC software. The developed simulation model can be effectively utilized to plan the reactive power compensation for newly designed wind power system. Shunt Flexible AC Transmission System (FACTS) devices, when placed at the mid-point of a long transmission line, play an important role in controlling the reactive power flow to the power network and hence both the system voltage fluctuations and transient

stability. This paper deals with the location of a shunt FACTS device to improve transient stability in a long transmission line with predefined direction of real power flow. The validity of the mid-point location of shunt FACTS devices is verified, with different shunt FACTS devices, namely SVC and STATCOM in a long transmission line using the actual line model. It has been observed that the FACTS devices, when placed slightly off-centre towards sending-end, give better performance in improving transient stability and the location depends on the amount of local/through load [106]. Operation of wind turbines has an impact on the power quality and reliability at the connected electric network. Power quality problems such as voltage flicker and harmonic distortion along with reliability issues are some major concern and in this work the flicker & harmonics issues are considered. Wind turbine connected to an induction generator and synchronous generator is modeled using PSCAD to analyze power quality and reliability problems. STATCOM unit is developed to inject reactive power to mitigate power quality problems and to get stable grid operation. Due to continuously varying wind speed components, the active and reactive power along with terminal voltage fluctuates continuously. By connecting STATCOM into the grid, the active power, reactive power and terminal voltage is maintained constant. The wind electric generators have power electronic converters which are used to sweep maximum power at the available speed and for efficient control introduce harmonics [107]. The most commonly used device for flicker mitigation is the SVC. However, the STATCOM has received much more attention recently. Compared with the SVC, the STATCOM has many advantages, such as overall superior functional characteristics, better performance, faster response, smaller size, cost reduction, and capable of providing both active and reactive power [108]-[110]. The STATCOM, consisting of a voltage source converter, uses advanced power switches to provide fast response and flexible voltage control for power quality improvement, which is suitable to application with rapidly fluctuating loads. Using high frequency PWM, the converter will create smooth current with low harmonic content. Reference [111], discussed the application of FACTS controller called Static Synchronous Compensator STATCOM to improve the performance of power grid with Wind Farms is investigated .The essential feature of the STATCOM is that it has the ability to absorb or inject fastly the reactive power with power grid. Therefore the voltage regulation of the power grid with STATCOM FACTS device is achieved. Moreover restoring the stability of the power system having wind farm after occurring severe disturbance such as faults or wind farm mechanical power variation is obtained with STATCOM controller. The dynamic model of the power system having wind farm controlled by proposed STATCOM is developed. Flexible AC transmission system a FACTS device such as Static Synchronous Compensator STATCOM to improve the stability in wind farm is studied [112]. They are able to provide rapid active and reactive power compensations to power systems, and therefore can be used to provide voltage support and power flow control, increase transient stability and improve power oscillation damping. Suitably located FACTS devices allow more efficient utilization of existing transmission networks.

Among the FACTS family, the shunt FACTS devices such as the STATCOM has been widely used to provide smooth and rapid steady state and transient voltage control at points in the network. This issue is even more critical in the case of micro-girds, since certain FACTS controllers, particularly STATCOMs, are being considered as a possible solution for some of the voltage and angle stability problems inherent to these power grids. Consequently, typical STATCOM models are validated here using system identification techniques to extract the relevant electromechanical mode information from time-domain signals [113]-[115]. System identification techniques are used to readily and directly compare fairly distinct STATCOM models, thus avoiding matrix based eigen-value studies of complex system models and/or modeling approximations. In [116], wind energy has been developed significantly over last decade and has been noted as the most rapidly growing technology and most cost-effective ways to generate electricity from renewable sources. On the other hand, the voltage of wind turbine driven generator is variable due to intermittent nature of wind energy. Therefore, the integration of large wind scheme can pose inherent security problems such as voltage fluctuations and power quality. Voltage control, power quality and reactive power compensation in a distribution network with embedded wind energy conversion system represent the main goal of this literature. Reference [117], grid connected Fixed Speed Wind Turbines (FSWT) may cause voltage stability problems which results in islanding of the generator from the grid. Voltage stability is a major issue to achieve the uninterrupted operation of wind farms equipped with FSWTs. In this literature the design of a STATCOM based on Cascaded H-Bridge (CHB)-Multi Level Converter (MLC) has been proposed. The wind power penetration has increased dramatically in the past few years, hence it has become necessary to address problems associated with maintaining a stable electric power system that contains different sources of energy including hydro, thermal, coal, nuclear, wind, and solar. In the past, the total installed wind power capacity was a small fraction of the power system and continuous connection of the wind farm to the grid was not a major concern. With an increasing share derived from wind power sources, continuous connection of wind farms to the system has played an increasing role in enabling uninterrupted power supply to the load, even in the case of minor disturbances. The wind farm capacity is being continuously increased through the installation of more and larger wind turbines. Voltage stability and an efficient fault ride through capability are the basic requirements for higher penetration. Wind turbines have to be able to continue uninterrupted operation under transient voltage conditions to be in accordance with the grid codes [118]. Grid codes are certain standards set by regulating agencies. Wind power systems should meet these requirements for interconnection to the grid. Different grid code standards are established by different regulating bodies, but Nordic grid codes are becoming increasingly popular [119]. One of the major issues concerning a wind farm interconnection to a power grid concerns its dynamic stability on the power system [120]. Voltage instability problems occur in a power system that is not able to meet the reactive power demand during faults and heavy loading conditions. Stand alone systems are

easier to model, analyze, and control than large power systems in simulation studies. A wind farm is usually spread over a wide area and has many wind generators, which produce different amounts of power as they are exposed to different wind patterns.

FACTS such as the STATCOM and the UPFC are being used extensively in power systems because of their ability to provide flexible power flow control [121]. The main motivation for choosing STATCOM in wind farms is its ability to provide busbar system voltage support either by supplying and/or absorbing reactive power into the system. The applicability of a STATCOM in wind farms has been investigated and the results from early studies indicate that it is able to supply reactive power requirements of the wind farm under various operating conditions, thereby improving the steady-state stability limit of the network [122]. Transient and short-term generator stability conditions can also be improved when a STATCOM has been introduced into the system as an active voltage/var supporter [121]-[123]. Voltage stability is a key issue to achieve the uninterrupted operation of wind farms equipped with doubly fed induction generators (DFIGs) during grid faults. This literature investigated the application of a STATCOM to assist with the uninterrupted operation of a wind turbine driving a DFIG, which is connected to a power network, during grid faults. The control schemes of the DFIG rotor- and grid-side converters and the STATCOM are suitably designed and coordinated. The system is implemented in real-time on a Real Time Digital Simulator. Results show that the STATCOM improves the transient voltage stability and therefore helps the wind turbine generator system to remain in service during grid faults [124]. Further on, continuous voltage control and reactive power compensation at the point of the WECS network connection is provided by using FACTS-based device. Among FACTS devices, the UPFC is chosen due to its versatile regulating capabilities [125]. The UPFC consists of shunt and series branches, which could be interchangeably used. Being located at the point of the WECS connection to the distribution network, it is made possible to simultaneously control the WECS bus voltage magnitude and/or series reactive power flow that WECS exchanges with the network. This countermeasure is expected to contribute in making assessed wind site viable for connecting larger number of wind turbines. Reference [126], has been presented an approach for enhancement of voltage stability of an interconnected power system employing distributed generators (DG) along with conventional generators. When the DG is from wind then voltage instability in the system is of great concern. In this paper a 28 bus test system is considered where the wind penetration varies from 10% to 99% over the day. This causes a large variation at different bus voltages violating the grid code. A shunt FACT device (SVC) is used to mitigate this problem at the buses connected to wind generators. Thereafter, suitable locations for the SVC placement are identified to enhance the voltage stability and reduce system power loss.

3.3. Power Oscillation Damping of Wind Power Systems Viewpoint:

In [127], damping of low frequency power oscillations is one of essential aspects of maintaining power system stability. In literature can be found publications on damping capability of Doubly Fed Induction Generator based wind turbines. Grid codes do not specify requirements for power oscillation damping. However, this is one of the existing problems in power systems. In [128] it is shown that additional control loop for STATCOM controller can help to damp power oscillations, while basic voltage support function is maintained. In [128] optimized neural network controller attenuates local plant oscillations of DFIG based wind farm, during post fault period. In similar way, i.e. by means of STATCOM control, the same problem is addressed in [128]. Additional control loop is added to voltage controller, to emulate rotor friction and consequently provide damping torque. The damping loops are based on integrated time absolute error of rotor speed and active power. Reference [128] states that with such arrangement output power oscillation are quickly damped after 3-phase fault. The same controller allows to damp torsional oscillations of DIFG turbine drive train, modeled as two-mass system [128]. Wind farms have not been considered yet in literature, to play specific role in the intra-area or inter-area oscillations. On other hand FACTS devices are widely recognized as one of solutions for this problem, so such studies could be performed.

Abdel magid et al., [129], the dynamic stability of a single wind turbine generator supplying an infinite bus through a transmission line was studied by developing the linearized model of the power system under different loading conditions. Clemens Jauch et al., [130], the effect of wind turbines on the transient fault behavior of the Nordic power system was investigated for different faults. Mohamed S.Elmoursi et al.,[131], a novel error driven dynamic controller for the STATCOM. FACTS device was designed to stabilize both a stand-alone wind energy conversion system as well as a hybrid system of wind turbine with Hydro Generators. Olof Samuelsson and Sture Lindahl, et al. 2005 [132], a new definition on rotor speed stability of asynchronous generators is proposed. Istvan Erlich et al. [133], a control structure for DFIG based turbines under unbalanced conditions is proposed. Varma R.K. and Tejbir S.Sidhu et al. [134], the application of VSC based transmission controllers for Wind energy conversion systems is discussed. Vladislav Akhmatov et al. [135], the dynamic behavior of the power system is analyzed with high wind power penetration is analyzed. N.Senthil Kumar and M.Abdullah Khan et al. [136], the impact of FACTS controllers on the rotor speed /rotor angle stability of power systems connected with wind farms is discussed.

3.4. Wind Power Transfer Capability Viewpoint:

This literature presented a voltage and frequency controller (VFC) for a 4-wire stand-alone wind energy conversion system (WECS) employing an asynchronous generator. The proposed VF controller consists of a three leg IGBT (Insulated Gate Bipolar Junction Transistor) based voltage source converter and a battery at its DC bus. The neutral terminal for the consumer loads is created using a T connected transformer, which consists of only two single phase transformers. The control algorithm of the VF controller is developed for the bidirectional flow capability of the active power and reactive power control by which it controls the WECS voltage and frequency under different dynamic conditions, such as varying consumer loads and varying wind speeds. The WECS is modeled and simulated in MATLAB using Simulink and PSB toolboxes. Extensive results are presented to demonstrate the capability of the VF controller as a harmonic eliminator, a load balancer, a neutral current compensator as well as a voltage and frequency controller [137]. The importance of renewable energy sources has been growing at a high rate as a result of being environment friendly. In particular, wind power is one of the most successfully utilized of such sources to produce electrical energy. Because of the randomness of wind speed, the reliability impact on this highly variable energy power is important aspect that needs to be assessed. In this paper, the impact on the reliability indices of wind speed correlation between two farms is considered [138].

3.5. Transient Stability of Wind Power Systems Viewpoint:

This paper presents a study of a DFIG wind power generation system for real-time simulations. For real-time simulations, the Real-Time Digital Simulator (RTDS) and its user friendly interface simulation software RSCAD are used. A 2.2MW grid-connected variable speed DFIG wind power generation system is modeled and analyzed in this study. The stator-flux oriented vector control scheme is applied to the stator/rotor side converter control, and the back-to-back PWM converters are implemented for the decoupled control [139]. This literature proposed a new doubly-fed induction generator (DFIG) system using a matrix converter controlled by direct duty ratio pulse-width modulation (DDPWM) scheme. DDPWM is a recently proposed carrier based modulation strategy for matrix converters which employs a triangular carrier and voltage references in a voltage source inverter. By using DDPWM, the matrix converter can directly and effectively generate rotor voltages following the voltage references within the closed control loop. The operation of the proposed DFIG system was verified through computer simulation and experimental works with a hardware simulator of a wind power turbine, which was built using a motor-generator set with vector drive. The simulation and experimental results confirm that a matrix converter with a DDPWM modulation scheme can be effectively applied for a DFIG wind power system [140]. Cost effective simulation schemes for Wind Power Generation Systems (WPGS) considering wind turbine types, generators and load capacities have been strongly investigated by researchers. As an alternative, a true weather conditions based simulation using real time digital simulators (RTDS) is experimented in this literature for the online real time simulation of the WPGS [141].

3.6. Loadability of Wind Power System Viewpoint:

Reference [142], has been presented an approach for enhancement of voltage stability of an interconnected power system employing distributed generators (DG) along with conventional generators. When the DG is from wind then voltage instability in the system is of great concern. In this paper a 28 bus test system is considered where the wind penetration varies from 10% to 99% over the day. This causes a large variation at different bus voltages violating the grid code. A shunt FACT device such as SVC is used to mitigate this problem at the buses connected to wind generators. Thereafter, suitable locations for the SVC placement are identified to enhance the voltage stability and reduce system power loss. In [143], the wind power industry has expanded greatly during the past few years, has served a growing market, and has spawned the development of larger wind turbines.

3.7. Voltage Security Viewpoint:

This literature presented a novel voltage stabilization and power quality enhancement scheme using a PWM switched modulated power filter compensator (MPFC), which is controlled by a dynamic tri-loop (voltage, current and dynamic power signals at the load bus).The error driven tri-loop controller is used to stabilize a standalone wind driven induction generator scheme. Full voltage stabilization and power quality enhancement is validated under electric load excursions [144].

3.8. Reduce Active power and Energy Losses Viewpoint:

The wind turbine is in several ways a unique power generating system because power train components are subject to highly irregular loading from turbulent wind conditions. The number of fatigue cycles experienced by major structural components can be far greater than that found for other rotating machines [145]. A wind turbines extreme conditions and high loads make coordination of maintenance an interesting issue. How much maintenance is needed? Are there any ways to minimize maintenance and yet have wind turbines ready to harvest power? These wind power plant issues are discussed today in research and development, and in operations and maintenance. The technical availability of wind turbines is high, around 98%, and is not only due to good reliability or maintenance management, but also due to fast and frequent service [146], [147]. Manufacturers seldom reveal data about their products and even more rarely share information about their failures, which is quite understandable. Preventive and corrective maintenance are performed as given in [148]. At the right moment, preventive maintenance will save money for the wind power plant owner. This is especially noticeable for remote site wind power plants situated, for example, offshore.

3.9. Dynamic Performance of Wind Power System Viewpoint:

Application of FACTS controller called Static Synchronous Compensator STATCOM to improve the performance of power grid with Wind Farms is investigated .The essential feature of the STATCOM is that it has the ability to absorb or inject fastly the reactive power with power grid. Therefore the voltage regulation of the power grid with STATCOM FACTS device is achieved. Moreover restoring the stability of the power system having wind farm after occurring severe disturbance such as faults or wind farm mechanical power variation is obtained with STATCOM controller. The dynamic model of the power system having wind farm controlled by proposed STATCOM is developed. To validate the powerful of the STATCOM FACTS controller, the studied power system is simulated and subjected to different severe disturbances. The results prove the effectiveness of the proposed STATCOM controller in terms of fast damping the power system oscillations and restoring the power system stability [149]. Flexible AC transmission system a FACTS device such as Static Synchronous Compensator STATCOM to improve the stability in wind farm is studied [150].

3.10. Mitigations of Harmonics Parameters of Wind Power Systems Viewpoints:

Wide-area coordinating control is becoming an important issue and a challenging problem in the power industry. This paper proposes a novel optimal wide-area monitor and wide-area coordinating neuro-controller (WACNC), based on wide-area measurements, for a power system with power system stabilizers, a large wind farm, and multiple FACTS devices. The wide-area monitor is a radial basis function neural network (RBFNN) that identifies the input-output dynamics of the nonlinear power system. Its parameters are optimized through a particle swarm optimization (PSO) based method. The WACNC is designed by using the dual heuristic programming (DHP) method and RBFNNs. It operates at a global level to coordinate the actions of local power system controllers. Each local controller communicates with the WACNC, receives remote control signals from the WACNC to enhance its dynamic performance, and therefore helps improve system-wide dynamic and transient performance [151]. Designing the WACC needs knowledge of the entire power system dynamics to be available to the designers. Due to the large-scale, nonlinear, stochastic, and complex nature of power systems, the traditional mathematical tools and control techniques are not sufficient to design such a WACC. This problem can be overcome by using neural networks (NNs) and adaptive-critic-design (ACD) [152], [153] based intelligent optimal nonlinear control techniques. However, previous works on NNs and ACDs based controllers focused on the local control of individual power system devices [154]-[156]; no work has been reported on WACC for different types of devices in a power system with renewable energy generation. This literature proposed a novel optimal WACNC for a power system with PSSs, a large wind farm, and FACTS devices. First, an optimal wide-area monitor is

designed by using a RBFNN [156] and PSO [157], to identify the input-output dynamics of the nonlinear plant. Based on this optimal wide-area monitor, the DHP method [152], [153] and RBFNNs are then used to design the WACNC. It uses wide-area measurements and operates at a global level to coordinate the actions of the local synchronous generator (with PSS), wind farm, and FACTS controllers. Each local controller communicates with the WACNC, and receives remote control signals from the WACNC as external input(s), to help improve system-wide dynamic and transient performance.

3.11. Reliability of Wind Power Systems Viewpoints:

Wind energy is a promising renewable energy source. In particular in Europe the installed capacity is growing at a considerable rate, approximately 20% annual growth rate for the past five years [158]. As the installed wind energy capacity grows, the considerations for the interaction between the wind energy installations and the grid, attracts more interest. Earlier, the most important consideration in this respect was to ensure a disconnection of wind turbines when there was a problem with the supplying voltage. Today, the focus regarding the interaction between the electric network and wind energy installation has been shifted, since the loss of such a considerable part of the power production (as wind energy constitute in some regions) due to network disturbances cannot be accepted any more [159]. Accordingly the important issue is to avoid a disconnection of a wind energy installation during a network disturbance. Moreover, it is of course also of great importance to be familiar with how a wind energy installation reacts to network disturbances. Induction generator (IG) is widely used as wind generator due to its simple, rugged and maintenance free construction. But as it has some stability problem, it is necessary to investigate the stability aspect of induction generator while connected to the power grid [160]. The voltage recovery after the network disturbance can be assisted by dynamic slip control and pitch control in a wound rotor induction generator based WPP [161]. Recently voltage-source or current-source inverters based FACTS devices such as SVC, STATCOM, dynamic voltage restorer (DVR), solid state transfer switch (SSTS) and UPFC have been used for flexible power flow control, secure loading and damping of power system oscillation [162]. Some of those are used also to improve transient and dynamic stability of wind power generation system. SVC is reported to improve the terminal voltage of induction generator by compensating the reactive power [163]. But STATCOM has somewhat better performance compared to SVC for reactive power compensation, which is reported clearly in [164]. It is reported that STATCOM can recover terminal voltage of wound rotor induction generator after the fault clearance. But as only induction generator is connected to the network, the Effect of STATCOM on the rest of the system is not presented there clearly. There are three major types of wind energy conversion systems (WECS) that are used to transform the harnessed mechanical energy into the electrical form [165]. The first system is the doubly fed (wound rotor) induction generator (DFIG) which utilizes a wound rotor machine. The DFIG allows variable speed

operation. The rotor winding is fed using a back-to-back voltage source converter. The wind turbine rotor is coupled to the generator through a gearbox. The DFIG receives the required reactive power needed for excitation from the grid. The inverter causes the generator shaft to be mechanically decoupled from the grid, and thus this system contributes negligible inertia to the grid [166]. The second system is the direct drive permanent magnet synchronous generator (PMSG), which also allows variable speed operation. The synchronous generator can have a wound rotor or be excited using permanent magnets. It is coupled to the grid via a back-to-back voltage source converter or a diode rectifier and voltage source converter. The synchronous generator is a low speed multi-pole generator; therefore, no gearbox is needed. That is why it is sometimes referred to as the direct drive WECS. Similar to the DFIG, the direct drive is decoupled from the grid through a power electronic interface, and hence it contributes a negligible amount of inertia to the power system [165]-[166]. The third system is the directly grid coupled squirrel cage induction generator (SCIG), used in constant speed wind turbines. This system is usually used in rural areas as a standalone system. The wind turbine shaft is coupled to the generator through a gearbox. When the system is grid connected, the required reactive power is fed from the grid. When this system is in a standalone situation, the required reactive power is fed from a shunt capacitor connected across the induction machine terminals, as depicted in fig. 15.
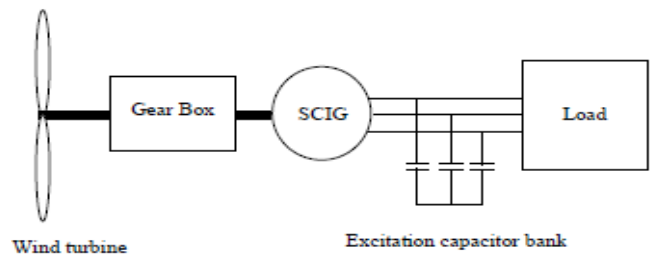

Fig. 15. Wind driven stand-alone SCIG

With a high wind power penetration in the grid, it is necessary that wind farms act in a more similar way to traditional power plants. This concerns voltage and reactive power control, frequency and active power control as well as having the ability to remain connected even after a short term voltage dip in the grid [167]. The latter is often referred to as having a low voltage ride through (LVRT) capability. In fact, special grid codes or grid regulations for wind power generation have been introduced during the last years putting strict requirement on the operation of the wind farms at PCC. The ability of a single wind power generator to follow the new grid requirements depends to a high extent on the generation technology used. Especially, the conventional technology with squirrel cage induction generator has problems with LVRT capability without the installation of additional reactive compensation. Today, still a significant share of the wind power production is with squirrel cage induction generators [168]. A wind farm grid based on squirrel cage induction generators is illustrated in Fig. 16(a). A large inductance can be found between the grid and the generator itself in the form of two transformers. Local capacitor banks supply most of the individual reactive power

demand of the generators. The LVRT problem consists of the following simplified sequence as illustrated in Fig. 16(b):

- The generators are initially in normal operation with balance between mechanical and electrical power.
- The voltage drops due to a grid disturbance and the wind farm experiences a low voltage period. Due to the low voltage period, both the active and reactive power output of the generators are reduced. The generator starts to accelerate due to higher mechanical than electrical torque.
- The grid disturbance is cleared after the generator has reached a higher speed and slip. The high slip leads to an increase in reactive power consumption, reduced terminal voltage and reduced active power production capability. As a result, the generator continuous to accelerate and the system is unable to recover.
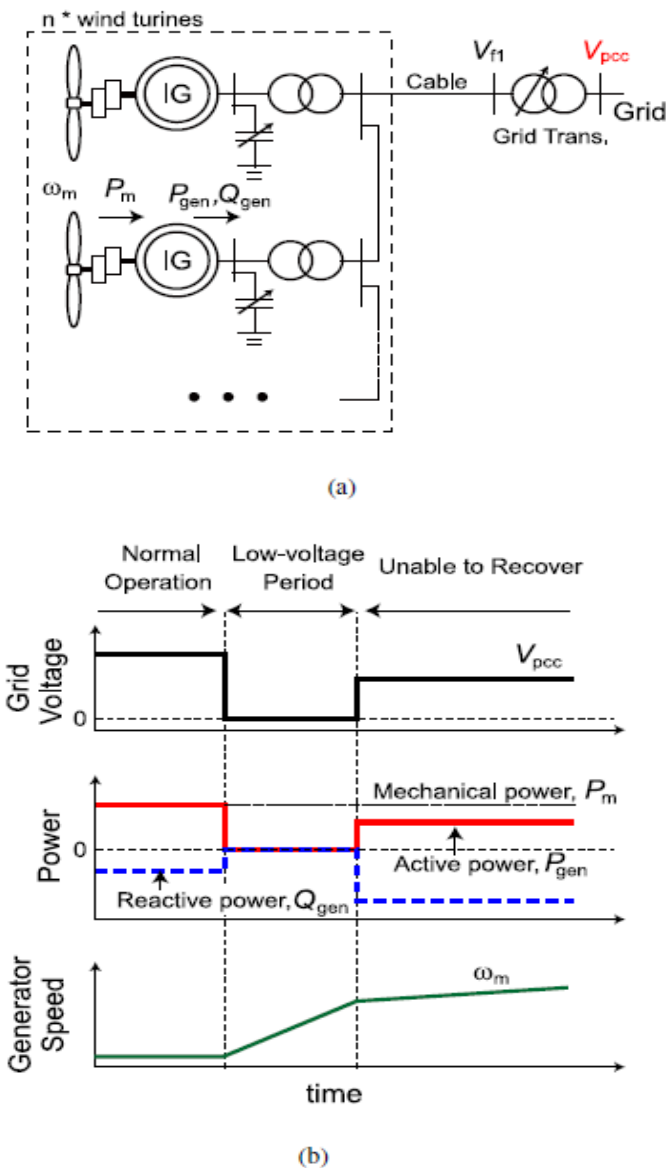

(a)

(b)

Figure 16. Illustration of problem with LVRT of induction generator based wind farms. (a) Example of wind farm configuration. (b) Sequence of events leading to voltage

collapse. There are principally two ways of improving the ability of the system to recover, either by reducing the turbine acceleration during the low voltage period or improving the deceleration after the low voltage period. Both can be improved by applying voltage support. The use of shunt compensation in the form of a STATCOM or SVC has been discussed to improve LVRT capability [169]-[170]. A major challenge is the required rating of the reactive compensator. It is then interesting to investigate alternative topologies in the form of series compensation, and see if the rating requirements can be reduced.

References [171], the planned offshore wind farms in Germany are basically located in North region. For wind integration in Germany, establishing new transmission lines and employing new technologies have become unavoidable. Establishing new transmission lines is very costly and difficult regarding environmental condition. One of the solutions is the utilization of FACTS. This literature discussed a method for determining the placement of series compensation to control line overload in power systems with wind power penetration. By a sensitivity based method critical lines can be identified quickly and accurately, to obtain desired wind feeding into the system. TCSC is applied for system stabilization as a typical FACTS device. This method is applied to realistic scenarios in a test system, which simulates reduced 380 kV network of Germany. Simulation results showed that the proposed method is effective and can enhance the transfer capability margin of existing power systems. Reference [172], the increasing power demand has led to the growth of new technologies that play an integral role in shaping the future energy market. Keeping in view of the environmental constraints, grid-connected wind turbines are promising increasing system reliability. This literature presented the impact of FACTS controllers on the long-term dynamic behavior of power systems connected with wind farms based on doubly-fed induction generator systems. Wind speed variations over a period of 1200 s are monitored from the regional meteorological website, and the voltage oscillations/real power injections of the wind farm are observed with and without FACTS devices. EUROSTAG is used for carrying out time domain simulations

3.12. Operations of Flexibility of Wind Power Systems Viewpoints:

In [173], used data collected at Central and South West Services Fort Davis wind farm to develop a neural network based prediction of power produced by each turbine. The power generated by electric wind turbines changes rapidly because of the continuous fluctuation of wind speed and direction. Reference [174], the issue of wind farm capacity is addressed through study of a simple but generic system. Wind-farm size is defined in terms of its rating relative to system fault level at the wind farm terminals. The voltage rise for a wind farm whose capacity is 20% of system fault rating is determined for various utility network reactance-to-resistance ratios (X/R). There are a number of further options which can extend the capacity limit. These depend on the wind turbine generator (WTG) technology used. With fixed-

speed WTGs, power factor correction (PFC) capacitance can be tailored to maximise the connected capacity. One suggested approach is to reduce the wind farm power factor target from say unity to 0.98, reducing the local voltage and hence enabling wind-farm expansion [175]. It is shown here that a flexible approach by developer and utility can relax the capacity constraint. The main problem is that there will be an increase in losses. We show that the increase is small for typical wind regimes, although it has been suggested that, with suitable wind-farm control and over-compensation under high demand/low wind conditions, the network losses could actually be reduced [175]. If dynamic in addition to steady-state voltage control is required, then the capacitance banks could be replaced by SVC or a STATCOM [176], although further improvement in wind farm capacity is not offered. Many wind farms under development or being planned use doubly-fed induction generators (DFIGs). These WTGs provide, among other advantages, the potential for reactive power adjustment within certain limits [177]. Consequently, continuous voltage regulation can be achieved in response to dynamic disturbances arising from load behaviour, network faults, etc. [178]. Here it is shown how judicious use of this facility can enable the maximum capacity to be deployed. We explore the capacity limit issue by considering a generic problem: a wind-farm connected through a distribution line with a range of X/R ratios. The wind-farm rating is chosen to be 20% of the system fault MVA. This is a 'large' wind farm, but by no means unheard of [179]. We then set the X/R ratio to unity, which is typical of rural 33kV networks in the UK. The impact of wind farm size on voltage rise is examined by increasing the number of WTGs operating at full load. The effect on capacity of various power factor correction strategies is then examined. The impact of each approach on losses is considered for a typical wind regime. Reference [180], a large penetration of wind generation info the power system will mean that poor power quality and poor stability margins cannot be tolerated from wind farms. This requires that methods to improve power qualify and stability for such systems be found. The static compensator (STATCOM) with hybrid battery energy storage (BES) has great potential to fulfill this role, though considerable advances in the control of this system are still to be made. From an economic point of view, rating the STATCOM for steady-state power-quality improvement duty is appropriate. Rating the STATCOM to absorb large amounts of additional power in excess of its transient overload capability during network faults is inappropriate. A hybrid of BES and braking resistor is therefore proposed. A new hybrid STATCOM–BES control technique is developed and discussed in the context of improving the stability and power quality to fixed speed, induction generator, and wind turbines. The variation of the network voltage, active and reactive power with the fluctuation of the wind generation is studied. A wind generation system with a STATCOM battery energy storage unit and the new control was simulated and the results demonstrate that both power quality and the stability margin can be improved significantly for wind farms. The STATCOM has been identified as the fastest responding device that can assist in improving the power quality and stability of the wind farms [181]-[186]. Previous studies have been limited to reactive power control only.

With the addition of energy storage, for example a battery energy storage (BES) unit, the STATCOM can provide more benefits to the wind farm and the associated power systems. Battery energy storage was chosen as an extremely well proven storage technology with low losses [187]. Other technologies, e.g. flywheels, are also suitable and when lifetime and maintenance costs are included, may be preferable. When power fluctuation occurs in the system, the BES unit can be used to level the power fluctuation by charging and discharging operation. Also, during a sag or fault the BES unit can be used to boost the stability margin by absorbing active power from the wind farm. Many STATCOMs have a (limited) transient overload capability and this can be used during sags or faults. In this paper, two applications of the STATCOM BES are studied: power quality and stability improvement of a wind turbine [185]. For stability improvement, a very large amount of energy may need to be absorbed in a very short space of time. It is not economic at present to rate the BES unit for the full value of this transient. However, rating the storage unit for its power-quality improvement duty and supplementing the BES unit with an additional energy sink, for example a braking resistor, gives a 'better-value' approach. In [188], the large growth in the wind power industry in the past years mainly focuses on a growing market and the development of large turbines and offshore farms. The high technical availability of wind turbines comes with a greater need for frequent maintenance. Current maintenance planning is not optimized, and it is possible to make maintenance more efficient. Condition monitoring systems (CMS) could resolve the growing wind power industry's need for better maintenance management and increased reliability. Such systems are commonly used in other industries. CMS could continuously monitor the performance of the wind turbine parts and could help determine specific maintenance timing. Reference [189], discussed that the capability of voltage-source converters (VSCs) to control the real power output of wind turbine generators (WTGs) can be applied to smooth power fluctuations due to wind turbulence. The paper calls attention to instability that can arise from: 1) the wind turbine itself and 2) the doubly fed induction generator (DFIG). Reference [190], a PI-based control algorithm to govern the net reactive power flowing between wind farms composed of doubly fed induction generators (DFIG) and the grid is proposed in this paper. The motivation underlying consists in demonstrating that secondary voltage control strategies may take advantage of such wind farms as if they were continuous reactive power sources. For that purpose, the local control structure of DFIGs is first described in some detail. The open-loop behavior of a 33 660-kW DFIG wind farm regarding the net power factor is then analyzed via simulation. Based on this study, a net reactive power control algorithm is devised for wind farms made up exclusively of DFIGs. Experimental results obtained by testing it both local and remotely, over a real wind farm located in Navarre—northern Spain—are also provided. In particular, net reactive power set-points supplied remotely to the wind farm are derived by an Optimal Power Flow (OPF) algorithm running at the operation central office of the utility company. In [191], described the use of voltage source converter (VSC)-based HVDC transmission system (VSC transmission) technology for connecting large doubly

fed induction generator (DFIG)-based wind farms over long distance. The operation principles of the proposed system are described, and new control strategies for normal and grid fault conditions are proposed. To obtain smooth operation, the wind farm side VSC (WFVSC) is controlled as an infinite voltage source that automatically absorbs power generated by the wind farm and maintains a stable local ac network. Fault ride through of the system during grid ac faults is achieved by ensuring automatic power balancing through frequency modulation using WFVSC and frequency control using DFIG. PSCAD/EMTDC simulations are presented to demonstrate robust performance during wind speed and power variations and to validate the fault ride through capability of the proposed system. In [192], the impact of the response of a wind farm (WF) on the operation of a nearby grid is investigated during network disturbances. Only modern variable speed wind turbines are treated in this work. The new E.ON Netz fault response code forWF is taken as the base case for the study. The results found in this literature are that the performance of the used Cigré 32-bus test system during disturbances is improved when the WF is complying with the E.ON code compared to the traditional unity power factor operation. Further improvements are found when the slope of the reactive current support line is increased from the E.ON specified value. In addition, a larger converter of a variable speed wind turbine is exploited that is to be used in order to improve the stability of a nearby grid by extending the reactive current support. By doing so, it is shown in this paper that the voltage profile at PCC as well as the transient stability of the grid are improved compared to the original E.ON code, in addition to the improvements already achieved by using the E.ON code in its original form. Finally, regarding the utilization of a larger converter, it is important to point out that the possible reactive power in-feed into the PCC from an offshore WF decreases with increasing cable length during network faults, making it difficult to support the grid with extra reactive power during disturbances. Installed wind power generation capacity is continuously increasing. Wind power is the most quickly growing electricity generation source with a 20% annual growth rate for the past five years [193]. In the past, requirements for wind turbines were focused mainly on protection of the turbines themselves and did not consider the effect on the power system operation since the penetration level of wind energy was fairly low. As the integration level of wind energy is increasing, concerns regarding the stability of the already existing power system are becoming of utmost importance and for a reliable and secure power system operation, the loss of a considerable part of the wind generators due to network disturbances cannot be accepted anymore [194]. Technical regulations for wind farms (WF) to be connected to a power system vary considerably from country to country. The differences in requirements depend on the wind power penetration level and on the robustness of the power network besides local traditional practices [195]. Reference [195] suggests that costly and challenging requirements should only be applied if they are technically required for reliable and stable power system operation. The FERC in the United States also suggests a system impact study by the transmission provider before applying any costly requirement like power factor requirement to WFs

[196]. Usually, fault ride-through (FRT) is now required by system operators; see for example [197]–[200]. However, in these grid codes, it is not specified explicitly how the FRT process (active and reactive power during a network fault) should be carried out. A newly updated grid code (updated April 2006) where this is clearly specified is the E.ON. grid code [201]. In this code, it is clearly presented how the requirements on the reactive current support should be fulfilled during network disturbances, and accordingly this grid code has been used as reference object in this study. A comment on the conclusion drawn in [195] is that today wind turbines of variable speed type have become more common than traditional fixed-speed turbines. The variable speed wind turbines are either of the doubly fed induction generator (DFIG) type or of the full power converter type [202]. In particular, the full power converter type turbine already contains the needed hardware set-up for making the turbine to act as a STATCOM (with limited capability).

This means that a controlled response of WFs during faults can be achieved with minor additional costs, and this feature should accordingly be utilized if it leads to grid stability improvements. It is therefore of great interest to study the impact of the response of WFs during disturbances, while complying with the grid codes, on the stability of the nearby grid. Such an investigation can give insight into the possibilities of achieving improved grid performance supports from modern wind turbines while complying with the grid codes. In Europe and around the world, many large wind farms have been planned. Many of these new wind farms will employ wind turbines based on DFIG, which offer several advantages when compared with fixed speed generators [203], [204]. These advantages, including speed control, reduced flicker, and four quadrant active and reactive power capabilities, are primarily achieved via control of a rotor side converter, which is typically rated at around 30% of the generator rating for a given rotor speed variation range of 25%. Fig. 1 shows the schematic diagram of a DFIG-based wind turbine. The connection of large wind farms to the grid over distances of tens of kilometers creates a number of technical, economical, and environmental challenges for the developers and system operators [205], [206]. Conventionally, ac connection has been used that offers some advantages such as low cost, relatively simple layout, the proven technology, etc. Yet for large wind farms with a long transmission distance, there are some serious disadvantages with ac connection technology:

- long ac cables produce large amounts of capacitive current, which can significantly reduce the cable transmission capacity and require large reactive power compensation;
- ac connections result in synchronous operation between the wind farm and the grid; therefore, faults occurring on the grid will directly affect the wind farm and vice versa.

Previous studies have identified the advantages of using HVDC transmission system, based on either VSC (VSC transmission) [207]–[211] or conventional line commutated converter [211]–[213] for integrating large wind farms to the grid. These advantages include:

- power flow is fully defined and controlled;
- transmission distance using dc is not affected by cable charging currents;
- fewer cables required and lower cable power losses.

Compared to conventional line commutated HVDC systems, the principal characteristics of VSC transmission are [211] as follows.

- It needs no external voltage source for commutation.
- It can independently control the reactive power flow at each ac network.
- Reactive power control is independent of active power control.

These features make VSC transmission technology very attractive for connecting weak ac systems, island networks, and renewable sources into a main grid. However, VSC transmission does have high power loss and high cost compared to conventional HVDC system [214]. In [207] and [208], an 8-MVA VSC transmission system was used to connect a 6-MW wind farm to the grid. However, little information was provided regarding the detailed system design and configuration. VSC transmission systems were also proposed in [209] and [210], for transmitting offshore wind power to the grid. However, the system operations considered are mainly under normal conditions, and little attention was given to network disturbances. Furthermore, the wind generators considered are either fixed speed [207]–[209] or synchronous generators [210]. However, many large wind farms under development will employ DFIG-based wind turbines whose operation and response to network disturbances are significantly different from other types of generators. In [213], line commutated HVDC systems were used to connect a large DFIG-based offshore wind farm into the grid. Again the study was only conducted under normal network conditions, and network fault was not considered. In [211], the authors provided preliminary studies on the use of both VSC and line commutated HVDC systems for the grid connection of wind farms based on DFIG. For the VSC system, the proposed control system during grid network fault was entirely based on fast communications between the VSC converter and the wind turbines. However, in practical system design, this is difficult to achieve. Reference [215], discussed the issue of the fault ride-through capability of a wind farm of induction generators, which is connected to an ac grid through an HVdc link based on VSCs. National grid codes require that wind turbines should stay connected to the power system during and after short circuit faults. In the latest literature, when the technology of HVdc based on VSCs is used to connect a wind farm to the power system, the blocking of the VSCs valves for a predefined short time interval is applied, in order to avoid the over currents and the tripping of the wind turbines. This paper proposes a control strategy that blocks the converters for a time interval which depends on the severity of the fault and takes special actions in order to alleviate the post-fault disturbances. In this way, the over currents are limited, the wind turbines manage to remain connected, and the ac voltage recovers quickly. Recently, renewable wind energy is enjoying a rapid growth globally to become an important green electricity source to replace polluting and exhausting fossil fuel. However, with

wind being an uncontrollable resource and the nature of distributed wind induction generators, integrating a large-scale wind-farm into a power system poses challenges, particularly in a weak power system. In the literature, the impact of STATCOM to facilitate the integration of a large wind farm (WF) into a weak power system is studied. First, an actual weak power system with two nearby large WFs is introduced. Based on the field SCADA data analysis, the power quality issues are highlighted and a centralized STATCOM is proposed to solve them, particularly the short-term (seconds to minutes) voltage fluctuations. Second, a model of the system, WF, and STATCOM for steady state and dynamic impact study is presented, and the model is validated by comparing with the actual field data. Using simulated PV and QV curves, voltage control and stability issues are analyzed, and the size and location of STATCOM are assessed. Finally, a STATCOM control strategy for voltage fluctuation suppression is presented and dynamic simulations verify the performance of proposed STATCOM and its control strategy [216]. However, with wind being a geographically and climatically uncontrollable resource and the nature of distributed wind induction generators, the stability and power quality issues of integrating large wind farm (WF) in grid may become pronounced, particularly into a weak power system. Conventionally, the low-cost mechanical switched cap (MSC) banks and transformer tap changers (TCs) are used to address these issues related to stability and power quality. However, although these devices help improve the power factor of WF and steady-state voltage regulation, the power quality issues, such as power fluctuations, voltage fluctuations, and harmonics, cannot be solved satisfactorily by them because these devices are not fast enough [218]. Moreover, the frequent switching of MSC and TC to deal with power quality issues may even cause resonance and transient overvoltage, add additional stress on wind turbine gearbox and shaft, make themselves and turbines wear out quickly and, hence, increase the maintenance and replacement cost [219]. Therefore, a fast shunt VAR compensator is needed to address these issues more effectively, as has been pointed out in many literatures [217], [219]–[222]. The STATCOM is considered for this application, because it provides many advantages, in particular the fast response time (1–2 cycles) and superior voltage support capability with its nature of voltage source [223].With the recent innovations in high-power semiconductor switch, converter topology, and digital control technology, faster STATCOM (quarter cycle) with low cost is emerging [224], which is promising to help integrate wind energy into the grid to achieve a more cost-effective and reliable renewable wind energy.

3.13. Operation of Wind Power Systems Viewpoints:

The development of wind power generation has rapidly progressed over the last decade. With the advancement in wind turbine technology, wind energy has become competitive with other fuel-based resources. The fluctuation of wind, however, makes it difficult to optimize the usage of wind power. The current practice ignores wind generation capacity in the unit commitment (UC), which discounts its usable capacity and may cause operational issues when the

installation of wind generation equipment increases. To ensure system reliability, the forecasting uncertainty must be considered in the incorporation of wind power capacity into generation planning. This paper discusses the development of an artificial-neural-network-based wind power forecaster and the integration of wind forecast results into UC scheduling considering forecasting uncertainty by the probabilistic concept of confidence interval [225]. The increasing penetration of wind turbine generators (WTGs) into power systems can affect many network operational aspects such as stability and power quality. The accurate, validated representation of these generators and their components for studying particular operational events, such as cut-in and soft-starting, short-circuit faults and generator switching, remains a challenge. Accurate simulation is particularly important for investigating stability interactions within weak grids or localised networks (e.g. micro-grids or islanded networks). One of the events producing major transient interaction between a WTG and a local grid is the grid connection itself. A simulation model of the use of a soft-starter during the grid connection of a wind turbine equipped with a squirrel cage induction generator and thyristor-based soft-start module is presented. This model has been validated using experimental measurements taken from a wind turbine generator in an operational wind farm site. The analysis focuses on verifying the transients produced during the short-time after the connection to the local grid. Existing literature presents insufficient details about this particular process as well as the practical performance of the soft-starter [226]. Reference [227], presented the grid requirements for the integration of wind farms into the Spanish Transmission System. In the particular case of voltage support capability, the Spanish Transmission System Operator (TSO), Red Electrica de Espana (REE) has defined a set of conditions to be met at the point of common coupling of a wind farm, not at terminals of a single wind turbine. A Verification, Validation, and Certification Procedure (VV&CP) to check compliance at terminals of a wind farm has been developed with the contribution and common agreement of all different wind power players and distribution system operators, leaded by the Spanish Wind Energy Association and supervised by REE. The VV&CP solves the problem defining a "Particular Procedure" based on testing or a "General Procedure" based on the simulation of the wind farm behavior. It is the scope of Energy to Quality in this literature, to discuss and confirm the VV&CP reliability and validity, supported by field testing, validated models of wind turbines and simulation of wind farms. In [228], suggested a novel approach based on Weibull distribution to determine the capacity of wind turbine generators (WTGs) using capacity factor (CF), normalized average power (PN), and the product of CF and PN under different values of tower height and rated wind speed. Five locations for installation of WTG in Taiwan are practically examined. The proposed Weibull distribution is employed to represent probability distribution of wind speed variation, while the important relationships among mean wind speed (MWS), standard deviation of wind speed, and both scale and shape parameters of the Weibull distribution are also derived. The cost of energy (COE) and capital costs of WTG under different tower heights and various locations

are also determined. It can be concluded from the simulation results of five installation locations of WTG in Taiwan that suitable values for both shape parameter and scale parameters of Weibull distribution as well as wind turbine capacity are identically important for selecting locations of installing WTG. With an increased [229] number of wind turbine generators (WTGs) connected to an electricity network the system operator may request that they participate in frequency control in the event of a sudden unbalancing of power generated and consumed on the system. In this paper the frequency response capability of the full converter variable speed wind turbine generator (FCWTG) with permanent magnet synchronous generator (PMSG) is investigated. A control scheme is developed that improves the frequency control performance, illustrating the importance of the initial active power output of the FCWTG. The frequency response capability of the WTG with doubly-fed induction machine (DFIG) has received significant research attention. This is because the DFIG does not automatically contribute an inertial response to frequency events like a fixed-speed induction machine based WTG does. In contrast to the DFIG, the frequency control of the FCWTG does not receive published research attention in proportion to its market share (approximately 20% [230]). Some lieratures on DFIG frequency response [231]–[233] have the power system frequency defined by a time series input, and the frequency response of the DFIG is a reaction to this change of frequency. This means that the DFIG response is not contributing to the frequency dynamics, so no improvement in frequency control can be observed.

In [234] the DFIG frequency response improves the frequency control of the power system, but it uses active power curtailment to keep some active power in reserve for a frequency response. In [235] the DFIG frequency response does contribute to the frequency control. However, it only has an emulated inertial response. The improvement in DFIG frequency control is still inferior to the fixed-speed WTG and the conventional synchronous generator. The improvement in frequency with augmented DFIG control is also presented in [236]. One of the main characteristics of wind power is the inherent variability and unpredictability of the generation source, even in the short-term. To cope with this drawback, hydro pumped storage units have been proposed in the literature as a good complement to wind generation due to their ability to manage positive and negative energy imbalances over time. This paper investigates the combined optimization of a wind farm and a pumped-storage facility from the point of view of a generation company in a market environment. The optimization model is formulated as a two-stage stochastic programming problem with two random parameters: market prices and wind generation. The optimal bids for the day ahead spot market are the "here and now" decisions while the optimal operation of the facilities are the recourse variables [237]. High-quality profiles of mean and turbulent statistics of the wind field upstream of a wind farm can be produced using a scanning Doppler lidar. Careful corrections for the spatial filtering of the wind field by the lidar pulse produce turbulence estimates equivalent to point sensors but with the added advantage of a larger sampling volume to increase the statistical accuracy of the estimates.

For a well-designed lidar system, this permits accurate estimates of the key turbulent statistics over various sub domains and with sufficiently short observation times to monitor rapid changes in conditions [238]. In [239], the emerging energy crisis resulting from a high price of crude oil has drawn attention about renewable energy all over the world. Thailand is a developing country located at the heart of Southeast Asia, with about 66 million of population as of 2006. The electricity supply industry structure under the government of Thailand has been managed by the Electricity Generating Authority of Thailand, the Metropolitan Electricity Authority, and the Provincial Electricity Authority for almost 50 years. According to the 2004 Power Development Plan, the country would have generation reserve at a marginal of 15%. Due to the rapid economic growth and difficulty in building new centralized generating facilities, this has the potential to create a security issue of electricity energy shortage and may develop a severe system blackout. Renewable energy issues have been widely discussed and debated over the country. Although solar energy is the most prominent renewable energy source due to the appropriate geographic of Thailand, it is still considered as a low density energy source which requires a large area of installation. Therefore, for the long-term investment, wind power seems to be a good candidate because it is quick to install, needs no fuel cost, and is environment friendly. When the transient interaction between a large wind farm and a power system is to be studied, there are two possible approaches to wind farm modelling. It can be modelled as one or more equivalent wind turbine generators (aggregate modelling) or each wind turbine generator (WTG) can be modelled separately (detailed modelling). When a power system with many wind farms is to be simulated, the aggregate approach becomes especially attractive. A successful aggregate model will reduce the simulation time without significantly compromising the accuracy of the results in comparison to the detailed model. Here, the aggregate modeling options for a wind farm with 5 MW full-converter WTGs (FCWTGs) using permanent magnet synchronous machines are presented. A braking resistor in the DC circuit of the FCWTG's converter system is employed as a means of satisfying the latest grid code requirements. It will be shown that with a braking resistor implemented in the FCWTG there is scope for significant model simplifications, which is particularly relevant for transient stability studies of large-scale systems [240]. Reference [241], a novel interface neuro-controller (INC) is proposed for the coordinated reactive power control between a large wind farm equipped with doubly fed induction generators (DFIGs) and a static synchronous compensator (STATCOM). The heuristic dynamic programming (HDP) technique and radial basis function neural networks (RBFNNs) are used to design this INC. It effectively reduces the level of voltage sags as well as the over-currents in the DFIG rotor circuit during grid faults, and therefore, significantly enhances the fault ride-through capability of the wind farm. The INC also acts as a coordinated external damping controller for the wind farm and the STATCOM, and therefore, improves power oscillation damping of the system after grid faults. Because of the concern about the environmental pollution and a possible energy crisis, there

has been a rapid increase in renewable energy sources worldwide in the past decade. Among various renewable energy sources, wind power is the most rapidly growing one. Nowadays, the majority of wind turbines are equipped with doubly fed induction generators (DFIGs). In the DFIG concept, the wound-rotor induction generator is grid-connected at the stator terminals, as well as at the rotor mains via a partially rated variable frequency ac/dc/ac converter (VFC), which only needs to handle a fraction (25%–30%) of the total power to achieve full control of the generator. The VFC consists of a rotor-side converter (RSC) and a grid-side converter (GSC) connected back-to-back by a dc-link capacitor. In order to meet power factor requirement (e.g., −0.95 to 0.95) at the connection point, most wind farms are equipped with switched shunt capacitors for static reactive compensation [242], [243].Moreover, because many wind farms are connected to electrically weak power networks, characterized by low short circuit ratios and under-voltage conditions, dynamic power electronic devices such as a SVC and a STATCOM have been increasingly used in wind farms to provide rapid and smooth reactive compensation and voltage control [244]. When connected to the grid and during a grid fault, the voltage sags at the connection point of the wind farm can cause a high current in the rotor circuit and the converter. Since the power rating of the VFC converter is only 25%–30% of the induction generator power rating, this over-current can lead to the destruction of the converter. Therefore, one of the key issues related to the wind farms equipped with DFIGs is the grid fault or low voltage ride-through capability. Much research effort has gone into this issue and several techniques have been proposed. One technique is blocking the RSC and short circuiting the rotor circuit by a crow-bar circuit to protect the converter from over current in the rotor circuit [242], [245], [246]. The wind turbine generators (WTGs) continue their operation to produce some active power, and the GSCs can be set to control the reactive power and voltage. When the fault has been cleared and when the voltage and the frequency in the power network have been reestablished, the RSC restarts and the WTG returns to normal operation. In this uninterrupted operation feature, voltage stability is a crucial issue. In the case of a weak power network and during a grid fault, the GSC cannot provide sufficient reactive power and voltage support due to its small power capacity, and there can be a risk of voltage collapse. As a result, the RSC will not restart and the WTG will be disconnected from the network. This problem can be solved by using dynamic reactive compensation. In [246], the authors investigated the application of a STATCOM to help with the uninterrupted operation of a wind farm equipped with DFIGs during grid faults. However, the focus of [246] was to investigate the DFIG behavior with the STATCOM for voltage support during grid faults. In addition, the power network used in [246] is a simple single machine infinite bus system, and there is no coordination between the wind farm and the STATCOM for reactive power control. The second solution to enhance the grid-fault ride-through capability of the DFIG wind turbines is to improve the control scheme of the RSC. A nonlinear controller and a fuzzy controller have been proposed in [247] and [248], respectively, for controlling the RSC. Compared with the conventional linear control

schemes, these control schemes reduce the over current in the rotor circuit during grid faults. Shunt flexible alternating current transmission system (FACTS) devices such as the SVC and the STATCOM provide rapid and smooth reactive compensation, and therefore, can reduce the level of voltage sags during grid faults. The application of a STATCOM to enhance the capability of a wind farm (equipped with DFIGs) to ride through grid faults in a multi-machine power system has been reported in [249]. However, the reactive power control of the wind farm and the STATCOM in [249] are independent without coordination; during grid faults, the voltage control is only achieved by the STATCOM. Reference [241] extends the work of [249] by proposing a novel coordinated reactive power control scheme. It acts as an interface controller between a wind farm and a STATCOM. The heuristic dynamic programming (HDP) [250], [251] method and radial basis function neural networks (RBFNNs) [252] are employed to design this nonlinear optimal adaptive interface neuro-controller (INC).

3.14. Control of Wind Power Systems Viewpoints:

In [253], addressed in regarding with the voltage stability is a key issue to achieve the uninterrupted operation of wind farms equipped with doubly fed induction generators (DFIGs) during grid faults. The investigated the application of a static synchronous compensator (STATCOM) to assist with the uninterrupted operation of a wind turbine driving a DFIG, which is connected to a power network, during grid, faults. The control schemes of the DFIG rotor- and grid-side converters and the STATCOM are suitably designed and coordinated. The system is implemented in real-time on a Real Time Digital Simulator. Results show that the STATCOM improves the transient voltage stability and therefore helps the wind turbine generator system to remain in service during grid faults. The worldwide concern about environmental pollution and a possible energy shortage has led to increasing interest in technologies for the generation of renewable electrical energy. Among various renewable energy sources, wind power is the most rapidly growing one in Europe and the United States. With the recent progress in modern power electronics, the concept of a variable-speed wind turbine (VSWT) equipped with a doubly fed induction generator (DFIG) is receiving increasing attention because of its advantages over other wind turbine generator concepts [242], [254]–[256]. In the DFIG concept, the induction generator is grid-connected at the stator terminals; the rotor is connected to the utility grid via a partially rated variable frequency ac/dc/ac converter (VFC), which only needs to handle a fraction (25%–30%) of the total DFIG power to achieve full control of the generator. The VFC consists of a rotor-side converter (RSC) and a grid-side converter (GSC) connected back-to-back by a dc-link capacitor. When connected to the grid and during a grid fault, the RSC of the DFIG may be blocked to protect it from over current in the rotor circuit [242], [255], [256]. The wind turbine typically trips shortly after the converter has blocked and automatically reconnects to the power network after the fault has cleared and the normal operation has been restored. In [242], the author proposed an uninterrupted operation feature of a DFIG wind turbine during grid faults. In this feature, the

RSC is blocked, and the rotor circuit is short-circuited through a crowbar circuit (an external resistor); the DFIG becomes a conventional induction generator and starts to absorb reactive power. The wind turbine continues its operation to produce some active power, and the GSC can be set to control the reactive power and voltage at the grid connection. The pitch angle controller might be activated to prevent the wind turbine from fatal over speeding. When the fault has cleared and when the voltage and the frequency in the utility grid have been reestablished, the RSC will restart, and the wind turbine will return to normal operation. However, in the case of a weak power network and during a grid fault, the GSC cannot provide sufficient reactive power and voltage support due to its small power capacity, and there can be a risk of voltage instability. As a result, utilities, typically, immediately disconnect the wind turbines from the grid to prevent such a contingency and reconnect them when normal operation has been restored. Therefore, voltage stability is the crucial issue in maintaining uninterrupted operation of wind turbines equipped with DFIGs [242]. With the rapid increase in penetration of wind power in power systems, tripping of many wind turbines in a large wind farm during grid faults may begin to influence the overall power system stability. It has been reported recently [257] that integration of wind farms into the East Danish power system could cause severe voltage recovery problems following a three-phase fault on that network. The problem of voltage instability can be solved by using dynamic reactive compensation. Shunt FACTS devices, such as the SVC and the STATCOM, have been widely used to provide high-performance steady state and transient voltage control at the PCC. The application of an SVC or a STATCOM to a wind farm equipped with fixed-speed wind turbines (FSWTs) and squirrel-cage induction generators (SCIGs) has been reported in [258] and [259] for steady-state voltage regulation and in [242] and [259] for short-term transient voltage stability. However, compared with the FSWT with a SCIG, the operation of the VSWT with a DIFG, particularly during grid faults, is more complicated due to the use of power electronic converters, and it has not yet been studied with the use of dynamic reactive compensation. Reference [253], investigated the application of a STATCOM to help with the uninterrupted operation of a VSWT equipped with a DFIG during grid faults. The STATCOM is shunt connected at the bus where the wind turbine is connected to the power network to provide steady-state voltage regulation and improve the short-term transient voltage stability. The DFIG and STATCOM control schemes are suitably designed and coordinated. The system is implemented in real-time on a Real Time Digital Simulator (RTDS). Power systems with high penetration of wind power usually require long-distance transmission to export wind power to the market. Inter-area oscillation is an issue faced in long-distance transmission. Can wind generation based on doubly fed induction generator (DFIG) help to damp oscillations and how? In this paper, a control scheme is developed for the DFIG with rotor-side converter to damp inter-area oscillations. The DFIG is modeled in MATLAB toolbox/Simulink utilizing its vector control scheme feature, and inner current control and outer active/reactive power control loops are modeled and designed. A two-area system that suffers from poor inter-area

oscillation damping along with a wind farm in the area that exports power is investigated. A damping controller is designed and time-domain simulations are used to demonstrate the effectiveness of the controller. The major contributions of the paper are as follows: 1) built a wind farm inter-area oscillation study system based on the classical two-area four-machine system, 2) established that in vector control scheme, active power modulation can best help to damp oscillations, 3) successfully designed a feedback controller using remote signals with good inter-area oscillation observability [260]. In [261], presented a control scheme based on a superconducting magnetic energy storage (SMES) unit to achieve both power flow control and damping enhancement of a novel hybrid wind and marine-current farm (MCF) connected to a large power grid. The performance of the studied wind farm (WF) is simulated by an equivalent 80-MW induction generator (IG) while an equivalent 60-MW IG is employed to simulate the characteristics of the MCF. A damping controller for the SMES unit is designed by using modal control theory to contribute effective damping characteristics to the studied combined WF and MCF under different operating conditions. A frequency-domain approach based on a linearized system model using eigen techniques and a time-domain scheme based on a nonlinear system model subject to disturbance conditions are both employed to validate the effectiveness of the proposed control scheme. It can be concluded from the simulated results that the proposed SMES unit combined with the designed damping controller is very effective to stabilize the studied combined WF and MCF under various wind speeds. The inherent fluctuations of the injected active power and reactive power of the WF and MCF to the power grid can also be effectively controlled by the proposed control scheme. In [262], integrating a battery energy storage system (BESS) with a large wind farm can smooth out the intermittent power from the wind farm. This paper focuses on development of a control strategy for optimal use of the BESS for this purpose. In this literature considers a conventional feedback-based control scheme with revisions to incorporate the operating constraints of the BESS, such as state of charge limits, charge/discharge rate, and lifetime. The goal of the control is to have the BESS provide as much smoothing as possible so that the wind farm can be dispatched on an hourly basis based on the forecasted wind conditions. In recent years, wind energy has shown a rapid growth as a clean and inexhaustible energy source all around the world [263], [264]. However, as the penetration levels increase, it is of considerable concern that a fluctuating power output of wind farms will affect operation of interconnected grids [265], especially weak power systems. Such cases may require somemeasures to smooth the output fluctuation to have a reliable power system [266]. Recent advances in electric energy storage technologies provide an opportunity of using energy storage to address the wind energy intermittency [267]. Electric energy can be stored electromagnetically, electrochemically, kinetically, or as potential energy. Two factors characterize the application of an energy storage technology. One is the amount of energy that can be stored in the device and the other is the rate at which energy can be transferred into or out of the storage device. These factors depend mainly on the characteristic of

the storage device itself [268]. A variety of storage technologies are available, which are capable of smoothing out the unpredictable fluctuating power output of the wind farms. Some of these storage technologies are super capacitors, superconducting magnetic energy storage, flywheels, batteries, compressed air energy storage, and hydro pumped storage. The basic issues with these storage technologies consist of the cost of these technologies, and operation and maintenance requirements [269]. Wind energy has many benefits, but high penetration of wind power can introduce technical challenges and issues, including grid interconnection, power quality, reliability, protection, generation dispatch, and control. Fig. 17 shows the typical power output profile of a large wind farm (50MWcapacity). The figure shows that the power output can have steep rises, sudden drops during the day. Integrating such a highly intermittent power resource into a power grid, especially into a weak part of the grid can pose serious challenges [270].
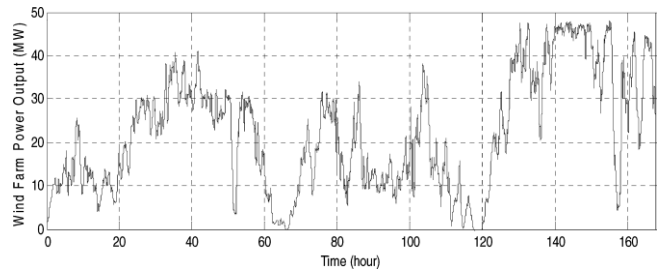

Fig. 17. Typical wind farm power output

Fig. 18 illustrates the use of BESS to compensate for the intermittent power output of the wind farm. The BESS is connected to the system at the point of common coupling and is charged/discharged through a power converter to smooth the net power injected to the system.
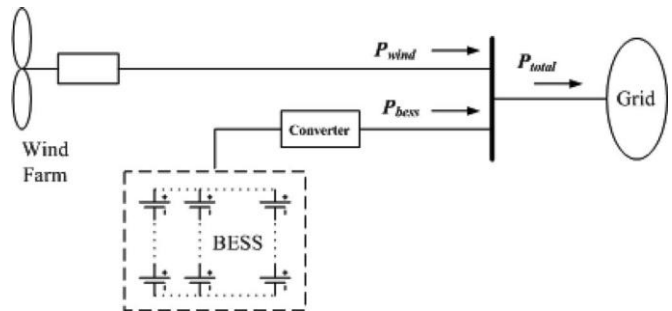

Fig. 18.BESS integration at a wind farm.

The main challenges with wind farm integration and energy storage can be listed as follows:

• Intermittency: The ability of a utility to change the power output of a generating unit as the load changes is the basis of economic dispatch [271]. For a wind farm to be dispatchable like the other conventional generation units, its output should be regulated at a desired dispatchability level.

• Ramp rates: Another issue with the large amount of wind generation is the fast power ramps of the wind farm output, both positive and negative [272]. These ramps should be limited in order to integrate the large amount of generation to the grid, minimize the

- high-cost ancillary service requirements, and reduce the impact on system reliability [269].
- Limitingwind farm power output: Large-scalewind power may cause congestion on the transmission lines that carry wind power (for example, when a large wind farm is integrated to a weak part of a system [263]), and hence, the power output of the wind farm may have to be curtailed to prevent congestion [273].

Reference [274], investigated the reliability effects on a composite generation and transmission system associated with the addition of large-scale wind energy conversion systems (WECS) using the state sampling Monte Carlo simulation technique. Three types of composite system were developed to represent the general conditions that exist in practical systems and used to conduct the studies presented in this paper. Load point and system indices for the three types of test systems are presented to illustrate the impact of adding wind farms in various system locations and the effect of varying the degree of wind speed correlation. In [275], a new interconnecting method has been discussed for a cluster of wind turbine/generators is proposed, and some examples of the basic characteristics of the integrated system are shown. This method can be achieved with a wind turbine generating system using a shaft generator system. A group of wind turbine/generators can be interconnected easily with the proposed method, and high reliability and electric output power with high quality are also expected. Moreover, since this method enables transmission of the generated power through a long-distance dc transmission line, the optimum site for wind turbines can be selected so as to acquire the maximum wind energy.

3.15. Planning of Wind Power Systems Viewpoints:

In [276], has been presented a system using an energy capacitor system (ECS) to smoothen the output power fluctuation of a variable-speed wind farm. The variable-speed wind turbine driving a permanent-magnet synchronous generator is considered to be connected to the ac network through a fully controlled frequency converter. The detailed modeling and control strategy of the frequency converter as well as variable-speed operation of a wind turbine generator system are demonstrated. Afterward, a suitable and economical topology of ECS composed of a current-controlled voltage-source inverter, dc–dc buck/boost converter, and an electric double layer capacitor (EDLC) bank is presented, including their control strategies. Exponential moving average is used to generate the real input power reference of ECS. Another novel feature of this paper is the incorporation of a fuzzy-logic-controlled reference signal adjuster in the control of the dc–dc buck/boost converter, in which the stored energy of the EDLC bank is utilized in an efficient way. Due to this controller, the energy storage capacity of the EDLC bank can be reduced in size, thus resulting in reduction of the overall cost of the ECS unit as well as decrease in irrepressible operations during high and low energy levels of the EDLC bank. Rising fuel costs, increased energy consumption, and growing environmental concerns have led mankind to look for alternate sources of energy apart from conventional fuels. One of the promising renewable energy sources is wind energy. For harnessing wind energy from a wind turbine or wind farm, wind resource assessment (WRA) needs to be carried out.WRA will highlight which site is optimum (in terms of economics and wind characteristics) for wind turbine installation and how much would be the estimated energy output from that particular site. This literature presented the estimate for annual wind energy yield for the Vadravadra site in Gau Island in Fiji. It also presents a method for finding the optimum wind turbine that can be installed at a site and the kind of wind turbine that should be installed at a site, where cyclone may hit the area [277]. In [278], an analytical approach has been presented for the reliability modeling of large wind farms is presented. A systematic method based on frequency and duration approach is utilized to model a wind farm like a multistate conventional unit, where the probability, frequency of occurrence, and departure rate of each state can be obtained using the regional wind regime of wind farm and wind turbine characteristics. The proposed method is capable of finding both annual frequency and average time of load curtailment analytically in the presence of wind power. A wind farm in the northern region of Iran with the wind speed registration of one year is studied in this paper. To accommodate time-varying patterns of wind speed, reliability analysis considering seasonal patterns of wind speed is also carried out. The results show that seasonal patterns significantly affect the reliability indexes. A reliability analysis is also performed using a load profile similar to that of Iran power network. It will be shown that the coincidence of high-load-demand and high-wind-speed periods makes the North Iran wind farm projects highly attractive from a reliability point of view.

3.16. Protection of Wind Power Systems Viewpoints:

Reference [279], has been discussed a new operational strategy for a small scale wind farm which is composed of both fixed and variable speed wind turbine generator systems (WTGS). Fixed speed wind generators suffer greatly from meeting the requirements of new wind farm grid code, because they are largely dependent on reactive power. Integration of flexible ac transmission systems (FACTS) devices is a solution to overcome that problem, though it definitely increases the overall cost. Therefore, in this paper, we focuses on a new wind farm topology, where series or parallel connected fixed speed WTGSs are installed with variable speed wind turbine (VSWT) driven permanent magnet synchronous generators (PMSG). VSWT-PMSG uses a fully controlled frequency converter for grid interfacing and it has abilities to control its reactive power as well as to provide maximum power to the grid. Suitable control strategy is developed in this paper for the multilevel frequency converter of VSWT-PMSG. A real grid code defined in the power system is considered to analyze the LVRT characteristic of both fixed and variable speed WTGSs. Moreover, dynamic performance of the system is also evaluated using real wind speed data. Therefore, it is important to investigate a suitable method to enhance the LVRT capability of fixed speed wind generators. Voltage or

current source inverter-based FACTS devices such as SVC, STATCOM, dynamic voltage restorer (DVR), solid state transfer switch (SSTS), and UPFC have been used for flexible power flow control, secure loading, and damping of power system oscillation [280]–[282]. FACTS/ESS, i.e., FACTS with energy storage system (ESS), has recently emerged as more promising devices for power system applications [283]. Some of those are even applicable to wind farm stabilization. STATCOM, SVC, superconducting magnetic energy storage system (SMES), and energy capacitor system (ECS) composed of electric double layer capacitor, and power electronic devices have already been proposed to enhance the LVRT capability of fixed speed wind farm [284]–[290]. However, the installation of FACTS devices at a wind farm composed of fixed speed wind generators increases the system overall cost. The problem of establishing [291] maximum size of a wind farm (WF) when it joins a WF cluster (WFC) is examined. It is shown that the clustering effect can be quantified by detailed simulation of system dynamics, using appropriate models for wind events, wind facilities, and power system equipment. This literature has been points out the inevitability of WFC formations and draws attention to their operational impacts. A case study is used to demonstrate how location and layout of a WF can influence system dynamics, and thus, restrict the WF size. Wind farm harmonic [292] emissions are a well-known power quality problem, but little data based on actual wind farm measurements are available in literature. In this paper, harmonic emissions of an 18MWwind farm are investigated using extensive measurements, and the deterministic and stochastic characterization of wind farm harmonic currents is analyzed. Specific issues addressed in the literature include the harmonic variation with the wind farm operating point and the random characteristics of their magnitude and phase angle. Reference [293], discussed the effectiveness of reactive power compensation using a multilevel, hexagram-converter-based STATCOM with one-cycle control (OCC) for a wind farm with fixed-speed turbines, and the interaction with the power system network. Comparison is made with several common types of multilevel voltage source converters used for STATCOM applications. A new voltage control method based on OCC principles for hexagram-based STATCOMs is proposed and proven by a wind farm power system simulation showing the improvement of voltage variations caused by wind speed changes. The experimental results from tests of a small-scale hexagram converter prototype have verified the proposed converter and control method. Wind turbine power generation is one of the fastest growing renewable technologies. This recent development started in the 1980s with wind turbines rated at a few tens of kilowatts of power and has progressed to today's mega watt range wind turbines. Earlier wind power farms did not significantly impact power grid operation and control, but now they play an active part in the grid, since the wind power penetration level has gone up considerably. As the power range of wind turbine generator systems (WTGSs) increases, control of active and reactive power, which typically are the system frequency and voltage control parameters, becomes more important. Wind turbines used with fixed-speed induction generators (FSIGs) provide a lower cost solution for wind power generation, but some

drawbacks exist, such as high starting currents and high demand for reactive power. FSIGs absorb variable reactive power that is one cause of voltage fluctuations at the points where wind farms connect to distribution and transmission lines. Wind farm voltage control is necessary to provide satisfactory conditions for the operation of fixed-speed WTGSs and to meet the integration requirements of the hosting utility. One possible solution for voltage control at the points where wind farms connect to distribution and transmission lines is a reactive power flow on demand that can be realized using a STATCOM. Recently, multilevel STATCOMs have drawn great interest in the wind power industry [294]-[297]. These converters synthesize a sinusoidal voltage by stepping up and down several voltage levels, using the converter's dc-side capacitors. Synthesized output voltage waveforms approach the sinusoidal wave with minimum harmonic distortion, and accordingly, decrease the losses in the coupling transformer. In [298], a power system with high wind power penetration, reliability-based reserve expansion is a major problem of system planning and operation due to the uncertainty and fast fluctuation of wind speeds. This paper studied the impact of high wind power penetration on the system reserve and reliability from long-term planning point of view utilizing universal generating function (UGF) methods. The reliability models of wind farms and conventional generators are represented as the corresponding UGFs, and the special operators for these UGFs are defined to evaluate the customer and the system reliabilities. The effect of transmission network on customer reliabilities is also considered in the system UGF. The power output models of wind turbine generators in a wind farm considering wind speed correlation and un-correlation are developed, respectively. A reliability-based reserve expansion method is proposed to determine the conventional reserve required for power systems with high wind power penetration. In [299], the variable output of a large wind farm presents many integration challenges, especially at high levels of penetration. The uncertainty in the output of a large wind plant can be covered by using fast-acting dispatchable sources, such as natural gas turbines or hydro generators. However, using dispatchable sources on short notice to smooth the variability of wind power can increase the cost of large-scale wind power integration. To remedy this, the inclusion of large-scale energy storage at the wind farm output can be used to improve the predictability of wind power and reduce the need for load following and regulation hydro or fossil-fuel reserve generation.

3.17. *Steady-State and Dynamic Stability by SVC and STATCOM in Wind Power Systems Viewpoints:*

Reference [300], has been discussed a control scheme based on a static synchronous compensator (STATCOM) to achieve both voltage control and damping enhancement of a grid-connected integrated 80-MW offshore wind farm (OWF) and 40-MW marine- current farm (MCF). The performance of the studied OWF is simulated by an equivalent doubly-fed induction generator (DFIG) driven by an equivalent wind turbine (WT) while an equivalent squirrel-cage rotor induction generator (SCIG) driven by an equivalent marine-current turbine (MCT) is employed to

simulate the characteristics of the MCF. A damping controller of the STATCOM is designed by using modal control theory to contribute effective damping characteristics to the studied system under different operating conditions. A frequency-domain approach based on a linearized system model using eigenvalue techniques and a time-domain scheme based on a nonlinear system model subject to various disturbances are both employed to simulate the effectiveness of the proposed control scheme. It can be concluded from the simulated results that the proposed STATCOM joined with the designed damping controller is very effective to stabilize the studied system under disturbance conditions. Both wind energy and ocean energy have been integrated together in the U.K. [301]–[303]. Ocean energy may include thermal energy, wave energy, offshore wind energy, tidal energy, ocean current energy, etc. Generators driven by marine-current turbine (MCT) combined with offshore generators driven by wind turbine (WT) will become a novel scheme for energy production in the future. Since oceans cover more than 70% surface of the earth, a hybrid power generation system containing both offshore wind farm (OWF) and marine-current farm (MCF) can be extensively developed at the specific locations of the world in the future. One of the simple methods of running an OWF is to connect the output terminals of several DFIGs together and then connect to a power grid through an offshore step-up transformer and undersea cables. To run an MCF may use several squirrel-cage induction generators (SCIGs) connected directly to the power grid through an offshore step-up transformer and undersea cables. Both WTs and MCTs have very similar operating characteristics but an SCIG-based MCF requires reactive power for magnetization while a DFIG-based OWF with two bi-directional power converters can control its output power factor to be close to unity. When the generated active power ofan SCIG-based MCF is varied due to marine-current fluctuations, the absorbed reactive power and the terminal voltage of the MCF can be significantly affected. In the event of increasing grid disturbances, e.g., grid faults, an energy storage system or a control device for a large-scale high-capacity power generation system is generally required to compensate fluctuating components when connecting to a power grid. A large-scale OWF may combine with different FACTS devices or energy-storage systems such as a STATCOM [304], [305], etc. The analyzed results of stability improvement of power systems using STATCOMs and the damping controller design of STATCOMs were presented in [306]. The design of an output feedback linear quadratic controller for a STATCOM and a variable-blade pitch of a wind energy conversion system to perform both voltage control and mechanical power control under grid-connection or islanding conditions were shown in [307]. System modeling and controller design for fast load voltage regulation and mitigation of voltage flicker using a STATCOM were demonstrated in [308]. A new D-STATCOM control algorithm enabling separate control of positive- and negative-sequence currents was proposed, and the algorithm was based on the developed mathematical model in the coordinates for a D-STATCOM operating under unbalanced conditions [309]. An in-depth investigation of the dynamic performance of a STATCOM and a static synchronous series compensator (SSSC) using digital

simulations was performed in [310]. The results of a study on the application of the recently developed STATCOM for the damping of torsional oscillations occurred in a series compensated AC system were studied while dynamic performance of the nonlinear system with an optimized STATCOM controller was evaluated under a three-phase fault condition [311]. Discussion and comparison of different control techniques such as PSS, static VAR compensator (SVC) and STATCOM for damping undesirable interarea oscillations in power systems were carried out in [312]. The conventional method of PI control for a STATCOM was compared and contrasted with various feedback control strategies, and a linear optimal control based on LQR control was shown to be superior in terms of response profile and control effort required [313]. A STATCOM based on a current source inverter (CSI) was proposed, and the nonlinear model of the CSI was modified to be a linear model through a novel modeling technique [314]. The integrated STATCOM/BESS was introduced for the improvement of dynamic and transient stability and transmission capability. The performance of the different FACTS/BESS combinations was compared and provided experimental verification of the proposed controls on a scaled STATCOM/BESS system [315]. A dynamic voltage control scheme based on a combination of SVC and STATCOM technology on a connected transmission system with IGs in a wind farm was discussed [316]. Reference [317], has been discussed the design of an offshore wind farm using a dc offshore grid based on resonant dc-dc converters. Multiphase resonant dc-dc converters are studied to step up the dc voltage from individual wind generators to a Medium Voltage (MV) dc bus and from the MV bus to an HVDC line that will connect the wind farm to shore. Compared to an equivalent ac grid based wind farm, a dc grid-based wind farm has slightly higher losses, but the weight of the magnetic components and cables is substantially lower. The analysis of operating permanent-magnet synchronous generators at variable and constant dc voltages shows that a fixed dc voltage has marginally higher efficiency than a variable dc voltage. However, using a variable dc voltage gives lower harmonics at the generator facing the voltage-source converter and the dc-dc step-up converter. An aggregated model of multiple parallel connected wind generators is developed and shown to accurately approximate a detailed PSCAD model during varying wind conditions and transients. In [318], has been introduced a new technique for the distributed voltage and frequency control of the local ac-grid in offshore wind farms based on synchronous generators. The proposed control technique allows the connection of the offshore wind farm using a diode based HVDC rectifier. The use of microgrid control techniques allowed the system comprising the wind farm and the diode HVdc rectifier to be operated in current or voltage control mode. Fault response to on-shore voltage sags of up to80%has been shown to be comparable to that of thyristor rectifiers. The proposed control technique has been shown to be robust against load changes in islanded operation, capacitor bank switching, diode-rectifier ac breaker tripping and wind turbine power limitation due to slow wind speeds. PSCAD simulations are used to prove the technical feasibility of the proposed control techniques both

in steady state and during transients. Several alternatives have been proposed for the voltage and frequency control of offshore ac grids using wind turbines based on doubly fed induction generators [319], [320]. Some techniques make use of an offshore STATCOM for this purpose [321]. The aforementioned techniques rely on the rectifier firing angle to control directly or indirectly the offshore grid voltage and frequency. Therefore, these techniques are not applicable to diode-based HVdc rectifiers.

3.18. Low-Voltage-Ride-Through (LVRT) Capability in Wind Power Systems Viewpoints:

In [322], Penghu, Taiwan, has the potential to be one of the most valuable sources of wind energy in the world. A 59-km submarine cable that connects Taiwan to Penghu Island is currently in the planning phase, and a large-scale offshore wind farm around Penghu will be developed. This will be the first offshore wind farm to be planned in Taiwan and will have a significant role in the development of renewable energy in this country. In the initial planning phase, various transient impact analyses must be performed. LVRT capability is one of the most critical items to be analyzed. The main target of this literature is to investigate the effect of LVRT technologies on the first Taiwan offshore wind farm planning. It begins by investigating the development of LVRT technologies, and then discusses the effect of grid strength on the preferred LVRT installation. The critical range of faults that can disconnect the wind farm from the grid with and without LVRT has been studied. Finally, the effect of LVRT characteristics on the transient stability of the power system in Taiwan is evaluated and the strategy of replacing the LVRT installations with reactive power compensation elements is proposed. In the early days of wind power generation, its penetration was low, and the sudden disconnection of a wind farm from the grid did not have a significant impact on the stability of the power system. As the amount of generated wind energy has increased to the point where wind farms generate hundreds of megawatts, their impact on the grid can no longer be ignored. Many utilities now require that wind turbines operate similarly to conventional generators. Therefore, new codes for connecting wind generators to the grid have been established in many countries. They cover such topics as LVRT capability, active power and frequency control, reactive power control, and voltage regulation [323]. Meeting LVRT requirement is particularly important in maintaining voltage stability, especially when wind generation is highly concentrated in one or a few locations. LVRT implies that wind generators must remain connected during most grid disturbances, including severe voltage drops. It was originally proposed by E.ON grid operator in Germany. Many utilities are imposing similar requirements. The implementation of LVRT requires different modifications to the system design, which translates to an increased cost in the wind power systems. Accordingly, effective and economic strategies for meeting LVRT requirement are required. Doubly fed induction generator (DFIG) wind turbines are the most widely used, especially in large wind farms. When DFIG systems are used, the main concern is to protect the rotor converter, and maintain the dc

bus voltage within an acceptable range. When the stator is directly connected to the grid, the transients that occur in the stator will be reflected in the rotor. Different solutions for protecting the converter have been proposed. During faults, power electronic devices are particularly important because they are sensitive to high fault currents and transient over-voltages on the dc bus [324]. Therefore, the implementation of LVRT in the DFIG is more complicated than in direct-drive wind turbines. Additionally, a different wind turbine type has different LVRT technology and capability. Importantly, the LVRT installations should be determined by the system conditions. For example, several offshore wind farms are geographically remote and have relatively weak transmission systems. Power system stability analyses, covering voltage, frequency, and rotor angle stability, are important to the successful operation of a power system and, therefore, must be performed very carefully before a large offshore wind farm is connected to the grid. Furthermore, strategies for improving dynamic and transient stability should be considered [325]. In this study, a model of the actual Taiwan power system in 2014 was established in PSS/E, and a base load flow and a fault current network were established. Dynamic simulations were performed to investigate the voltage, frequency, and rotor angle profiles when faults were applied in this wind power integrated system. In the past, wind generators were regarded as devices for distributed generation and thus were made to trip following even minor disturbances. However, as the penetration of wind power penetration increases, their impact on the grid can no longer be ignored. Today, wind turbines are required to operate like conventional generators in many utilities; consequently, many new grid codes for wind generators have been established [326], governing their LVRT capability, reactive power capability, and real power control. Of these requirements, LVRT capability represents the greatest challenge to wind turbine manufacturers. LVRT requires that wind generators must remain connected to the grid and stable during most grid faults, so that they contribute to the grid stability. For example, according to the U.S. wind farm grid code, if the voltage of a wind farm remains above 15% of the nominal voltage for a period that does not exceed 0.625 s, the plant must stay online [327]. To enhance the LVRT capability of wind farms, several approaches have been proposed. They can be divided into three categories: improvement of the control of the power converter, installation of additional hardware, and determination of the optimal PCC. Several novel rotor flux control algorithms, such as the robust controller algorithm, have been proposed [328]. These methods are usually activated promptly to allow the rotor-side converter sufficient time to oppose the fault-related current components that are induced by the stator flux. They require no additional hardware, but only a change in the control algorithm during the fault. However, under severe faults that reduce terminal voltage, the flux control method is of limited use. Some researchers [329] have indicated that a pitch controller can be used to increase the transient stability of wind generators. The limitation on the rate-of-change of pitch control is important during grid faults because it governs the rate at which the aerodynamic power can be reduced to prevent over-speeding. However, the mechanical

response is slow because of the time delay of the pitch controller system, and so its ability to enhance transient LVRT is quite limited. A commonly used solution for satisfying the LVRT requirement by the additional hardware installation method involves the use of an active crowbar circuit [330], which provides a low-impedance path for the rotor current during the fault. This method is relatively simple and cost-effective. However, upon activation of the crowbar, control over the machine is lost, and the DFIG behaves as a squirrel cage induction machine; therefore, the issue of reactive power consumption during grid faults must be addressed. Another method that involves the installation of hardware is to insert an energy storage system (ESS) [331], such as batteries or super capacitors, at the dc bus inside the rotor-side converter, where the energy produced during the fault is momentarily stored and is later exported to the grid following fault clearing. The ESS can also be applied under steady-state conditions to attenuate power fluctuation caused by wind variations. However, larger ESS systems require more space; accordingly, a dc chopper can be added inside the dc-link [332]. This dc chopper dissipates the excess power through its resistor and maintains the dc-bus voltage in a safe range during the critical period. In addition to the rotor resistance control method, reactive power compensators, such as FACTS devices can also be utilized to enhance reactive power supply and improve the LVRT characteristic of a wind generator [333]. However, the usage of FACTS devices clearly increases the cost of wind power integration. Notably, the LVRT characteristic can change the cost of wind generators, so the LVRT capability must be carefully designed based on the penetration of wind power and network characteristic. The most widely used type of generator for units above 1MW is the doubly fed induction machine. The application of the partial- scale converter to the rotor of the generator makes DFIG wind turbines attractive economically. However, this converter arrangement requires an advanced protection system [334], as it is more sensitive to disturbances on the grid than is a full power converter. In [335], with the increasing penetration of wind power into electric power grids, energy storage devices will be required to dynamically match the intermittency of wind energy. This paper proposes a novel two-layer constant power control scheme for a wind farm equipped with doubly fed induction generator (DFIG) wind turbines. Each DFIG wind turbine is equipped with a super-capacitor energy storage system (ESS) and is controlled by the low-layer wind turbine generator (WTG) controllers and coordinated by a high-layer wind farm supervisory controller (WFSC). To enable WTGs to effectively participate in frequency and active power regulation, unit commitment, economic dispatch, and electricity market operation, energy storage devices will be required to dynamically match the intermittency of wind energy. In [336], the authors investigated and compared different feasible electric energy storage technologies for intermittent renewable energy generation, such as wind power. Currently, pumped water and compressed air are the most commonly used energy storage technologies for power grids due to their low capital costs [337]. However, these two technologies are heavily dependent on geographical location with relatively low round-trip efficiency. Compared with their peers, batteries

and super-capacitors are more efficient, have a quicker response to demand variations, and are easy to develop and ubiquitously deployable. Compared to batteries, super-capacitors have a higher power density, higher round-trip efficiency, longer cycle life, and lower capital cost per cycle [338]. Therefore, super-capacitors are a good candidate for short-term (i.e., seconds to minutes) energy storage that enables WTGs to provide the function of frequency regulation and effectively participate in unit commitment and electricity market operation. The use of super-capacitors [338] or batteries [339]–[341] as energy storage devices for WTGs has been studied by some researchers. However, these studies only focused on control and operation of individual WTGs and did not investigate the issues of WTGs to participate in grid regulation. Reference [342], has been discussed the effects of installing variable current-limit reactors (CLRs) and adjusting load tap changers (LTCs) on the performance of a commercial wind farm in Taiwan using computer simulations. The companion paper (Part I) demonstrates the field-measured results, simulation model, and simulation results of the studied Jang-Bin wind farm with 23 2-MW doubly fed induction generator-type wind turbine generators connected to the utility system through a 23/161-kV 60-MVA step-up main transformer (MT) from six feeders. Six CLRs, which were originally designed to limit short-circuit currents under faulted conditions, are connected in series with the six feeders. The LTCs of the MT are used to adjust/regulate the secondary-side voltage at the 23-kV bus. Some simulated steady-state and transient results of the studied wind farm with variable values of the proposed CLRs and LTCs are analyzed and compared. In [343], a control scheme for wind farms based on synchronous generators connected to a single power converter is presented. The scheme is applicable to HVDC interfaced offshore or remote wind farms. The proposed control scheme is based on computing the optimal wind farm electrical frequency depending on the different incoming wind speeds. The power converter regulates the system frequency by adjusting the power injected to the HVDC circuit. Fault ride-through is also possible by reducing rapidly the injected active power. The proposed scheme is validated by means of simulations with a wind farm composed of four wind turbines. Onshore wind farms are nowadays capable of not only generating power but also providing support to the grid where they are connected providing ancillary services [344] or contributing to power system stability [345] while riding through faults in the grid [346], [347]. Onshore wind farms can actually be considered as wind power plants as they can be operated as conventional power plants [348].

3.19. Others Parameters of Wind Power Systems Viewpoints:

Remote and offshore wind farms need HVDC or HVAC lines to interface them to the main grid [349]. Above a certain critical distance, HVDC technology stands as the appropriate solution, which can be based on line commutated converters HVDC-LCC [350]–[352] or voltage source converters HVDC-VSC [353]–[355]. In both cases, HVDC systems require a power converter at the connection point of the wind farms, allowing a centralized control for the whole wind farm. Some offshore wind farms employ only this

central power converter with squirrel cage induction generators [356] or synchronous generators [357], [358], while others combine a central power converter with individual converters and doubly fed induction generators [355] in each wind turbine. Jovcic [357], [358] proposed a variable frequency wind farm grid to maximize power generation, based on the approach of [359], which is well demonstrated for a single wind turbine: applying a power reference $P^* = K\omega^3$ or the equivalent torque reference $T^* = K\omega^2$ [360], [361] with the appropriate constant, the wind turbine generation is maximized. This approach is broadly used for maximum power point tracking of a single wind turbine controlled by a dedicated power converter. However, the performance of this approach is not demonstrated for a wind farm with multiple wind turbines and a single power converter, when the different wind turbines are generating at different wind speeds. Offshore wind farms connected by means of HVDC have to reduce power rapidly when faults onshore occur in order to prevent over-voltages in HVDC circuits. Moreover, this has to be done without using fast communication systems to assure system reliability. Several solutions have been proposed recently [362], [363], including the use of braking resistors to dissipate the power, wind farm frequency increase to reduce power generation letting the wind turbines accelerate, wind farm voltage reduction or directly reducing the power in the converter. The present work presents a control scheme for wind farms (or clusters or wind turbines inside a wind farm) with wind turbines based on synchronous generators connected to a single HVDC-VSC converter. The configuration can be used for HVDC connections (with an already existing HVDC-VSC converter) and also with full power back-to-back power converters. The main advantage of the proposed configuration is that no power converters are required in the individual wind turbines and therefore cost is reduced and reliability is increased. The drawbacks include the lost of part of the wind energy when wind speeds are different (discussed in Section II), the need for auxiliary power converters to supply auxiliary equipment in the wind turbines and the more reduced control capability over the wind turbine mechanical system, compared to the use of individual power converters. Since wind generation is one of the most mature renewable energy technologies, it will have the greatest share of future renewable energy portfolio. Due to the special characteristics of the wind generation, it requires extensive research to explore the best choice for wind power integration. In light of the practical project experience, this paper explores the feasibility of using HVdc transmission technology, particularly multi terminal HVdc (MTDC), as one of the preferable solutions to solve the grid interconnection issue of wind generation. This paper mainly focuses on the application of the hybrid MTDC to integrate wind farms into the electric power grid. A five-terminal hybrid MTDC model system including a large capacity wind farm is set up in PSCAD/EMTDC, in which the corresponding control strategy is designed [364].

Currently, there are two different HVdc technologies available, i.e., the current-source converter (CSC)-based HVdc technology using thyristor and the voltage-source converter (VSC)-based HVdc technology using gate turn-off thyristor (GTO). A VSC possesses the advantages of controlling active and reactive power flow independently, operating as a static synchronous compensator (STATCOM) to dynamically compensate ac-bus voltage without using the ac harmonic filter [365], [366]. These features make VSC attractive for connection with wind farms. However, the power level and switching losses linked with the high-frequency pulsewidth modulation (PWM) operation of the VSC are serious and challenging issues that need to be dealt with in VSC-based high-power applications. On the other hand, the classical CSC-HVdc has been used for decades for bulk power transmission and proven to be superior to VSC-HVdc in terms of operating cost and stability [367]. For a strong ac system, the CSC may be a preferable option. Therefore, a hybrid MTDC system could be established by combining the advantages of both the VSC and the CSC. MTDC system can be evolved from the two-terminal system, so can the control strategy. The typical CSC operating modes include the dc voltage control, the dc current control, extinction angle control, firing angle control, and so on [368]. Depending on the control target, the control modes of the VSC include constant dc voltage and constant dc current control on the dc side and constant ac voltage and reactive power control on the ac side [369]. As far as MTDC is concerned, the transition and set point of each control mode is tightly coordinated between converters involved. It can be concluded that voltage droop mode and master–local control mode are primarily intended for MTDC system [370], [371]. The former indicates that the output voltage falls with the increase of the output current to guarantee the stable operation of MTDC. The latter means that one converter is assigned to control the dc voltage, while the remaining ones adopt the dc current or the dc power control. In light of the fact that the voltage droop mode is lack close-loop control and the current assignation characteristic is worse, therefore, in this paper, a similar control strategy to the master–local control scheme is implemented on a hybrid- MTDC system including a large-scale wind farm. The power reversal of a hybrid MTDC can be only performed with reconnections of dc terminals owing to the distinct requirement of VSC and CSC for power flow reversal [372], i.e., the power reversal of CSC deals with the dc voltage polarity reversing, while the direction of the current keeps unchanged. For VSC, in contrast, the dc voltage polarity remains the same, while the current direction alters. It seems to be a major limitation to the application of hybrid MTDC. However, as for wind power integration, wind farms are usually located at the remote areas which are far away from the load centers. The power flow always keeps unidirectional from wind farms to loads. The hybrid MTDC is well suited for this type of application. Many studies have explored the hybrid two-terminal or multi terminal technology or the wind power generation technology. However, very few papers have focused on the issue of combination hybrid MTDC with wind power integration. In [373], a two-terminal hybrid HVdc topology was presented. The sending end adopted a line-commutated converter (LCC) with a STATCOM to regulate the active power produced by doubly fed induction generator (DFIG) wind farms, while the receiving end was equipped with a current source inverter to feed the active

power into the main ac grid. This configuration required additional STATCOM to provide stator voltage support for DFIG due to the LCC that was assigned to function as a rectifier. Reference [374] proposed a hybrid MTDC to transfer wind power into the ac grid. A CSC was utilized to send the wind power aggregated by multiple VSCs to the ac side. Nevertheless, the study was constrained to the system performance under the normal operation condition without considering fault scenarios. Reference [375], the prospective inrush currents during the energization of wind turbine transformers in a large offshore wind farm during islanded operation were estimated by time-domain simulations covering different energizing scenarios. In this way, worst case procedures could be identified. The energization of the farm was carried out by an auxiliary diesel-driven synchronous generator placed on the offshore platform. The available information from all of the components and excitation control was implemented in PSCAD-EMTDC. In [376], the problem of accurately forecasting wind energy has garnered a great deal of attention in recent years. There are always some errors associated with any forecasting methodology. In [377], has been presented two RX models of a wind-driven wound-rotor induction generator (WRIG) with dynamic slip control for load-flow calculations of a large-scale wind farm connected to a distribution system. In [378], the west coast and islands of Taiwan have abundant wind resource, which offers a great opportunity for large-scale offshore wind power generation.

4. Summary of The Paper

The following tables give summary of the paper as:

Table 1. Comparison of Services Performed By Different FACTS Devices

Table 1 show that the comparisons of services performed by different FACTS controllers such as SVC, STATCOM, TCSC, SSSC, TCPAR, UPFC etc. in wind power farms.

Table 2. Covered Studies of Facts Applicability to WPP Challenges

Legend: SCIG – squirrel cage induction generator,
DFIG – doubly fed induction generator,
FSC – full scale converter between generator and grid

Table 2 show that the covered studies of FACTS controllers such as SVC, STATCOM, TCSC, SSSC, TCPAR, UPFC etc. applicability to wind power farms challenges.

5. Results and Discussions

The following tables give results and discussions of the paper as:

196

S.No.	Performance parameters of wind power farms	No. of literatures review out of 378 literatures	% of literatures review out of 378 literatures
1	General literatures regarding with application of FACTS controllers in wind power farms	16	4.23
2	Sub-synchronous Resonance (SSR) Problems in Wind Power System Viewpoint	15	3.97
3	Voltage Stability of Wind Power Systems Viewpoint	95	25.13
4	Power Oscillation Damping of Wind Power Systems Viewpoint	10	2.65
5	Wind Power Transfer Capability Viewpoint	02	0.53
6	Transient Stability of Wind Power Systems Viewpoint	03	0.79
7	Loadability of Wind Power System Viewpoint	02	0.53
8	Voltage Security Viewpoint	01	0.26
9	Reduce Active power and energy losses Viewpoint	04	1.06
10	Dynamic Performance of Wind Power System Viewpoint	02	0.53
11	Mitigations of Harmonics parameters of Wind Power Systems Viewpoints	07	1.85
12	Reliability of Wind Power Systems Viewpoints	15	3.97
13	Operations of Flexibility of Wind Power Systems Viewpoints	52	13.76
14	Operation of Wind Power Systems Viewpoints	28	7.41
15	Control of Wind Power Systems Viewpoints	23	6.08
16	Planning of Wind Power Systems viewpoint	03	0.79
17	Protection of Wind Power Systems viewpoint	21	5.56
18	Steady-State and Dynamic Stability by SVC and STATCOM in Wind Power Systems Viewpoints	22	5.82
19	Low-Voltage-Ride-Through (LVRT) capability in Wind Power Systems Viewpoints	27	7.14
20	Others Parameters of Wind Power Systems Viewpoints	30	7.94

From above tables it is concluded that the 4.23% of total literatures are reviews based on general literatures regarding with application of facts controllers in wind power farms, 3.97% of total literatures are reviews based on sub-synchronous resonance (SSR) problems in wind power system viewpoint, 25.13% of total literatures are reviews on voltage stability of wind power systems viewpoint, 2.65% of total literatures are reviews based on power oscillation damping of wind power systems viewpoint, 0.53% of total literatures are reviews based on wind power transfer capability viewpoint, 0.79% of total literatures are reviews based on transient stability of wind power systems viewpoint, 0.53% of total literatures are reviews based on loadability of wind power system viewpoint, 0.26% of total literatures are reviews based on voltage security viewpoint, 1.06% of total literatures are reviews based on reduce active power and energy losses viewpoint, 0.53% of total literatures are reviews based on dynamic performance of wind power system viewpoint, 1.85% of total literatures are reviews based on mitigations of harmonics parameters of wind power systems viewpoints, 3.97% of total literatures are reviews based on reliability of wind power systems viewpoints, 13.76% of total literatures are reviews based on operations of flexibility of wind power systems viewpoints, 7.41% of total literatures are reviews based on operation of wind power systems viewpoints, 6.08% of total literatures are reviews based on control of wind power systems viewpoints, 0.79% of total literatures are reviews based on planning of wind power systems viewpoint, 5.56% of total literatures are reviews based on protection of wind power systems viewpoint, 5.82% of total literatures are reviews based on steady-state and dynamic stability by svc and STATCOM in wind power systems viewpoints, 7.14% of total literatures are reviews based on low-voltage-ride-through (LVRT) capability in wind power systems viewpoints,7.95% of total literatures are reviews based on others parameters of wind power systems viewpoints.

Finally it is concluded that the maximum research work carryout from the enhancement of voltage stability in wind power farms by FACTS controllers such as SVC, TCSC, TCPAR STATCOM. SSSC, UPFC, and HPFC.

6. Conclusion

This paper has been attempt the critical review on the applications of FACTS controllers such as TCSC, SVC, TCPAR, STATCOM, SSSC, UPFC, IPFC, HPFC in wind farms for enhancement of damping ratio of systems, power transfer capability, active and reactive losses, loadability, voltage profile, voltage security, operation, control, planning, protection, others performance parameters point of view in wind power farms. Also this paper discussed the current status of the research and developments in the field of the application of FACTS controllers for enhancement of different performance parameters in wind power farms. Authors strongly believe that this survey article will be very much useful to the researchers and scientific engineers for finding out the relevant references in the field of the application of FACTS controllers in wind power farms for enhancement of different performance parameters of systems.

Acknowledgements

References

[1] J. G. Slootweg and W. L. Kling, "Impacts of distributed generation on power system transient stability", IEEE Power Engineering Society Summer Meeting, vol. 2, pp. 862- 867, 2002.

[2] J. G. Slootweg and W. L. Kling, Wind power in power systems, John Wiley and Sons, Ltd., 2005.

[3] M. P. Palsson, T. Toftevaag, K. Uhlen, J. O. G. Tande, "Large-scale wind power integration and voltage stability limits in regional networks". IEEE Power Engineering Society Summer Meeting, vol. 2, pp. 762 - 769 , 2002.

[4] U. Eminoglu and M. H. Hocaoglu, "Effect of SVCs on transmission system voltage profile for different static load models". Universities Power Engineering Conference, vol.1, pp. 11-14, Sep, 2004.

[5] C.H.Cheng and Y.Y Hsu, "Application of a power system stabiliser and a static VAr controller to a multimachine power system" IEE Proceedings on Generation, Transmission and Distribution, vol. 137,no. 1,pp. 8-12 Jan. 1990.

[6] K. S. Narendra and K. Parthasarathy, "Identification and control of dynamical systems using neural networks", IEEE Trans. Neural Networks, vol. 1, no. 1, pp. 4-27, Mar. 1990.

[7] J. G. Slootweg, and W. L. King, "Is the Answer Blowing in the Wind? ,"IEEE Trans. Power & Energy Magazine, vol. 3, pp. 26-33, Nov./ Dec. 2003.

[8] T. Ackerman, Power Wind Power in Power Systems, John Wiley & Sons, 2005.

[9] IEEE Working Committee Report, "Third Supplement to a Bibliography for the Study of Sub-synchronous Resonance between Rotating Machines and Power Systems," IEEE Trans. on Power Systems, vol. 6, no. 2, pp. 830-834, May 1991.

[10] IEEE Committee Report, "Reader's Guide to Subsynchronous Resonance," IEEE Trans. on Power Systems, vol. 7, no. 1, pp. 150-157, February 1992.

[11] N. G. Hingorani and L. Gyugyi, Understanding FACTS, IEEE Press, 1996.

[12] R.M. Mathur and R.K. Varma, Thyristor-Based FACTS Controllers for Electrical Transmission Systems IEEE Press and Wiley Interscience, New York, USA, Feb. 2002.

[13] A. E. Hammad and M. El-Sadek, "Application of a Thyristor Controlled VAR Compensator for Damping Subsynchronous Oscillations in Power Systems," IEEE Trans. on Power Apparatus and Systems, vol. PAS-1-3, no. 1, pp. 198-212, Jan. 1984.

[14] P. Pourbeik, R. J. Koessler, D. L. Dickmander, and W. Wong, "Integration of Large Wind Farms into Utility Grids (Part 2 – Performance Issues)," in Proc. 2003 IEEE Power Engineering Society General Meeting Conf, pp. 1520-1525.

[15] T. Thiringer and J. A. Dahlberg, "Periodic Pulsations from a Three-Bladed Wind Turbine," IEEE Trans. on Energy Conversion, vol. 16, no. 2, pp. 128-133, June 2001.

[16] E. N. Henrichsen and P. J. Nolan, "Dynamics and Stability of Wind Turbine Generators," IEEE Trans. on Power Apparatus and Systems, vol. PAS-101, no. 8, pp. 2640-2648, Aug. 1982.

[17] T.J.E. Miller, Reactive Power Control in Electric System, John Wiley & Sons, 1982.

[18] IEEE Committee Rep., "First benchmark model for computer simulation of subsynchronous resonance," IEEE Trans. Power Appl. Syst., vol. PAS- 96, no. 5, pp. 1565–1572, Sep./Oct. 1977.

[19] IEEE Subsynchronous Resonance Working Group, "Terms, definitions and symbols for subsynchronous oscillations," IEEE Trans. Power Apparatus and Systems, vol. PAS-104, no. 6, pp. 1326– 1334, 1985.

[20] A. B. L. Anderson, P. M. and J. E. Van Ness, Subsynchronous resonance in power systems, New York: IEEE Press, 1990.

[21] P. Pourbeik, R. J. Koessler, D. L. Dickmander, and W. Wong, "Integration of large wind farms into utility grids (Part 2-Performance issues)," in Proc. IEEE Power Eng. Soc. General Meeting Conf, pp. 1520–1525, 2003.

[22] M. Bongiorno, J. Svensson, and L. Angquist, "On control of static synchronous series compensator for SSR mitigation," IEEE Trans. Power Electron., vol. 23, no. 2, pp. 735–743, Mar. 2008.

[23] H. A. Mohammadpour, M. R. Alizadeh Pahlavani, and A. Shoulaie, "On control of gate-controlled series capacitor for SSR and power oscilation

damping ," CPE2009, 6th international Conf workshop, pp. 196–203, 2009.

[24] N.G. Hingorani, L. Gyugyi, Understanding FACTS: Concepts and technology of flexible ac transmission system, IEEE Press, NY, 2000.

[25] R.M. Mathur and R.K. Varma, Thyristor-Based FACTS Controllers for Electrical Transmission Systems IEEE Press and Wiley Interscience, New York, USA, Feb. 2002.

[26] R. K. Varma and S. Auddy, "Mitigation of subsynchronous oscillations in a series compensated wind farm using static var compensator," in Proc. IEEE Power Eng. Soc. General Meeting Conf, pp. 1–7, Paper 06 GM1272, 2006.

[27] R. K. Varma, S. Auddy, and Y. Semsedini, "Mitigation of subsynchronous resonance in a series-compensated wind farm using FACTS controllers," IEEE Trans. Power Del., vol. 23, no. 3, pp. 1645–1654, Jul. 2008.

[28] E. V. Larsen, J. J. Sanchez-Gasca, and J. H. Chow, "Concepts for design of FACTS controllers to damp power swings," IEEE Trans. Power Syst., vol. 10, no. 2, pp. 948–956, May 1995.

[29] F. Domingues de Jesus, E. Hirokazu Watanabe, L. Felipe Willcox de Souza and J. E. R. Alves, "SSR and Power Oscillation Damping Using Gate-Controlled Series Capacitors (GCSC)," IEEE Trans. Power Delivery., vol. 22, no. 3, pp. 1806–1812, July 2007.

[30] R. K. Varma, Y. Semsedini and S. Auddy, "Mitigation of Subsynchronous Oscillations in a Series Compensated Wind Farm with Thyristor Controlled Series Capacitor (TCSC)," in Proc. IEEE Power Eng. Soc. General Meeting Conf, pp. 1–7, 2007.

[31] M. S. El-Moursi, B. Bak-Jensen, M. H. Abdel-Rahman "Novel STATCOM Controller for Mitigating SSR and Damping Power System Oscillations in a Series Compensated Wind Park," IEEE Trans. Power Delivery., vol. 25, no. 2, pp. 429–441, Feb 2010.

[32] David G. Wilson and Rush D. Robinett, "Nonlinear Power Flow Control Applications to Conventional Generator Swing Equations Subject to Variable Generation," SPEEDAM 2010, International Symposium on Power Electronics, Electrical Drives, Automation and Motion.

[33] S.G.Thakare, and H.S.Dalvi, K.D.Joshi, "Statcom Based Fuzzy Controller For Grid Connected Wind Generator," Second International Conference on Emerging Trends in Engineering and Technology, ICETET-09.

[34] N. Dizdarevic, M. Majstrovic, and G. Andersson, "FACTS-based reactive power compensation of wind energy conversion system," Paper accepted for presentation at 2003 IEEE Bologna PowerTech Conference, June 23-26, Bologna, Italy.

[35] N. Dizdarevic, Unrfed Power Flow Controller in olleviotion of voltage slabiliry problem, Ph.D. thesis, University of Zagreb, Croatia, Oct. 2001, [Onlinc]. Available: www.cihD.hrl-ndizdar.

[36] J. Charles Smith, "Winds of change: issues in utility wind integration," IEEE Power and energy magazine, November/December 2005.

[37] I. Erlich and U. Bachmann, "Grid code requirements concerning connection and operation of wind turbines in Germany," in IEEE PES general meeting, June 2005, pp. 2230–2234.

[38] Claudio L.Souza et. al.,: "Power System Transient Stability Analysis Including Synchronous and Induction Generator", IEEE porto Power Tech Proceedings, Vol.2, pp.6, 2001.

[39] Sun, Tao, Chen, Z., Blaabjerg F.,"Voltage Recovery of Grid-Connected Wind Turbines After a Short-Circuit Fault" The 29' Annual Conference of the IEEE Industrial Electroics Society, IECON 2003, Roanoke, Virginia, USA, p.p.2723-2728, 2003.

[40] S. M. Muyeen, Mohammad Abdul Mannan, Mohd. Hasan Ali, Rion Takahashi, Toshiaki Murata, Junji Tamura," Stabilization of Grid Connected Wind Generator by STATCOM", Power Electronics and Drives Systems, 2005. PEDS 2005. International Conference on Volume 2, Issue , 28-01 Nov. 2005.

[41] Tarek Ahmed, Osamu Noro, Eiji Hiraki and Mutsuo Nakaoka, "Terminal Voltage Regulation Characteristics by Static Var Compensator for a Three-Phase Self-Excited Induction Generator", IEEE Transaction on Industry Applications, Vol.40, No.4, pp.978-988, July/August 2004.

[42] Y. L. Tan, "Analysis of Line Compensation by Shunt-Connected FACTS Controllers: A Comparison between SVC and STATCOM", IEEE Power Engineering Review, pp.57-58, August 1999.

[43] Claudio L.Souza et. al., "Power System Transient Stability Analysis including Synchronous and Induction Generator," IEEE Porto Power Tech Proceedings, Vol.2, pp.6, 2001.

[44] Daad-Saoud Z., "Application of STATCOMs to Wind Farms," IEE Proc. Gener. Transm.Distrib.Vol.145, No.5, pp.511-517, 1998.

[45] Sun, Tao, Chen et. al., "Flicker Mitigation of Grid Connected Wind Turbines Using STATCOM," Proc. Of 2nd IEE International Conference on Power Electronics, Machines and Drives, PEMD04, 2004.

[46] Z. Chen, F. Blaabjerg, Y Hu, "Voltage Recovery of Dynamic Slip Control Wind Turbines with a STATCOM," International Power Electronic Conference (IPEC05), S29-5, pp.1093-1100, 2005.

[47] S. M. Muyeen et al., "Stabilization of Grid Connected Wind Generator by STATCOM," International Conference on Power Electronics and Drive Systems (IEEE PEDS 2005), Conference CDROM, pp. 1584-1589, Malaysia, 2005.

[48] S.M.Muyeen et al., "Application of Fuzzy Logic Control Based STATCOM to Stabilize Wind Turbine Generator System," XVII International Conference on Electrical Machines (ICEM 2006), Paper No.198, Chania, Crete Island, Greece, Sep 2-5, 2006.

[49] S. M. Muyeen et al., "Transient Stability Analysis of Wind Generator System with the Consideration of

Multi-Mass Shaft Model," International Conference on Power Electronics and Drive Systems (IEEE PEDS 2005), Conference CDROM, pp.511-516, Malaysia, 2005.

[50] Salman K. Salman and Anita L. Teo, "Windmill Modeling Consideration and Factors Influencing the Stability of a Grid-Connected Wind Power-Based Embedded Generator," IEEE Transactions on Power Systems, Vol.18, No.2, pp.793-802, 2003.

[51] Gaurav Kumar Kasal, and Bhim Singh, "Voltage and Frequency Controllers for an Asynchronous Generator-Based Isolated Wind Energy Conversion System," IEEE Transactions On Energy Conversion, Vol. 26, No. 2, June 2011, pp.40-416.

[52] Z. Chen and Y. Hu, "Power system dynamics influenced by a power electronic interface for variable speed wind energy conversion systems", International Universities Power Engineering Conference, Vol. 2, pp. 659-663, September, 2004.

[53] R. Grunbaum, P. Halvarsson, D. Larsson and P. R. Jones, "Conditioning of power grids serving off-shore wind farms based on asynchronous generator", Conference on Power Electronics, Machine and Drives, Vol. 1, pp. 34-39, March/April, 2004.

[54] T. Sun, Z. Chen and F. Blaabjerg, "Flicker mitigation of grid connected wind turbines using STATCOM", Conference on Power Electronics, Machine and Drives, Vol. 1, pp. 175-180, March/April, 2004.

[55] M. I. Marei, T. H. M. El-Fouly, E. F. El-Saadany and M. M. A. Salama, "A flexible wind energy scheme for voltage compensation and flicker mitigation", IEEE Power Engineering Society General Meeting, Vol. 4, pp. 2497-2500, July, 2003.

[56] Z. Saad-Saoud, M. L. Lisboa, J. B. Ekanayake, N. Jenkins and G. Strbac, "Application of STATCOMs to wind farms", IEE Proceedings- Generation, Transmission and Distribution, Vol. 145, No. 5, pp. 511- 516, September, 1998.

[57] K. H. Sobtink, K. W. Renz and H. Tyll, "Operational experience and field tests of the SVG at Rejsby Hede", International Conference on Power System Technology, Vol. 1, pp. 318-322, August, 1998.

[58] H. Byung-Moon, L. Burn-Kyoo, J. Young-Soo and L. Kwang-Yeol, "Application feasibility analysis of STATCOM for wind power system with induction generator", Transactions of the Korean Institute of Electrical Engineers, Vol. 53, No. 6, pp. 309-315, June, 2004.

[59] X. Wu, A. Arulampalam, C. Zhan and N. Jenkins, "Application of a static reactive compensator (STATCOM) and a dynamic braking resistor (DBR) for the stability enhancement of a wind farm", Wind Engineering, Vol. 27, No. 2, pp. 93-106, 2003.

[60] J. Sung-ll, C. Jeong-Hwan, P. In-ki, H. Hye-Mi, C. Don-Man, K. Kwang-Ho and Y. Neung-Soo, "A study on the STATCOM applications for efficient operations of wind farm", Transactions of the Korean Institute of Electrical Engineers, Vol. 52, No. 5, pp. 250-256, May, 2003.

[61] K. H. Sobrink, J. K. Pedersen, K. O. H. Pedersen, F. Schettler, K. Bergmann and N. Jenkins, "Reactive power compensation of 24 MW wind farm using a 12-pulse voltage-source converter", International Conference on Large High Voltage Electric Systems, Vol. 4, August/September, 1998.

[62] A. Papantoniou and A. Coonick, "Simulation of FACTS for wind farm applications", IEE Colloquium on Power Electronics for Renewable Energy (Digest No: 1997/170), June, 1997.

[63] N. Dizdarevic and M. Majstrovic, "FACTS-based reactive power compensation of wind energy conversion system", IEEE Power Tech Conference Proceedings, Vol. 2, June, 2003.

[64] N. Dizdarevic, M. Majstrovic and G. Andersson, "Reactive power compensation of a wind energy conversion system using Unified Power Flow Controller", International Journal of Energy Technology and Policy, Vol. 3, No. 3, pp. 269-298, 2005.

[65] A. Papantoniou and A. Coonick, "Fuzzy Logic Control of a Unified Power Flow Controller for Wind Farm Applications", IEE Colloquium on Power Electronics for Renewable Energy, pp. 9/1-9/6, June, 1997.

[66] A. Kehrli and M. Ross, "Understanding grid integration issues at wind farms and solutions using voltage source converter FACTS technology", IEEE Power Engineering Society General Meeting, Vol. 3, pp. 1828- 1831, July, 2003.

[67] J. E. Hill, "A practical example of the use of distribution static compensator (D-STATCOM) to reduce voltage fluctuations", IEE Colloquium on Power Electronics for Renewable Energy (Digest No: 1997/170), June, 1997.

[68] P. K. S. Khan and J. K. Chatterjee, "Integration of solid-state lead-lag VAr compensator and self-excite induction generator for low cost power generation", National Power Engineering Conference, pp. 185-192, December, 2003.

[69] M. Noroozian, H. Knudsen and M. Bruntt, "Improving wind farm performance by reactive power compensation", proceedings of the IASTED International Conference Power and Energy Systems, pp. 437- 442, September, 2000.

[70] K. H. Sobrink, K. W. Renz and H. K. Tyll, "FACTS faces into wind", International Power Generation, Vol. 19, No. 6, pp. 51-52, November, 1996.

[71] R. C. Bansal, T. S. Bhatti and D. P. Kothari, "A novel mathematical modelling of induction generator for reactive power control of isolated hybrid power systems", International Journal of Modelling and Simulation, Vol. 24, No. 1, pp. 1-7, 2004.

[72] R. C. Bansal, "Reactive power compensation of wind-diesel hybrid power systems usibg Matlab/Simulink" International Journal of Energy Technology and Policy, Vol. 3, No. 3, pp. 237-252, 2005.

[73] M. Palsson, T. Toftevaag, K. Uhlen and J. O. G. Tande, "Large-scale Wind Power Integration and Voltage Stability Limits in Regional Networks", IEEE Power Engineering Society Summer Meeting, Vol. 2, pp. 762-769, 2002.

[74] M. Palsson, T. Toftevaag, K. Uhlen and J. O. G. Tande, "Control Concepts to Enable Increased Wind Power Penetration", IEEE Power Engineering Society General Meeting, Vol. 3, 1984-1990, July, 2003.

[75] N. Laverdure, S. Bacha, D. Roye, B. Raison and F. Dumas, "Elements of modeling of wind power systems with energy management: two structures in comparison", IEEE Annual Conference of the Industrial Electronics Society, Vol. 2, pp. 1083-1088, November, 2002.

[76] A. L. T. Garcia, J. M. M. Ortega and E. R. Ramos, "Reactive power compensation strategies for wind generation in distribution systems: a power quality approach" International Journal of Energy Technology and Policy, Vol. 3, No. 3, pp. 196-212, 2005.

[77] L. T. Ha and T. K. Saha, "Investigation of power loss and voltage stability limits for large wind farm connections to a subtransmission network", IEEE Power Engineering Society General Meeting, Vol. 2, pp. 2251-2256, June, 2004.

[78] C. D. Vournas and E. G. Potamianakis, "Investigation of short-term voltage instability problems and countermeasures", IEEE PES Power Systems Conference and Exposition, Vol. 1, pp. 385-391, October, 2004.

[79] W. Freitas, M. B. C. Salles, J. C. M. Vieira, A. Morelato, L. C. P. da Silva and V. F. da Costa, "Impacts of dynamic reactive power compensation devices on the performance of wind power generators" International Journal of Energy Technology and Policy, Vol. 3, No. 3, pp. 223-236, 2005.

[80] T. E. Sharaf-Eldin, M. S. Abou-Elalaa and T. K. Aboul-Seoud, "Controlled performance of a wind driven self-excited induction generator" Alexandria Engineering Journal, Vol. 43, No. 6, pp. 801-807, November, 2004.

[81] E. Muljadi, C. P. Butterfield, R. Yinger and H. Romanowitz, "Energy storage and reactive power compensation in a large windfarm" AIAA Aerospace Sciences Meeting and Exhibit, pp. 114-123, January, 2004.

[82] K. A. Nigim, A. F. Zobaa and I El-Amin, "An introduction to reactive power compensation of wind farms" International Journal of Energy Technology and Policy, Vol. 3, No. 3, pp. 185-195, 2005.

[83] Jun-ling Wu, Shuang-xi Zhou, Jian-feng Sun, Shou-sun Chen and Qinghe Meng, "Analysis on maximum power injection of wind farm connected to power system" Power System Technology, Vol. 28, No. 20, pp. 28-32, October, 2004.

[84] O. Anaya-Lara, F. Hughes, N. Jenkins, and G. Strbac, "Influence of windfarms on power system dynamic and transient stability," Wind Engineering, vol. 30, no. 2, pp. 107-27, 2006.

[85] J. Slootweg and W. Kling, "The impact of large scale wind power generation on power system oscillations," Electric Power Systems Research, vol. 67, no. 1, pp. 9 - 20, 2003.

[86] E. Hagstrom, I. Norheim, and K. Uhlen, "Large-scale wind power integration in norway and impact on damping in the nordic grid," Wind Energy vol. 8, no. 3, pp. 375-384, JUL-SEP 2005.

[87] G. Tsourakis, B. Nomikos, and C. Vournas, "Effect of wind parks with doubly fed asynchronous generators on small-signal stability," Electric Power Systems Research, vol. 79, no. 1, pp. 190 - 200, 2009.

[88] G. Rogers, Power System Oscillations, 1st ed., ser. Power Electronics and Power Systems. Kluwer Academic Publishers, 2000, ISBN-10: 0792377125.

[89] E. Lerch, D. Povh, and L. Xu, "Advanced svc control for damping power system oscillations," Power Systems, IEEE Transactions on, vol. 6, no. 2, pp. 524-535, may 1991.

[90] N. Mithulananthan, C. Canizares, J. Reeve, and G. Rogers, "Comparison of pss, svc, and statcom controllers for damping power system oscillations," Power Systems, IEEE Transactions on, vol. 18, no. 2, pp. 786 - 792, may 2003.

[91] E.-Z. Zhou, "Application of static var compensators to increase power system damping," Power Systems, IEEE Transactions on, vol. 8, no. 2, pp. 655 -661, may 1993.

[92] G. Liu, Z. Xu, Y. Huang, and W. Pan, "Analysis of inter-area oscillations in the south china interconnected power system," Electric Power Systems Research, vol. 70, no. 1, pp. 38 - 45, 2004.

[93] T. Smed and G. Andersson, "Utilizing hvdc to damp power oscillations," Power Delivery, IEEE Transactions on, vol. 8, no. 2, pp. 620 -627, apr 1993.

[94] V. Akhmatov, "Variable-speed wind turbines with doubly-fed induction generators, part I: Modelling in dynamic simulation tools," Wind Engineering, vol. 26, no. 2, p. 85, 2002.

[95] R. de Almeida and J. Lopes, "Participation of doubly fed induction wind generators in system frequency regulation," Power Systems, IEEE Transactions on, vol. 22, no. 3, pp. 944-950, Aug. 2007.

[96] T. Kniippel, J. Thisted, B. Andresen, M. N. Frydensbjerg, V. Akhmatov, and J. N. Nielsen, "Grid support capabilities of full-load converter interfaced wind turbines," in POWER-GEN India & Central Asia. PennWell Corporation, April 2010.

[97] V. Akhmatov, "Variable-speed wind turbines with doubly-fed induction generators part II: Power system stability," Wind Engineering, vol. 26, no. 3, p. 171, 2002.

[98] F. Hughes, O. Anaya-Lara, N. Jenkins, and G. Strbac, "A power system stabilizer for dfig-based wind generation," Power System, IEEE Transactions on, vol. 21, no. 2, pp. 763-772, 2006.

[99]   K. Elkington, "Modelling and control of doubly fed induction generators in power systems: Towards understanding the impact of large wind parks on power system stability," PhD Thesis, KTH, Electric Power Systems, SE-100 44, Stockholm, Sweden, April 2009, ISBN: 978-91-7415-264-7.

[100]   Z. Miao, L. Fan, D. Osborn, and S. Yuvarajan, "Control of dfig based wind generation to improve inter-area oscillation damping," Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, pp. 1-7, July 2008.

[101]   C. Martinez, G. Joos, and B. Ooi, "Power system stabilizers in variable speed wind farms," in Power Energy Society General Meeting, 2009.PES '09. IEEE, July 2009, pp. 1 - 7 .

[102]   N. Kshatriya, U. D. Annakkage, F. M. Hughes, and A. M. Gole, "Optimized partial eigenstrucrure assignment-based design of a combined pss and active damping controller for a dfig," Power Systems, IEEE Transactions on, vol. 25, no. 2, pp. 866 -876, may 2010.

[103]   P. Ledesma and C. Gallardo, "Contribution of variable-speed wind farms to damping of power system oscillations," 2007 IEEE Lausanne Power Tech, pp. 190-194, 2007.

[104]   Sung-Il Jang, Jeong-Hwan Choi, In-Ki Park, Hye-Mi Hwang, Don-Man Choi, Kwan-Ho Kim, Neung Soo Yoo A, "A Study on the STATCOM Application for Efficient Operations of Wind Farm," May 2003, Volume 52 Number 5 pp.250-256.

[105]   Byung-Moon Han, Bum-Kyoo Lee, Young-Soo Jon, Kwang-YeolLee A, "Application Feasibility Analysis of STATCOM for Wind Power System with Induction Generator," June 2004, Volume 53 Number 6 pp.309-315.

[106]   Sidhartha Panda, and Ramnarayan N. Patel, "Improving Power System Transient Stability with An off–Centre Location of Shunt Facts Devices," Journal of Electrical Engineering, Vol. 57, No. 6, 2006, pp.365–368.

[107]   V.Suresh Kumar, Ahmed F.Zobaa, R.Dinesh Kannan, and K.Kalaiselvi, "Power Quality and Stability Improvement in Wind Park System Using STATCOM," Jordan Journal of Mechanical and Industrial Engineering, Volume 4, Number 1, Jan. 2010, Pages 169 – 176.

[108]   A.Arulampalam, M.Barnes & N.Jenkins, Power quality and stability improvement of a wind farm using STATCOM, Proc. IEE Generation, Transmission & Distribution, Vol. 153, No.6, 2006, 701-710.

[109]   Z.Saad-Saoud, M.L.Lisboa, J.B.Ekanayake, N. Jenkins & G.Strbac, Application of STATCOMs to wind farms, Proc. IEE Generation, Transmission & Distribution, Vol.145, No. 5, 1998, 511–516.

[110]   A.Arulampalam, J.B.Ekanayake & N.Jenkins, Application study of a STATCOM with energy storage, Proc. IEE Generation, Transmission & Distribution, Vol. 150, No. 3, 2003, 373–384.

[111]   G. Elsady1, Y. A. Mobarak2, and A-R Youssef, "STATCOM for Improved Dynamic Performance of Wind," Proceedings of the 14th International Middle East Power Systems Conference (MEPCON'10), Cairo University, Egypt, December 19-21, 2010, Paper ID 207.

[112]   Lie Xu Liangzhong Yao Sasse, C.," Comparison of using SVC and STATCOM for wind farm integration", International Conference on Power System Technology, pp. 1-7, Oct 2006.

[113]   C. A. Ca˜nizares, M. Pozzi, and E. Uzunovic, "STATCOM modeling for voltage and angle stability studies", International Journal of Electrical Power & Energy Systems, vol. 25, no. 6, pp. 431–441, June 2003.

[114]   E. Uzunovic, C. A. Canizares, J. Reeve, "Fundamental Frequency Model of Static Synchronous Compensator", in: Proc. North American Power Symposium (NAPS), Laramie, Wyoming, pp. 49–54, 1997.

[115]   D. N. Koseterev, "Modeling Synchronous Voltage Source Converters in Transmission System Planning Studies", IEEE Trans. Power Delivery Vol.12, No.2, pp. 947–952, 1997.

[116]   Mohamed A. El-Sayed, "Integrating Wind Energy into Weak Power Grid Using Fuzzy Controlled TSC compensator," International Conference on Renewable Energies and Power Quality (ICREPQ'10), Granada (Spain), 23rd to 25th March, 2010.

[117]   K.Malarvizhi, and K.Baskaran, "Enhancement of Voltage Stability in Fixed Speed Wind Energy Conversion Systems using FACTS Controller," International Journal of Engineering Science and Technology Vol. 2(6), 2010, 1800-1810.

[118]   T. Sun, Z. Chen, F. Blaabjerg, "Voltage recovery of grid-connected wind turbines with DFIG after a short-circuit fault," 2004 IEEE 35th Annual Power Electronics Specialists Conference, vol. 3, pp. 1991-97, 20-25 June 2004.

[119]   M. Molinas, S. Vazquez, T. Takaku, J.M. Carrasco, R. Shimada, T. Undeland, "Improvement of transient stability margin in power systems with integrated wind generation using a STATCOM: An experimental verification," International Conference on Future Power Systems, 16-18 Nov. 2005.

[120]   E. Muljadi, C.P. Butterfield, "Wind Farm Power System Model Development," World Renewable Energy Congress VIII, Colorado, Aug-Sept 2004.

[121]   S.M. Muyeen, M.A. Mannan, M.H. Ali, R. Takahashi, T. Murata, J. Tamura, "Stabilization of Grid Connected Wind Generator by STATCOM," IEEE Power Electronics and Drives Systems, Vol. 2, 28-01 Nov. 2005.

[122]   Z. Saad-Saoud, M.L. Lisboa, J.B. Ekanayake, N. Jenkins, G. Strbac, "Application of STATCOMs to wind farms," IEE Proceedings – Generation, Transmission, Distribution, vol. 145, pp.1584-89, Sept 1998.

[123]   L. Chun, J. Qirong, X. Jianxin, "Investigation of Voltage Regulation Stability of Static Synchronous

Compensator in Power System," IEEE Power Engineering Society Winter Meeting, vol. 4, 2642-47, 23-27 Jan. 2000.

[124] Wei Qiao, Ganesh Kumar Venayagamoorthy, and Ronald G. Harley, "Real-Time Implementation of a STATCOM on a Wind Farm Equipped With Doubly Fed Induction Generators Farms in Power Grid," IEEE Transactions On Industry Applications, Vol. 45, No. 1, January/February 2009.

[125] N. Dizdarevic, Unified Power Flow Controller in alleviation of voltage stability problem, Ph.D. thesis, University of Zagreb, Croatia, Oct. 2001, [Online]. Available: www.eihp.hr/~ndizdar.

[126] Ramaprasad Panda, Prasant kumar Satpathy, and Subrata Paul, "Application of SVC to mitigate voltage instability in a Wind system connected with Grid," International Journal Of Power System Operation and Energy Management (IJPSOEM) Volume-1, Issue-1, pp. 90-96, 2011.

[127] A. Adamczyk, R. Teodorescu, and P. Rodriguez, "Control of Full-Scale Converter Based Wind Power Plants for Damping of Low Frequency System Oscillations," Paper accepted for presentation at the 2011 IEEE Trondheim Power Tech.

[128] W. Qiao, G.K. Venayagamoorthy, R.G. Harley, "Coordinated Reactive Power Control of a Large Wind Farm and a STATCOM Using Heuristic Dynamic Programming", IEEE Ttrans. on Energy Conversion, Vol. 24, No. 2, Jun 2009.

[129] Abdel – Magid Y.L. and El-Amin I.M., (1987)"Dynamic Stability of wind –turbine generators under widely varying load conditions", Electrical Power and Energy Systems, Vol.9, No.3, pp.180-188,1987.

[130] Clemens Jauch, Poul Sorensen, Ian Norheim, Carsten Rasmussen, (2007) "Simulation of the Impact of Wind power on the transient fault behavior of the Nordic Power System", Electric Power System Research, Vol. 77, pp.135-144.

[131] Mohamed S.Elmoursi, Adel M.Sharaf,(2006), "Novel STATCOM controllers for voltage stabilization of standalone Hybrid schemes", International Journal of Emerging Electric Power Systems, Vol.7, Issue 3, Art 5,pp. 1-27.

[132] Olof Samuelsson and Sture Lindahl, (2005),"On Speed Stability", IEEE Transactions on Power Systems, Vol.20, No.2,pp. 1179-1180.

[133] Istvan Erlich, Jorg Kretschmann, Jens Fortmann, Stephan Mueller-Engelhardt and Holger Wrede, (2007),"Modeling of Wind Turbines Based on Doubly-Fed Induction Generators for Power System Stability Studies", IEEE Transactions on Power Systems, Vol.22, No.3, 2007, pp.909-919, 2007.

[134] Varma R.K. and Tejbir S.Sidhu, (2006)"Bibliographic Review of FACTS and HVDC applications in Wind Power Systems", International Journal of Emerging Electric Power Systems, Vol.7, No. 3, pp. 1-16.

[135] Vladislav Akhmatov, (2003),"Analysis of dynamic behavior of electric power systems with large amount of wind power", Ph.D thesis, Technical University of Denmark.

[136] Senthil Kumar.N. , Abdullah Khan.M., (2008) ,"Impact of FACTS controllers on the dynamic stability of power systems connected with Wind Farms", Wind Engineering, Vol.32, No.2, pp.115-132.

[137] Gaurav Kumar Kasal and Bhim Singh, "Three-Phase 4-Wire Isolated Wind Energy Conversion System Employing VSC with a T-Connected Transformer for Neutral Current Compensation," Journal of Electrical Engineering & Technology Vol. 4, No. 2, pp. 211~218, 2009.

[138] Liang Wu, Jeongje Park, Jaeseok Choi and A. A. EI-Keib, "Probabilistic Reliability Evaluation of Power Systems Including Wind Turbine Generators Considering Wind Speed Correlation," Journal of Electrical Engineering & Technology Vol. 4, No. 4, pp. 485~491, 2009.

[139] Gilsung Byeon, In Kwon Park and Gilsoo Jang, "Modeling and Control of a Doubly-Fed Induction Generator (DFIG) Wind Power Generation System for Real-time Simulations," Journal of Electrical Engineering & Technology Vol. 5, No. 1, pp. 61~69, 2010.

[140] Ji-Heon Lee, Jong-Kyou Jeong, Byung-Moon Han, Nam-Sup Choi and Han-Ju Cha, "DFIG Wind Power System with a DDPWM Controlled Matrix Converter," Journal of Electrical Engineering & Technology Vol. 5, No. 2, pp. 299~306, 2010.

[141] Win-Won Park, Sang-Geun Han, and In-Keun Yu, "Real Weather Condition Based Simulation of Stand-Alone Wind Power Generation Systems Using RTDS,"KIEE International Transactions on EMECS, Vol.4-B, No.3, pp.146-152, 2004.

[142] Ramaprasad Panda1, Prasant kumar Satpathy, Subrata Paul, "Application of SVC to mitigate voltage instability in a Wind system connected with GRID," International Journal Of Power System Operation and Energy Management (IJPSOEM), Volume-1, Issue-1, pp.90-96, 2011.

[143] Johan Ribrant, and Lina Margareta Bertling, "Survey of Failures in Wind Power Systems With Focus on Swedish Wind Power Plants During 1997–2005," IEEE Transactions On Energy Conversion, Vol. 22, No. 1, pp.167-173, March 2007.

[144] A.M. Sharaf, and Weihua Wang, "A Low-Cost Voltage Stabilization and Power Quality Enhancement Scheme for a Small Renewable Wind Energy Scheme," IEEE ISIE 2006, July 9-12, 2006, pp.1946-1956, Montreal, Quebec, Canada.

[145] European Wind Energy Association.(2003). Wind energy—the facts, H. Chandler, Ed. [Online]. Available: http://www.ewea.org.

[146] L.Bertling, "Pre-study on reliability-centered maintenance forwind power systems with focus on condition monitoring systems," KTH (Royal Inst. Technol.)School Electr.Eng., Stockholm, Sweden, Elforsk project 2356, 2005.

[147] T. K. Hansen, private communication, Jan. 2006.

[148] L. Bertling, R. N. Allan, and R. Eriksson, "A reliability-centred asset maintenance method for assessing the impact of maintenance in power distribution systems," presented at the IEEE PES General Meeting, San Francisco, Jun. 2005, TPWRS-00271–2003. R3.

[149] G. Elsady, Y. A. Mobarak, and A-R Youssef, "STATCOM for Improved Dynamic Performance of Wind Farms in Power Grid," Proceedings of the 14th International Middle East Power Systems Conference (MEPCON'10), Cairo University, Egypt, December 19-21, 2010, Paper ID 207.

[150] Lie Xu Liangzhong Yao Sasse, C.," Comparison of using SVC and STATCOM for wind farm integration", International Conference on Power System Technology, pp. 1-7, Oct 2006.

[151] Wei Qiao, Ganesh K. Venayagamoorthy, and Ronald G. Harley, "DHP-Based Wide-Area Coordinating Control of a Power System with a Large Wind Farm and Multiple FACTS Devices," Proceedings of International Joint Conference on Neural Networks, Orlando, Florida, USA, August 12-17, 2007.

[152] P. J. Werbos, "Approximate dynamic programming for real-time control and neural modeling," in Handbook of Intelligent Control, D. White and D. Sofge, Eds., New York: Van Nostrand Reinhold, 1992, pp. 493-526.

[153] D. V. Prokhorov and D. C. Wunsch, "Adaptive critic designs," IEEE Trans. Neural Networks, vol. 8, no. 5, pp. 997-1007, Sept. 1997.

[154] G. K. Venayagamoorthy, R. G. Harley, and D. C. Wunsch, "Implementation of adaptive critic-based neurocontrollers for turbogenerators in a multimachine power system," IEEE Trans. Neural Networks, vol. 14, no. 5, pp. 1047-1064, Sept. 2003.

[155] J-W Park, R. G. Harley, and G. K. Venayagamoorthy, "New External Neuro-controller for Series Capacitive Reactance Compensator in a Power Network," IEEE Trans. Power Systems, vol. 19, no. 3, pp. 1462-1472, Aug. 2004.

[156] W. Qiao and R. G. Harley, "Indirect adaptive external neuro-control for a series capacitive reactance compensator based on a voltage source PWM converter in damping power oscillations," IEEE Trans. Industrial Electronics, vol. 54, no. 1, Feb. 2007, in press.

[157] J. Kennedy and R. C. Eberhart, "Particle swarm optimization," in Proc. of IEEE International Conference on Neural Networks, Piscataway, NJ, USA, Nov. 27-Dec. 1, 1995, vol. 4, pp. 1942-1948.

[158] J. Charles Smith, "Winds of change: issues in utility wind integration," IEEE Power and energy magazine, November/December 2005.

[159] I. Erlich and U. Bachmann, "Grid code requirements concerning connection and operation of wind turbines in Germany," in IEEE PES general meeting, June 2005, pp. 2230–2234.

[160] Claudio L.Souza et. al.,: "Power System Transient Stability Analysis Including Synchronous and Induction Generator", IEEE porto Power Tech Proceedings, Vol.2, pp.6, 2001.

[161] Sun, Tao, Chen, Z., Blaabjerg F.,"Voltage Recovery of Grid-Connected Wind Turbines After a Short-Circuit Fault" The 29' Annual Conference of the IEEE Industrial Electroics Society, IECON 2003, Roanoke, Virginia, USA, p.p.2723-2728, 2003.

[162] S. M. Muyeen, Mohammad Abdul Mannan, Mohd. Hasan Ali, Rion Takahashi, Toshiaki Murata, Junji Tamura," Stabilization of Grid Connected Wind Generator by STATCOM", Power Electronics and Drives Systems, 2005. PEDS 2005. International Conference on Volume 2, Issue , 28-01 Nov. 200.

[163] Tarek Ahmed, Osamu Noro, Eiji Hiraki and Mutsuo Nakaoka, "Terminal Voltage Regulation Characteristics by Static Var Compensator for a Three-Phase Self-Excited Induction Generator", IEEE Transaction on Industry Applications, Vol.40, No.4, pp.978-988, July/August 2004.

[164] Y. L. Tan, "Analysis of Line Compensation by Shunt-Connected FACTS Controllers: A Comparison between SVC and STATCOM", IEEE Power Engineering Review, pp.57-58, August 1999.

[165] J. G. Slootweg, S. W. H de Haan, H. Polinder, and W. L. Kling, "Modeling Wind Turbines in Power System Dynamics Simulations." Proceedings of the 2001 IEEE Power Engineering Society Summer Meeting, Vol. 1, pp. 22-26, July 2001.

[166] G. Lalor, J. Ritchie, S. Rourke, D. Flynn and M. J. O'Malley, "Dynamic frequency control with increasing wind generation." Proceedings of the 2004 IEEE Power Engineering Society General Meeting, Vol. 2, pp. 1715-1720, June 2004.

[167] Erlich, W. Winter, and A. Dittrich, "Advanced grid requirements for the integration of wind turbines into the german transmission system," IEEE PES General Meeting, pp. 1–7, 2006.

[168] A. Luna, P. Rodriguez, R. Teodorescu, and F. Blaabjerg, "Low voltage ride through strategies for SCIG wind turbines in distributed power generation systems," Power Electronics Specialist Conference, pp. 2333–2339, June 2008.

[169] M. Molinas, J. A. Suul, and T. M. Undeland, "Low voltage ride through of wind farms with cage generators: STATCOM versus SVC," IEEE Trans. on Power El., vol. 23, pp. 1104–1117, 2008.

[170] L. Qi, J. Langston, and M. Steurer, "Applying a STATCOM for stability improvement to an existing wind farm with fixed-speed induction generators," PES General Meeting, pp. 1–6, 2008.

[171] Arefeh Danesh Shakib, Ervin Spahić, and Gerd Balzer, "Optimal Location of Series FACTS Devices toControl Line Overloads in Power Systems with High Wind Feeding," Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania.

[172] N.S. Kumar, and J.G. Krishnan, "Application of FACTS Controllers for Wind Power Smoothening in Grid-connected Doubly-fed Induction Generator

Systems," Australian Journal of Electrical and Electronics Engineering, Vol. 8, No.1, 2011.

[173] Shuhui Li, Donald C. Wunsch, Edgar A. O'Hair, and Michael G. Giesselmann, "Using Neural Networks to Estimate Wind Turbine Power Generation," IEEE Transactions On Energy Conversion, Vol. 16, No. 3, September 2001.

[174] N. Dinic, B. Fox, D. Flynn, L. Xu and A. Kennedy, "Increasing wind farm capacity," IEE Proc.-Gener.Transm.Distrib., Vol. 153, No. 4, July 2006.

[175] Tande, J.O.V.: 'Applying power quality characteristics of wind turbines for assessing impact on voltage quality', Wind Energy, 2002, 5, pp. 37–52.

[176] Slootweg, J.G., de Haan, S.W.H., Polinder, H., and Kling, W.L.: 'Wind power and voltage control' in Ackermann, T. (Ed.): 'Wind power in power systems' (Wiley, 2005).

[177] Cartwright, P., Holdsworth, L., Ekanayake, J. B., and Jenkins, N.: 'Co-ordinated voltage control strategy for a doubly-fed induction generator based wind farm', IEE Proc., Gener. Transm.Distrib., 2004, 151, (4), pp. 495–502.

[178] Slootweg, J.G., de Haan, S.W.H., Polinder, H., and Kling, W.L.: 'Voltage control methods with grid connected wind turbines', Wind Eng., 2001, 25, pp. 353–366.

[179] Romanowitz, H.,Muljadi, E., Butterfield, C. P., and Yinger,R.: 'VAr support from distributed wind energy resources'. Presented at the World Renewable Energy Congress VIII (CD Record), Denver, 2004.

[180] A. Arulampalam, M. Barnes, N. Jenkins and J.B. Ekanayake, "Power quality and stability improvement of a wind farm using STATCOM supported with hybrid battery energy storage," IEE Proc.-Gener.Transm.Distrib., Vol. 153, No. 6, November 2006.

[181] Saad-Saoud, Z., Lisboa, M.L., Ekanayake, J.B., Jenkins, N., and Strbac, G.: 'Application of STATCOMs to wind farms', IEE Proc. Gener. Transm.Distrib., 1998, 145, (5), pp. 511–516.

[182] A book written by the project group at the conclusion of a project to install and monitor the performance of an 8MVAr ASVC at Rejsby Hede wind farm in Jutland. 'Power quality improvements of wind farms', Denmark, June 1998, ISBN 87-90707-05-2.

[183] Arulampalam, A., Ekanayake, J.B., and Jenkins, N.: 'Application study of a STATCOMwith energy storage', IEE Proc. Gener. Transm.Distrib., 2003, 150, (3), pp. 373–384.

[184] Hitachi, I.A., and Suzuki, H.: 'Levelling of power fluctuation of wind power generation using sodium-sulfur battery'. Proc. of 6th Int. Conf. on Batteries for Utility Energy Storage, Germany, September 1999, pp. 7T3–7T3.

[185] Arulampalam, A.: 'Power-quality improvement with battery-supported voltage-source converters'. Thesis submitted to University of Manchester of Science and Technology, November 2002.

[186] Bousseau, P.: 'Solutions for the grid integration of wind farms – A survey'. Proc. of 2004 European Wind Energy Conf., November 2004, pp. 12–16.

[187] Ribeiro, P.F., Johnson, B.K., Crow, M.L., Arsoy, A., and Liu, Y.: 'Energy storage systems for advanced power applications' (invited paper), Proc. IEEE, 2001, 89, (12), pp. 1744–1756.

[188] Julia Nilsson, and Lina Bertling, "Maintenance Management of Wind Power Systems Using Condition Monitoring Systems—Life Cycle Cost Analysis for Two Case Studies," IEEE Transactions On Energy Conversion, Vol. 22, No. 1, March 2007.

[189] Changling Luo, Hadi Banakar, Baike Shen, and Boon-Teck Ooi, "Strategies to Smooth Wind Power Fluctuations of Wind Turbine Generator," IEEE Transactions On Energy Conversion, Vol. 22, No. 2, June 2007.

[190] Gerardo Tapia, Arantxa Tapia, and J. Xabier Ostolaza, "Proportional–Integral Regulator-Based Approach to Wind Farm Reactive Power Management for Secondary Voltage Control," IEEE Transactions On Energy Conversion, Vol. 22, No. 2, June 2007.

[191] Lie Xu, Liangzhong Yao, and Christian Sasse, "Grid Integration of Large DFIG-Based Wind Farms Using VSC Transmission," IEEE Transactions On Power Systems, Vol. 22, No. 3, August 2007.

[192] Nayeem Rahmat Ullah, Torböjrn Thiringer, and Daniel Karlsson, "Voltage and Transient Stability Support by Wind Farms Complying With the E.ON Netz Grid Code," IEEE Transactions On Power Systems, Vol. 22, No. 4, November 2007.

[193] J. C. Smith, "Winds of change: Issues in utility wind integration," IEEE Power Energy Mag., vol. 3, no. 6, pp. 20–25, Nov./Dec. 2005.

[194] I. Erlich and U. Bachmann, "Grid code requirements concerning connection and operation of wind turbines in Germany," in Proc. IEEE Power Eng. Soc. General Meeting, Jun. 2005, pp. 2230–2234.

[195] F. Van Hulle, Large Scale Integration of Wind Energy in the European Power Supply: Analysis, Issues and Recommendations, EWEA Tech Rep., 2005.

[196] Interconnection forWind Energy, Federal Energy Regulatory Commission Tech. Rep., 2005.

[197] S. Kraftnät, AffäRsverket Svenska Kraftnäts Föreskrifter Och Allmänna Råd Om Driftsäkerhetsteknik Utformning av Produktionsanläggningar (in Swedish) Tech. Rep. SvKFS 2005:2.

[198] Wind Turbines Connected to Grids with Voltages Above 100 kV – Technical Regulation for the Properties and the Regulation of Wind Turbines, Elkraft System and Eltra Regulation, 2004, Draft version TF 3.2.5.

[199] Technical Rquirements for the Connection of Generation Facvilities to the Hydro-Québec Transmission System: Supplementary Requirements for Wind Generation, Hydro-Québec Tech. Rep., 2005.

[200] Wind Power Facility Technical Requirements, Alberta Electric System Operator Tech. Rep., 2004.

[201] Grid Code: High and Extra High Voltage, E.ON Netz GmbH Tech. Rep., 2006, Status:1.

[202] T. Ackermann, Ed., Wind Power in Power Systems New York,Wiley, 2005.

[203] S. Muller, M. Deicke, and R. W. De Doncker, "Doubly fed induction generator systems for wind turbines," IEEE Ind. Appl. Mag., vol. 8, no. 3, pp. 26–33, May/Jun. 2002.

[204] R. Pena, J. C. Clare, and G. M. Asher, "Double fed induction generator using back-to-back PWM converter and its application to variable speed wind-energy generation," Proc. Inst. Elect. Eng., Elect. Power Appl., vol. 143, no. 3, pp. 231–241, 1996.

[205] E. Eriksson, P. Halvarsson, D. Wensky, and M. Hausler, "System approach on designing an offshore windpower grid connection," in Proc. 4th Int. Workshop Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, Sweden, Oct. 2003.

[206] S. M. Bolik, "Grid requirements challenges for wind turbines," in Proc. 4th Int. Workshop Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, Sweden, Oct. 2003.

[207] K. H. Sobrink, P. L. Sorensen, P. Christensen, N. Sandersen, K. Eriksson, and P. Holmberg, "DC feeder for connection of a wind farm," in Proc. Cigre Symp., Malaysia, Sep. 1999.

[208] A. K. Skytt, P. Holmberg, and L. E. Juhlin, "HVDClight for connection of wind farms," in Proc. 2nd Int. Workshop Transmission Networks for Offshore Wind Farms, Sweden, Mar. 2001.

[209] X. I. Koutiva, T. D. Vrionis, N. A. Vovos, and G. B. Giannakopoulos, "Optimal integration of an offshore wind farm to a weak grid," IEEE Trans. Power Del., vol. 21, no. 2, pp. 987–994, Apr. 2006.

[210] W. Lu and B. T. Ooi, "Optimal acquisition and aggregation of offshore wind power by multiterminal voltage-source HVDC," IEEE Trans. Power Del., vol. 18, no. 1, pp. 201–206, Jan. 2003.

[211] L. Xu and B. R. Andersen, "Grid connection of large offshore wind farms using HVDC,"Wind Energy, vol. 9, no. 4, pp. 371–382, Jul./Aug. 2006.

[212] N. Kirby, L. Xu, M. Lucket, and W. Siepmann, "HVDC transmission for large offshore windfarms," Inst. Elect. Eng. Power Eng. J., vol. 16, no. 3, pp. 135–141, Jun. 2002.

[213] D. Xiang, L. Ran, J. R. Bumby, P. Tavner, and S. Yang, "Coordinated control of an HVDC link and doubly fed induction generators in a large offshore wind farm," IEEE Trans. Power Del., vol. 21, no. 1, pp. 463–471, Jan. 2006.

[214] B. R. Andersen, L. Xu, P. Horton, and P. Cartwright, "Topologies for VSC transmission," Inst. Elect. Eng. Power Eng. J., vol. 16, no. 3, pp. 142–150, Jun. 2002.

[215] Theodoros D. Vrionis, Xanthi I. Koutiva, Nicholas A. Vovos, and Gabriel B. Giannakopoulos, "Control of an HVdc Link Connecting a Wind Farm to the Grid for Fault Ride-Through Enhancement," IEEE Transactions On Power Systems, Vol. 22, No. 4, November 2007.

[216] Chong Han, Alex Q. Huang, Mesut E. Baran, Subhashish Bhattacharya, Wayne Litzenberger, Loren Anderson, Anders L. Johnson, and Abdel-Aty Edris, "STATCOM Impact Study on the Integration of a Large Wind Farm into a Weak Loop Power System," IEEE Transactions On Energy Conversion, Vol. 23, No. 1, March 2008.

[217] T. Ackermann, Wind Power in Power Systems. New York:Wiley, 2005.

[218] J.W. Smith and D. L. Brooks, "Voltage impacts of distributed wind generation on rural distribution feeders," in Proc. IEEE PES Transmiss.Distrib. Conf. Exhib., Oct. 28–Nov. 2, 2001, vol. 1, pp. 492–497.

[219] A. Kehrli and M. Ross, "Understanding grid integration issues at wind farms and solutions using voltage source converter FACTS technology," in Proc. IEEE PES Gen. Meeting, Jul. 13–17, 2003, vol. 3, pp. 1822–1827.

[220] Z. Saad-Saoud, M. L. Lisboa, J. B. Ekanayake, N. Jenkins, and G. Strbac, "Application of STATCOMs towind farms," Inst. Elect. Eng. Proc.Gener.Transmiss.Distrib., vol. 145, no. 5, pp. 511–516, Sep. 1998.

[221] F. Zhou, G. Joos, and C. Abbey, "Voltage stability in weak connection wind farms," in Proc. IEEE PES Gen. Meeting, Jun. 12–16, 2005, vol. 2, pp. 1483–1488.

[222] L. T. Ha and T. K. Saha, "Investigation of power loss and voltage stability limits for large wind farm connections to a subtransmission network," in Proc. IEEE PES Gen. Meeting, Jun. 6–10, 2004, vol. 2, pp. 2251–2256.

[223] N. G. Hingorani and L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems. Piscataway, NJ: IEEE Press, 2000.

[224] C.Han, Z.Yang, B. Chen,W. Song, A. Q. Huang, A. Edris, M. Ingram, and S. Atcitty, "System integration and demonstration of a 4.5 MVA STATCOM based on emitter turn-off (ETO) thyristor and cascade multilevel converter," in Proc. IEEE IECON, Nov. 6–10, 2005, pp. 1329–1334.

[225] Kittipong Methaprayoon, Chitra Yingvivatanapong, Wei-Jen Lee, and James R. Liao, "An Integration of ANN Wind Power Estimation Into Unit Commitment Considering the Forecasting Uncertainty," IEEE Transactions On Industry Applications, Vol. 43, No. 6, November/December 2007.

[226] G. Quinonez-Varela and A. Cruden, "Modelling and validation of a squirrel cage induction generator wind turbine during connection to the local grid," IET Gener.Transm.Distrib., 2008, 2, (2), pp. 301–309.

[227] A. Morales, X. Robe, M. Sala, P. Prats, C. Aguerri, E. Torres, " Advanced grid requirements for the integration of wind farms into the Spanish

transmission system, IET Renew. Power Gener., 2008, Vol. 2, No. 1, pp. 47–59.

[228] Tai-Her Yeh and Li Wang, "A Study on Generator Capacity for Wind Turbines Under Various Tower Heights and Rated Wind Speeds Using Weibull Distribution," IEEE Transactions On Energy Conversion, Vol. 23, No. 2, June 2008.

[229] James F. Conroy, and Rick Watson, "Frequency Response Capability of Full Converter Wind Turbine Generators in Comparison to Conventional Generation," IEEE Transactions On Power Systems, Vol. 23, No. 2, May 2008.

[230] A. Hansen and L. Hansen, "Wind turbine concept market penetration over 10 years (1995–2004)," Wind Energy, vol. 10, no. 1, pp. 81–97, Jan. 2007.

[231] J. Enanayake and N. Jenkins, "Comparison of the response of doubly fed and fixed speed induction generator wind turbines to changes in system frequency," IEEE Trans. Energy Convers., vol. 19, no. 4, pp. 800–802, Dec. 2004.

[232] G. Ramtharan et al., "Frequency support from doubly fed induction generator wind turbines," IET Renew. Power Gen., vol. 1, no. 1, pp. 3–9, Mar. 2007.

[233] L. Holdsworth et al., "Power system frequency response from fixed speed and doubly fed induction generator based wind turbines," Wind Energy, vol. 7, no. 1, pp. 21–35, Mar. 2004.

[234] R. de Almeida et al., "Primary frequency control participation provided by doubly fed induction wind generators," in Proc. 15th Power Systems Computation Conf., Liege, Belgium, Aug. 2005.

[235] G. Lalor et al., "Frequency control and wind turbine technologies," IEEE Trans. Power Syst., vol. 20, no. 4, pp. 1905–1913, Nov. 2005.

[236] J. Morren et al., "Wind turbines emulating inertia and supporting primary frequency control," IEEE Trans. Power Syst., vol. 21, no. 1, pp. 433–434, Feb. 2006.

[237] Javier García-González, Rocío Moraga Ruiz de la Muela, Luz Matres Santos, and Alicia Mateo González, "Stochastic Joint Optimization of Wind Generation and Pumped-Storage Units in an Electricity Market," IEEE Transactions On Power Systems, Vol. 23, No. 2, May 2008.

[238] Rod Frehlich, and Neil Kelley "Measurements of Wind and Turbulence Profiles With Scanning Doppler Lidar for Wind Energy Applications," IEEE Journal Of Selected Topics In Applied Earth Observations And Remote Sensing, Vol. 1, No. 1, March 2008.

[239] Chai Chompoo-inwai, Chow Chompoo-inwai, Monthon Leelajindakrairerk, Sulee Banjongjit, Pradit Fuangfoo, and Wei-Jen Lee, "Design Optimization of Wind Power Planning for a Country With Low–Medium-Wind-Speed Profile" IEEE Transactions On Industry Applications, Vol. 44, No. 5, September/October 2008.

[240] J. Conroy R. Watson, "Aggregate modelling of wind farms containing full-converter wind turbine generators with permanent magnet synchronous machines: transient stability studies," IET Renew. Power Gener., 2009, Vol. 3, No. 1, pp. 39–52.

[241] Wei Qiao, Ronald G. Harley, and Ganesh Kumar Venayagamoorthy, "Coordinated Reactive Power Control of a Large Wind Farm and a STATCOM Using Heuristic Dynamic Programming IEEE Transactions On Energy Conversion, Vol. 24, No. 2, June 2009.

[242] V. Akhmatov, "Analysis of dynamic behavior of electric power systems with large amount of wind power" Ph.D. dissertation, Tech. Univ. Denmark, Kgs. Lyngby, Denmark, Apr. 2003.

[243] J. Hochheimer, "Wind generation integration & operation—Technical challenges/issues," in Proc. IEEE PES General Meet.2006, Montreal, Canada.

[244] S. W. Steven, "Wind parks as power plants," in Proc. IEEE PES General Meet.2006, Montreal, Canada.

[245] J. Morren and S. W. H. de Haan, "Ridethrough of wind turbines with doubly-fed induction generator during voltage dip," IEEE Trans. Energy Convers., vol. 20, no. 2, pp. 435–441, Jun. 2005.

[246] W. Qiao, G. K. Venayagamoorthy, and R. G. Harley, "Real-time implementation of a STATCOM on a wind farm equipped with doubly fed induction generators," in Proc. IEEE IAS 41st Annu. Meet., Tampa, FL, Oct. 8–12, 2006, pp. 1073–1080.

[247] A. Mullane, G. Lightbody, and R. Yacamini, "Wind-turbine fault ridethrough enhancement," IEEE Trans. Power Syst., vol. 20, no. 4, pp. 1929–1937, Nov. 2005.

[248] R. G. de Almeida, J. A. P. Lopes, and J. A. L. Barreiros, "Improving power system dynamic behavior through doubly fed induction machines controlled by static converter using fuzzy control," IEEE Trans. Power Syst., vol. 19, no. 4, pp. 1942–1950, Nov. 2004.

[249] W. Qiao, R. G. Harley, and G. K. Venayagamoorthy, "Effects of FACTS devices on a power system which includes a large wind farm," in Proc. IEEE PES Power Syst. Conf. Expo. 2006, Atlanta, GA, pp. 2070–2076.

[250] P. J. Werbos, "Approximate dynamic programming for real-time control and neural modeling," in Handbook of Intelligent Control, D. White and D. Sofge, Eds. New York: Van Nostrand Reinhold, 1992, pp. 493–526.

[251] D. V. Prokhorov and D. C. Wunsch, "Adaptive critic designs," IEEE Trans. Neural Netw., vol. 8, no. 5, pp. 997–1007, Sep. 1997.

[252] W. Qiao and R. G. Harley, "Indirect adaptive external neuro-control for a series capacitive reactance compensator based on a voltage source PWM converter in damping power oscillations," IEEE Trans. Ind. Electron., vol. 54, no. 1, pp. 77–85, Feb. 2007.

[253] Wei Qiao, Ganesh Kumar Venayagamoorthy, and Ronald G. Harley, "Real-Time Implementation of a STATCOM on a Wind Farm Equipped With Doubly Fed Induction Generators," IEEE

Transactions On Industry Applications, Vol. 45, No. 1, January/February 2009.

[254] R. Datta and V. T. Ranganathan, "Variable-speed wind power generation using doubly fed wound rotor induction machine—A comparison with alternative schemes," IEEE Trans. Energy Convers., vol. 17, no. 3, pp. 414–421, Sep. 2002.

[255] M. V. A. Nunes, J. A. Pecas Lopes, H. H. Zurn, U. H. Bezerra, and R. G. Almeida, "Influence of the variable-speed wind generators in transient stability margin of the conventional generators integrated in electrical grids," IEEE Trans. Energy Convers., vol. 19, no. 4, pp. 692–701, Dec. 2004.

[256] J. Morren and S. W. H. de Haan, "Ridethrough of wind turbines with doubly-fed induction generator during a voltage dip," IEEE Trans. Energy Convers., vol. 20, no. 2, pp. 435–441, Jun. 2005.

[257] M. Bruntt, J. Havsager, and H. Knudsen, "Incorporation of wind power in the East Danish power system," in Proc. IEEE Power Tech., Budapest, Hungary, Aug. 29–Sep. 2, 1999, pp. 202–205.

[258] Z. Saad-Saoud, M. L. Lisboa, J. B. Ekanayake, N. Jenkins, and G. Strbac, "Application of STATCOMs to wind farms," Proc. Inst. Elect. Eng.— Gener. Transm.Distrib., vol. 145, no. 5, pp. 511–516, Sep. 1998.

[259] C. Chompoo-Inwai, C. Yingvivatanapong, K. Methaprayoon, and W.-J. Lee, "Reactive compensation techniques to improve the ridethrough capability of wind turbine during disturbance," IEEE Trans. Ind. Appl., vol. 41, no. 3, pp. 666–672, May/Jun. 2005.

[260] Zhixin Miao, Lingling Fan, Dale Osborn, and Subbaraya Yuvarajan "Control of DFIG-Based Wind Generation to Improve Interarea Oscillation Damping," IEEE Transactions On Energy Conversion, Vol. 24, No. 2, June 2009.

[261] Li Wang, Shiang-Shong Chen, Student, Wei-Jen Lee, and Zhe Chen, "Dynamic Stability Enhancement and Power Flow Control of a Hybrid Wind and Marine-Current Farm Using SMES," IEEE Transactions On Energy Conversion, Vol. 24, No. 3, September 2009.

[262] Sercan Teleke, Mesut E. Baran, Alex Q. Huang, Subhashish Bhattacharya, and Loren Anderson, "Control Strategies for Battery Energy Storage for Wind Farm Dispatching," IEEE Transactions On Energy Conversion, Vol. 24, No. 3, September 2009.

[263] C. Han, A. Q. Huang, W. Litzenberger, L. Anderson, A.-A. Edris, M. Baran, S. Bhattacharya, and A. Johnson, "STATCOM impact study on the integration of a large wind farm into a weak loop power system," in Proc. IEEE Power Syst. Conf. Expo., Oct. 29–Nov. 1, 2006, pp. 1266– 1272.

[264] K. Yoshimoto, T. Nanahara, and G. Koshimizu, "New control method for regulating state-of-charge of a battery in hybrid wind power/battery energy storage system," in Proc. IEEE Power Syst. Conf. Expo., Oct. 29–Nov. 1, 2006, pp. 1244–1251.

[265] H. Holttinen and R. Hirvonen, "Power system requirements for wind power," in Wind Power in Power Systems, T. Ackermann, Ed. New York: Wiley, 2005, pp. 143–167.

[266] P. Lundsager and E. I.Barring-Gould, "Isolated systemswith wind power," in Wind Power in Power Systems, T. Ackermann, Ed. New York:Wiley, 2005, pp. 299–329.

[267] T.Hennessy andM.Kuntz, "The multiple benefits of integrating electricity storage with wind energy," in Proc. IEEE Power Eng. Soc. Gen. Meeting, Jun. 12–16, 2005, pp. 1952–1954.

[268] P. F. Ribeiro, B. K. Johnson, M. L. Crow, A. Arsoy, and Y. Liu, "Energy storage systems for advanced power applications," Proc. IEEE, vol. 89, no. 12, pp. 1744–1756, Dec. 2001.

[269] Bonneville Power Administration.(2006, Sep.). Renewable Energy Technology Roadmap, Technology Innovation Office [Online]. Available:http://www.bpa.gov/corporate/business/in novation/docs/2006/RM- 06_Renewables-Final.pdf.

[270] C. Han, A. Q. Huang, M. E. Baran, S. Bhattacharya, W. Litzenberger, L. Anderson, A. L. Johnson, and A.-A. Edris, "STATCOM impact study on the integration of a large wind farm into a weak loop power system," IEEE Trans. Energy Convers., vol. 23, no. 1, pp. 226–233, Mar. 2008.

[271] D. M. Logan, J. S. Baylor, D. Cotcher, and D. Krauss, "Communicating the value of dispatchability for non-utility generation projects," IEEE Trans. Power Syst., vol. 10, no. 3, pp. 1408–1413, Aug. 1995.

[272] D. Hawkins and M. Rothleder, "Evolving role of wind forecasting in market operation at the CAISO," in Proc. IEEE Power Syst. Conf. Expo., Oct. 29–Nov. 1, 2006, pp. 234–238.

[273] E. Muljadi, C. P. Butterfield, R. Yinger, and H. Romanowitz, "Energy storage and reactive power compensator in a large wind farm," presented at the 42nd AIAA Aerosp. Sci. Meeting Exhib., Reno, NV, Jan. 5–8, 2004.

[274] Roy Billinton, Yi Gao, and Rajesh Karki, "Composite System Adequacy Assessment Incorporating Large-Scale Wind Energy Conversion Systems Considering Wind Speed Correlation," IEEE Transactions On Power Systems, Vol. 24, No. 3, August 2009.

[275] Shoji Nishikata, and Fujio Tatsuta "A New Interconnecting Method for Wind Turbine/Generators in a Wind Farm and Basic Performances of the Integrated System" IEEE Transactions On Industrial Electronics, Vol. 57, No. 2, February 2010.

[276] S. M. Muyeen, Rion Takahashi, Toshiaki Murata, and Junji Tamura, "Integration of an Energy Capacitor System With a Variable-Speed Wind Generator", IEEE Transactions On Energy Conversion, Vol. 24, No. 3, September 2009.

[277] Ravita D. Prasad, R. C. Bansal, and M. Sauturaga "Wind Energy Analysis for Vadravadra Site in Fiji Islands: A Case Study" IEEE Transactions

OnEnergy Conversion, Vol. 24, No. 3, September 2009.

[278] Ahmad Salehi Dobakhshari, and Mahmud Fotuhi-Firuzabad, "A Reliability Model of Large Wind Farms for Power System Adequacy Studies" IEEE Transactions On Energy Conversion, Vol. 24, No. 3, September 2009.

[279] S. M. Muyeen, Rion Takahashi, Toshiaki Murata, and Junji Tamura, "A Variable Speed Wind Turbine Control Strategy to Meet Wind Farm Grid Code Requirements" IEEE Transactions On Power Systems, Vol. 25, No. 1, February 2010.

[280] L. Gyugyi, "Unified power-flow control concept for flexible ac transmission systems," Proc. Inst. Elect. Eng. C, vol. 139, no. 4, pp. 323–331, 1992.

[281] L. Gyugyi, "Dynamic compensation of AC transmission lines by solidstate synchronous voltage sources," IEEE Trans. Power Del., vol. 9, no. 2, pp. 904–911, Apr. 1994.

[282] H. F. Wang, F. Li, and R. G. Cameron, "Facts control design based on power system nonparametric models," Proc. Inst. Elect. Eng., Gen., Transm., Distrib., vol. 146, no. 5, pp. 409–415, 1999.

[283] L. Zhang, C. Shen, M. L. Crow, L. Dong, S. Pekarek, and S. Atcitty, "Performance indices for the dynamic performance of FACTS and FACTS with energy storage," Elect. Power Compon. Syst., vol. 33, no. 3, pp. 299–314, Mar. 2005.

[284] Z. Saad-Saoud, M. L. Lisboa, J. B. Ekanayake, N. Jenkins, and G. Strbac, "Application of STATCOMs to wind farms," Proc. Inst. Elect. Eng., Gen., Transm., Distrib., vol. 145, no. 5, pp. 511–516, 1998.

[285] S. M. Muyeen, M. A. Mannan, M. H. Ali, R. Takahashi, T. Murata, and J. Tamura, "Stabilization of wind turbine generator system by STATCOM," IEEJ Trans. PE, vol. 126-B, no. 10, pp. 1073–1082, 2006.

[286] T. Ahmed, E. Hiraki, M. Nakaoka, and O. Noro, "Static VAr compensator- based terminal voltage regulation scheme of self-excited induction generator driven by variable speed prime mover for clean renewable energy," in Proc. 4th Int. Power Electronics and Motion Control Conf. (IPEMC), 2004, vol. 3, no. 14–16, pp. 1219–1224.

[287] F. Zhou, G. Joos, C. Abbey, L. Jiao, and B. T. Ooi, "Use of large capacity SMES to improve the power quality and stability of wind farms," in Proc. IEEE Power Engineering Society General Meeting, Jun. 2004, vol. 2, pp. 2025–2030.

[288] M. H. Ali, T. Murata, and J. Tamura, "Minimization of fluctuations of line power and terminal voltage of wind generator by fuzzy logiccontrolled SMES," Int. Rev. Elect. Eng. (I.R.E.E.), vol. 1, no. 4, pp. 559–566, Oct. 2006.

[289] T. Kinjo, T. Senjyu, N. Urasaki, and H. Fujita, "Output levelling of renewable energy by electric double-layer capacitor applied for energy storage system," IEEE Trans. Energy Convers., vol. 21, no. 1, pp. 221–227, 2006.

[290] S. M. Muyeen, R. Takahashi, M. H. Ali, T. Murata, and J. Tamura, "Transient stability augmentation of power system including wind farms by using ECS," IEEE Trans. Power Syst., vol. 23, no. 3, pp. 1179–1187, Aug. 2008.

[291] Hadi Banakar, and Boon Teck Ooi, Clustering of Wind Farms and its Sizing Impact IEEE Transactions On Energy Conversion, Vol. 24, No. 4, December 2009.

[292] Luis Sainz, Juan Jose Mesas, Remus Teodorescu, and Pedro Rodriguez, "Deterministic and Stochastic Study of Wind Farm Harmonic Currents" IEEE Transactions On Energy Conversion, Vol. 25, No. 4, December 2010.

[293] Mikhail N. Slepchenkov, Keyue Ma Smedley, and Jun Wen, "Hexagram-Converter-Based STATCOM for Voltage Support in Fixed-Speed Wind Turbine Generation Systems" IEEE Transactions On Industrial Electronics, Vol. 58, No. 4, April 2011.

[294] Y. Cheng, C. Qian, M. L. Crow, S. Pekarek, and S. Atcitty, "A comparison of diode-clamped and cascaded multilevel converters for a STATCOM with energy storage," IEEE Trans. Ind. Electron., vol. 53, no. 5, pp. 1512–1521, Oct. 2006.

[295] D. Hawkins, J. Blatchford, and Y. Makarov, "Wind integration issues and solutions in California," in Proc. IEEE PES GM, Tampa, FL, Jun. 2007, 9 pp.23-34.

[296] T. Sun, Z. Chen, and F. Blaabjerg, "Voltage recovery of grid-connected wind turbines after a short-circuit fault," in Proc. 29th IEEE IECON, Roanoke, VA, 2003, pp. 2723–2728.

[297] W. Qiao, G. K. Venayagamoorthy, and R. G. Harley, "Real-time implementation of a STATCOM on a wind farm equipped with doubly fed induction generators," IEEE Trans. Ind. Appl., vol. 45, no. 1, pp. 98–107, Jan. 2009.

[298] Yi Ding, Peng Wang, Member, IEEE, Lalit Goel, Poh Chiang Loh, and Qiuwei Wu "Long-Term Reserve Expansion of Power Systems With High Wind Power Penetration Using Universal Generating Function Methods," IEEE Transactions On Power Systems, Vol. 26, No. 2, May 2011.

[299] Ted K. A. Brekken, Alex Yokochi, Annette von Jouanne, Zuan Z. Yen, Hannes Max Hapke, and Douglas A. Halamay, "Optimal Energy Storage Sizing and Control for Wind Power Applications," IEEE Transactions On Sustainable Energy, Vol. 2, No. 1, January 2011.

[300] Li Wang, and Chia-Tien Hsiung "Dynamic Stability Improvement of an Integrated Grid-Connected Offshore Wind Farm and Marine-Current Farm Using a STATCOM," IEEE Transactions On Power Systems, Vol. 26, No. 2, May 2011.

[301] S. E. B. Elghali, R. Balme, K. L. Saux, M. E. H. Benbouzid, J. F. Charpentier, and F. Hauville, "A simulation model for the evaluation of the electrical power potential harnessed by a marine current turbine," IEEE J. Ocean. Eng., vol. 32, no. 4, pp. 786–797, Oct. 2007.

[302] W. M. J. Batten, A. S. Bahaj, A. F. Molland, and J. R. Chaplin, "Hydrodynamics of marine current turbines," Renewab. Energy, vol. 31, no. 2, pp. 249–256, Feb. 2006.

[303] L. Myers and A. S. Bahaj, "Simulated electrical power potential harnessed by marine current turbine arrays in the alderney race," Renewab. Energy, vol. 30, no. 11, pp. 1713–1731, Sep. 2005.

[304] H. Chong, A. Q. Huang, M. E. Baran, S. Bhattacharya, W. Litzenberger, L. Anderson, A. L. Johnson, and A. A. Edris, "STATCOM impact study on the integration of a large wind farm into a weak loop power system," IEEE Trans. Energy Convers., vol. 23, no. 1, pp. 226–233, Mar. 2008.

[305] H. Gaztanaga, I. Etxeberria-Otadui, D. Ocnasu, and S. Bacha, "Real-time analysis of the transient response improvement of, fixed-speed wind farms by using a reduced-scale STATCOM prototype," IEEE Trans. Power Syst., vol. 22, no. 2, pp. 658–666, May 2007.

[306] K. R. Padiyar and N. Prabhu, "Design and performance evaluation of subsynchronous damping controller with STATCOM," IEEE Trans. Power Del., vol. 21, no. 3, pp. 1398–1405, Jul. 2006.

[307] W. L. Chen and Y. Y. Hsu, "Controller design for an induction generator driven by a variable-speed wind turbine," IEEE Trans. Energy Convers., vol. 21, no. 3, pp. 635–625, Sep. 2006.

[308] A. Jain, K. Joshi, A. Behal, and N. Mohan, "Voltage regulation with STATCOMs: Modeling, control and results," IEEE Trans. Power Del., vol. 21, no. 2, pp. 726–735, Apr. 2006.

[309] B. Blˇazˇic and I. Papic, "Improved D-STATCOM control for operation with unbalanced currents and voltages," IEEE Trans. Power Del., vol. 21, no. 1, pp. 225–233, Jan. 2006.

[310] A. H. Norouzi and A. M. Sharaf, "Two control schemes to enhance the dynamic performance of the STATCOM and SSSC," IEEE Trans. Power Del., vol. 20, no. 1, pp. 435–442, Jan. 2005.

[311] K. V. Patil, J. Senthil, J. Jiang, and R. M. Mathur, "Application of STATCOM for damping torsinal oscillations in series compensated AC system," IEEE Trans. Energy Convers., vol. 13, no. 3, pp. 237–243, Sep. 1998.

[312] N. Mithulananthan, C. A. Canizares, J. Reeve, and G. J. Rogers, "Comparison of PSS, SVC, and STATCOM controllers for damping power system oscillations," IEEE Trans. Power Syst., vol. 18, no. 2, pp. 786–792, May 2003.

[313] P. Rao, M. L. Crow, and Z. Yang, "STATCOM control for power system voltage control applications," IEEE Trans. Power Del., vol. 15, no. 4, pp. 1311–1317, Oct. 2000.

[314] Y. Ye, M. Kazerani, and V. H. Quintana, "Current-source converter based STATCOM: Modeling and control," IEEE Trans. Power Del., vol. 20, no. 2, pp. 795–800, Apr. 2005.

[315] Z. Yang, C. Shen, L. Zhang, M. L. Crow, and S. Atcitty, "Integration of a STATCOM and battery energy storage," IEEE Trans. Power Syst., vol. 16, no. 2, pp. 254–260, May 2001.

[316] R. Griinbanm, P. Halvarsson, D. Larsson, and P. R. Jones, "Conditioning of power grids serving offshore wind farms based on asynchronous generator," in Proc. Conf. Power Electronics, Machine and Drives, Mar./Apr. 2004, vol. 1, pp. 34–39.

[317] Jonathan Robinson, Dragan Jovcic, and Géza Joós, "Analysis and Design of an Offshore Wind Farm Using a MV DC Grid," IEEE Transactions On Power Delivery, Vol. 25, No. 4, October 2010.

[318] Ramon Blasco-Gimenez, Salvador A˜n´o-Villalba, Johel Rodr´ıguez-D'Derl´ee, Francisco Morant, and Soledad Bernal-Perez "Distributed Voltage and Frequency Control of Offshore Wind Farms Connected With a Diode-Based HVdc Link," IEEE Transactions On Power Electronics, Vol. 25, No. 12, December 2010.

[319] R. Pena, J. C. Clare, and G. M. Asher, "Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation," in Proc. IEE Electr.Power Appl., vol. 143, no. 3, pp. 231–241, 1996.

[320] R. Li, S. Bozhko, and G. Asher, "Frequency control design for offshore wind farm grid with LCC-HVDC link connection," IEEE Trans. Power Electron., vol. 23, no. 3, pp. 1085–1092, May 2008.

[321] S. Bozhko, G. Asher, R. Li, J. Clare, and L. Yao, "Large offshore DFIGBased wind farm with Line-Commutated HVDC connection to the main grid: Engineering studies," IEEE Trans. Energy Convers., vol. 23, no. 1, pp. 119–127, Mar. 2008.

[322] Wen-Tsan Liu, Yuan-Kang Wu, Ching-Yin Lee, and Chao-Rong Chen "Effect of Low-Voltage-Ride-Through Technologies on the First Taiwan Offshore Wind Farm Planning IEEE Transactions On Sustainable Energy, Vol. 2, No. 1, January 2011.

[323] Z. Chen and F. Blaabjerg, "Wind farm—A power source in future power systems," Renew. Sustain. Energy Rev., vol. 13, no. 6–7, pp. 1288–1300, Aug./Sep. 2009.

[324] J. Morren and S. W. H. de Haan, "Ridethrough of wind turbines with doubly-fed induction generator during a voltage dip," IEEE Trans. Energy Convers., vol. 20, no. 2, pp. 435–441, 2005.

[325] C. Chompoo-Inwai, C.Yingvivatanapong, K. Methaprayoon, and W.-J. Lee, "Reactive compensation techniques to improve the ride-through capability of wind turbine during disturbance," IEEE Trans. Ind. Appl., vol. 41, no. 3, pp. 666–672, May/Jun. 2005.

[326] M. Tsili and S. Papathanassiou, "A review of grid code technical requirements for wind farms," IET Renewable Power Generation, vol. 3, no. 3, pp. 308–332, 2009.

[327] Federal Energy Regulatory Commission (FERC), Interconnection for wind energy Docket No.RM05-4-000, Order No. 661, Jun. 2005, Issue 2.

[328] D. Xiang, L. Ran, P. J. Tavner, and S. Yang, "Control of a doubly fed induction generator in a

wind turbine during grid fault ride-through," IEEE Trans. Energy Convers., vol. 21, no. 3, pp. 652–662, Sep. 2006.

[329] A. K. Thet and H. Saitoh, "Pitch control for improving the low-voltage ride-through of wind farm," in Proc. 2009 Asia and Pacific Transmission and Distribution Conf. Exposition, 2009, pp. 1–4.

[330] G. Joos, "Wind turbine generator low voltage ride through requirements and solutions," in Proc. Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the 21st Century, 2008, pp. 1–7.

[331] S. M. Muyeen, R. Takahashi, T. Murata, J. Tamura, M. H. Ali, Y. Matsumura, A. Kuwayama, and T. Matsumoto, "Low voltage ride through capability enhancement of wind turbine generator system during network disturbance," IET Renew. Power Generation, vol. 3, no. 1, pp. 65–74, 2009.

[332] M. Z. C. Wanik and I. Erlich, "Simulation of microturbine generation system performance during grid faults under new grid code requirements," in Proc. 2009 IEEE Power Tech. Conf., Bucharest, 2009, pp. 1–8.

[333] M. Molinas, J. A. Suul, and T. Undeland, "Low voltage ride through of wind farms with cage generators: STATCOM versus SVC," IEEE Trans. Power Electron., vol. 23, no. 3, pp. 1104–1117, May 2008.

[334] A. D. Hansen and G. Michalke, "Fault ride-through capability of DFIG wind turbines," Renew. Energy, vol. 32, no. 9, pp. 1594–1610, Jul. 2007.

[335] Liyan Qu, Member, IEEE, and Wei Qiao, "Constant Power Control of DFIG Wind Turbines With Super-capacitor Energy Storage," IEEE Transactions On Industry Applications, Vol. 47, No. 1, January/February 2011.

[336] J. P. Barton and D. G. Infield, "Energy storage and its use with intermittent renewable energy," IEEE Trans. Energy Convers., vol. 19, no. 2, pp. 441–448, Jun. 2004.

[337] D. Rastler, "Electric energy storage, an essential asset to the electric enterprise: Barriers and RD&D needs," California Energy Commission Staff Workshop Energy Storage Technol., Policies Needed Support California's RPS Goals 2020, Sacramento, CA, Apr. 2, 2009.

[338] C. Abbey and G. Joos, "Supercapacitor energy storage for wind energy applications," IEEE Trans. Ind. Appl., vol. 43, no. 3, pp. 769–776, May/Jun. 2007.

[339] B. S. Borowy and Z. M. Salameh, "Dynamic response of a stand-alone wind energy conversion system with battery energy storage to wind gust," IEEE Trans. Energy Convers., vol. 12, no. 1, pp. 73–78, Mar. 1997.

[340] M.-S.Lu, C.-L.Chang, W.-J. Lee, and L. Wang, "Combining the wind power generation system with energy storage equipments," IEEE Trans. Ind. Appl., vol. 45, no. 6, pp. 2109–2115, Nov./Dec. 2009.

[341] A. Yazdani, "Islanded operation of a doubly-fed induction generator (DFIG) wind-power system with integrated energy storage," in Proc. IEEE Canada Elect. Power Conf., Montreal, QC, Canada, Oct. 25–26, 2007, pp. 153–159.

[342] Li Wang, Tai-Her Yeh, Wei-Jen Lee, and Zhe Chen, "Analysis of a Commercial Wind Farm in Taiwan Part II: Different Current-Limit Reactors and Load Tap Changers on System Performance," IEEE Transactions On Industry Applications, Vol. 47, No. 2, March/April 2011.

[343] Oriol Gomis-Bellmunt, Adrià Junyent-Ferré, Andreas Sumper and Joan Bergas-Jané, "Control of a Wind Farm Based on Synchronous Generators With a Central HVDC-VSC Converter," IEEE Transactions On Power Systems, Vol. 26, No. 3, August 2011.

[344] N. Ullah, K. Bhattacharya, and T. Thiringer, "Wind farms as reactive power ancillary service providers technical and economic issues," IEEE Trans. Energy Convers., vol. 24, no. 3, pp. 661–672, Sep. 2009.

[345] Z. Miao, L. Fan, D. Osborn, and S. Yuvarajan, "Control of DFIG based wind generation to improve interarea oscillation damping," IEEE Trans. Energy Convers., vol. 24, no. 2, pp. 415–422, Jun. 2009.

[346] O. Gomis-Bellmunt, A. Junyent-Ferré, A. Sumper, and J. Bergas-Jané, "Ride-through control of a doubly fed induction generator under unbalanced voltage sags," IEEE Trans. Energy Convers., vol. 23, no. 4, pp. 1036–1045, Dec. 2008.

[347] A. Sumper, O. Gomis-Bellmunt, A. Sudria-Andreu, R. Villafafila- Robles, and J. Rull-Duran, "Response of fixed speed wind turbines to system frequency disturbances," IEEE Trans. Power Syst., vol. 24, no. 1, pp. 181–192, Feb. 2009.

[348] L.-R.Chang-Chien and Y.-C.Yin, "Strategies for operating wind power in a similar manner of conventional power plant," IEEE Trans. Energy Convers., vol. 24, no. 4, pp. 926–934, Dec. 2009.

[349] N. B. Negra, J. Todorovic, and T. Ackermann, "Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms," Elect. Power Syst. Res., vol. 76, no. 11, pp. 916–927, 2006.

[350] J. Arrillaga, High Voltage Direct Current Transmission, 2nd ed. London, U.K.: Inst. Elect. Eng., 1998.

[351] S. Bozhko, G. Asher, R. Li, J. Clare, and L.Yao, "Large offshore DFIG based wind farm with line-commutated HVDC connection to the main grid: Engineering studies," IEEE Trans. Energy Convers., vol. 23, no. 1, pp. 119–127, Mar. 2008.

[352] D. Xiang, L. Ran, J. Bumby, P. Tavner, and S. Yang, "Coordinated control of an HVDC link and doubly fed induction generators in a large offshore wind farm," IEEE Trans. Power Del., vol. 21, no. 1, pp. 463–471, Jan. 2006.

[353] T. Ackermann, "Transmission systems for offshore wind farms," IEEE Power Eng. Rev., vol. 22, no. 12, pp. 23–27, Dec. 2002.

[354] L. Xu and B. Andersen, "Grid connection of large offshore wind farms using HVDC," Wind Energy, vol. 9, no. 4, pp. 371–382, 2006.

[355] L. Xu, L. Yao, and C. Sasse, "Grid integration of large DFIG-based wind farms using VSC transmission," IEEE Trans. Power Syst., vol. 22, no. 3, pp. 976–984, Aug. 2007.

[356] T. Vrionis, X. Koutiva, N. Vovos, and G. Giannakopoulos, "Control of an HVDC link connecting a wind farm to the grid for fault ride-through enhancement," IEEE Trans. Power Syst., vol. 22, no. 4, pp. 2039–2047, Nov. 2007.

[357] D. Jovcic, "Offshore wind farm with a series multiterminal CSI HVDC," Elect. Power Syst. Res., vol. 78, pp. 747–755, 2008.

[358] D. Jovcic and N. Strachan, "Offshore wind farm with centralised power conversion and DC interconnection," IET Gen., Transm., Distrib., vol. 3, pp. 586–595, 2009.

[359] M. Chinchilla, S. Arnaltes, and J. C. Burgos, "Control of permanent magnet generators applied to variable-speed wind-energy systems connected to the grid," IEEE Trans. Energy Convers., vol. 21, no. 1, pp.130–135, Mar. 2006.

[360] D. Goodfellow and G. Smith, "Control strategy for variable speed of a fixed-pitch wind turbine operating in a wide speed range," in Proc. 8th BWEA Conf., Cambridge, U.K., 1986, pp. 219–228.

[361] R. Pena, J. J. C. Clare, and G. Asher, "Doubly fed induction generator using back-to-back PWM converters and its application to variable speed wind-energy generation," Proc. Inst. Elect. Eng., Elect. Power Appl., vol. 143, no. 3, pp. 231–241, 1996.

[362] C. Feltes, H. Wrede, F. Koch, and I. Erlich, "Enhanced fault ride through method for wind farms connected to the grid through VSC based HVDC transmission," IEEE Trans. Power Syst., vol. 24, no. 3, pp. 1537–1546, Aug. 2009.

[363] R. L. Hendriks, R. Volzke, and W. L. Kling, "Fault ride-through strategies for VSC-connected wind parks," in Proc. Eur. Wind Energy Conf. (EWEC2009), Marseille, France, 2009, pp. 1–6.

[364] Xia Chen, Haishun Sun, Jinyu Wen, Wei-Jen Lee, Xufeng Yuan, Naihu Li, and Liangzhong Yao "Integrating Wind Farm to the Grid Using Hybrid Multiterminal HVDC Technology," IEEE Transactions On Industry Applications, Vol. 47, No. 2, March/April 2011.

[365] L. Xu and B. R. Andersen, Grid Connection of Large Offshore Wind Farms Using HVDC. New York: Wiley-Interscience, Dec. 2005, pp. 371–382.

[366] L. Xu, L. Yao, and C. Sasse, "Grid integration of large DFIG based wind farms using VSC transmission," IEEE Trans. Power Syst., vol. 22, no. 3, pp. 976–984, Aug. 2007.

[367] D. Xiang, L. Ran, and J. R. Bumby, "Coordinated control of an HVDC link and doubly fed induction generators in a large offshore wind farm," IEEE Trans. Power Del., vol. 21, no. 1, pp. 463–471, Jan. 2006.

[368] A. Hammad, R. Minghetti, J. Hasler, P. Eicher, R. Bunch, and D. Goldsworthy, "Controls modeling and verification for the pacific intertie HVDC 4-terminal scheme," IEEE Trans. Power Del., vol. 8, no. 1, pp. 367–375, Jan. 1993.

[369] N. Flourentzou, V. G. Agelidis, and G. D. Demetriades, "VSC-Based HVDC power transmission system: An overview," IEEE Trans. Power Electron., vol. 24, no. 3, pp. 592–602, Mar. 2009.

[370] B. K. Johnson, R. H. Lasseter, F. L. Alvarado, and R. Adapa, "Expandable multiterminal DC systems based on voltage droop," IEEE Trans. Power Del., vol. 8, no. 4, pp. 1926–1932, Oct. 1993.

[371] H. Jiang and A. Ekstrom, "HVDC systems in urban areas of large cities," IEEE Trans. Power Del., vol. 13, no. 4, pp. 1278–1284, Oct. 1998.

[372] Z. Zhao andM. R. Iravani, "Application of GTO voltage source inverter in a hybrid HVDC link," IEEE Trans. Power Del., vol. 9, no. 1, pp. 369–377, Jan. 1994.

[373] B. R. Andersen and L. Xu, "Hybrid HVDC system for power transmission to island networks," IEEE Trans. Power Del., vol. 19, no. 4, pp. 1884–1980, Oct. 2004.

[374] W. Pan, Y. Chang, and H. Chen, "Hybrid Multi-terminal HVDC system for large scale wind power," in Proc. IEEE PES Power Syst. Conf. Expo., 2006, pp. 755–759.

[375] I. Arana, A. Hernandez, G. Thumm, and J. Holboell "Energization of Wind Turbine Transformers With an Auxiliary Generator in a Large Offshore Wind Farm During Islanded Operation," IEEE Transactions On Power Delivery, Vol. 26, No. 4, October 2011.

[376] Saurabh Tewari, Charles J. Geyer, and Ned Mohan "A Statistical Model for Wind Power Forecast Error and its Application to the Estimation of Penalties in Liberalized Markets," IEEE Transactions On Power Systems, Vol. 26, No. 4, November 2011.

[377] Li Wang, Yu-Hung Lin, and Yi-Ting Chen "Load-Flow Analysis of a Wind Farm Containing Multiple Wind-Driven Wound-Rotor Induction Generators With Dynamic Slip Control Using RX Models," IEEE Transactions On Sustainable Energy, Vol. 2, No. 3, July 2011.

[378] Yuan-Kang Wu, Member, IEEE, Ching-Yin Lee, and Ging-He Shu "Taiwan's First Large-Scale Offshore Wind Farm Connection—A Real Project Case Study With a Comparison of Wind Turbine," IEEE Transactions On Industry Applications, Vol. 47, No. 3, May/June 2011.