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Operation And Control Of Wind Power Station Using Facts Devices Controller.

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Abstract : *This paper presents aintroduction and use of facts controller inwind power station for improve voltage profile damping oscillations,load ability,reduce active and reactive power losses,sub-state-of-the-art on enhancement of different performance parameters of power systems such as voltage profile, 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, load ability, 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).*

I. 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 are 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 on state 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].

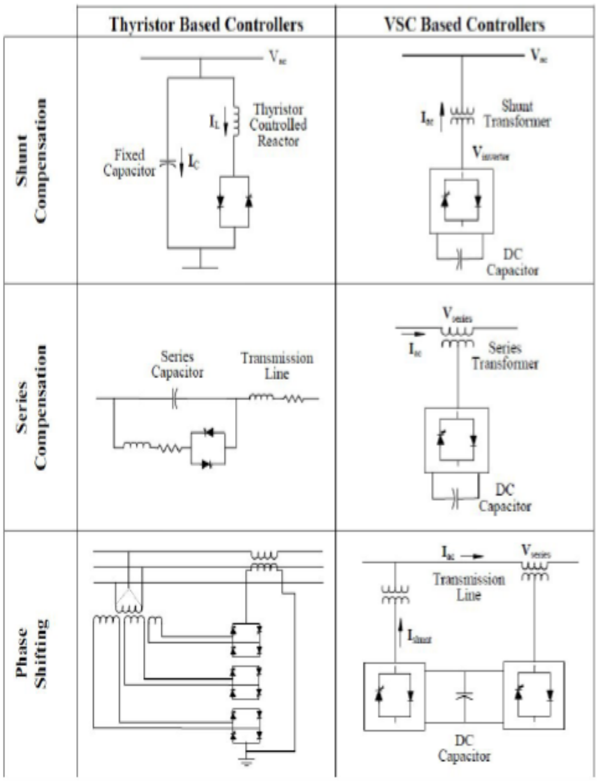


Fig. 1. Summary of different FACT controllers

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 generators have 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], load ability 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 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.

Worldwide concern about the environmental pollution and a possible energy crisis has led to increasing interest in innovative technologies for generation of clean and renewable electrical energy. Among a variety of renewable energy sources, wind power is the most rapidly growing one in the power industry. The traditional wind turbine generator (WTG) systems employ squirrel-cage induction generators (SCIGs) to generate wind power. These WTGs have no speed control capability and cannot provide voltage or frequency support when connected the power grid [1], [2]. During the past decade, the concept of a variable-speed wind turbine driving a doubly fed induction generator (DFIG) has received increasing attention because of its noticeable advantages over other WTG systems [2]-[5]. Most existing wind farms and those in planning employ this type of WTGs. Compared to the fixed-speed SCIG wind turbines, the DFIG wind turbines can provide decoupled active and reactive power control of the generator, more efficient energy production, improved power quality, improved dynamic performance and grid fault ride-through capability. However, compared to the conventional synchronous generators, the reactive power control

capability of the DFIG wind turbines is limited. Moreover, many WTGs are installed in remote, rural areas with good wind resources. These remote areas usually have electrically weak power grids, characterized by low short circuit ratios and under-voltage conditions. In such grid conditions and during a grid fault, the DFIGs may not be able to provide sufficient reactive power support. Without any external dynamic reactive compensation, there can be a risk of voltage instability in the power grid [2]. To prevent further contingencies, utilities typically require the immediate disconnection of the WTGs from the grid, and allow reconnection when normal operation has been restored. This is possible, as long as wind power penetration remains low. However, in some power systems, the penetration of wind power is increasing rapidly and is starting to influence overall power system behavior. Moreover, due to growing demands and limited resources, the power industry is facing challenges on the electricity infrastructure. As a consequence, it will become necessary to maximize the use of all generating sources, including WTGs, to support the network voltage and frequency not only during steady-state conditions but also during disturbances. In the era of a deregulated electricity industry, the policy of open access to transmission systems, which helped create competitive electricity markets, led to a huge increase in energy transactions over the grid and possible congestion in transmission systems. On the other hand, because of new constraints placed by economical and environmental factors, the trend in power system planning and operation is toward maximum utilization of existing electricity infrastructure with tight operating and stability margins. Under these conditions, power systems become more complex to operate and to control, and, thus, more vulnerable to a disturbance. In a conventional power system, synchronous generators are the key components related to the system stability. The control of a synchronous generator is achieved by an automatic voltage regulator (AVR) to maintain constant terminal voltage and a speed governor to maintain constant power and constant speed at some set point. During large disturbances, the synchronous generators and their controllers are often unable to respond fast enough to keep the system stable. A power system stabilizer (PSS) can extend the stability limits of a power system by providing supplemental damping to the oscillation of a synchronous generator's rotor speed through the generator excitation. However, in the case of low-frequency oscillations between generators separated by high system reactance, the PSS may not be able to provide sufficient damping [6]. The controllability of a power system can be further enhanced by using powerelectronics- based flexible ac transmission system (FACTS) devices [7]. By rapidly controlling the voltage, impedance, and phase angle of the ac transmission systems, FACTS controllers have shown powerful capability in voltage regulation, power flow control, power oscillation damping, and improving transient stability. Therefore, the use of FACTS devices allows more efficient utilization of existing electricity infrastructure.Power systems are large-scale, nonlinear, nonstationary, stochastic and complexsystems distributed over large geographic areas. The standard power system controllers are local noncoordinated linear controllers. Each of them controls some local quantity to achieve a local optimal performance, but has no information on the entire system performance. Consequently, the entire power system is normally operated at a nonoptimal operating condition. Further, the possible interactions among these local controllers might lead to adverse effects causing inappropriate control effort by different controllers. As a result, when severe system-wide disturbances or contingencies occur, these local controllers are not always able to guarantee stability. Therefore, wide-area coordinating control (WACC) is becoming an important issue in the power industry. The control and operation of power systems rely on the availability and quality of sensor measurements. Measurements are inevitably subjected to faults caused by sensor failure, broken or bad connections, bad communication, or malfunction of some hardware or software. These faults may result in the failure of the power system controllers and consequently severe contingencies in the power system. To avoid such contingencies, fault-tolerance is an essential requirement for power system control and operation. In addition to the fault-tolerant design, the concept of sensorless control provides another approach to improve the system reliability, as well as to reduce the cost associated with using sensors, e.g., the anemometers used by most variable-speed WTGs. This chapter discusses some issues and challenges related to the control and operation of voltage source converter (VSC)-based FACTS devices, WTGs, and the associated power network. The main concerns relate to voltage regulation, power flow control, power oscillation damping, transient stability, fault tolerance and reliability of power systems with wind power generation and VSC-based FACTS devices. Wind Turbine Control Scheme

II. 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.

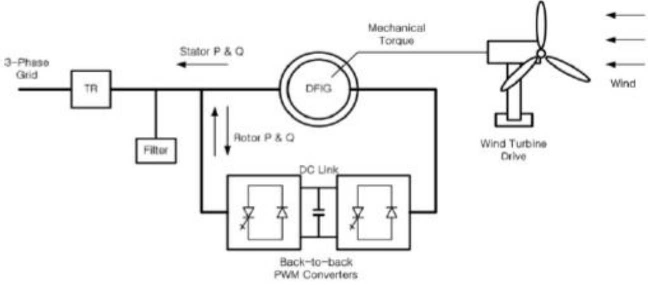


Fig.6. Structure of DFIG wind power generation system

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.

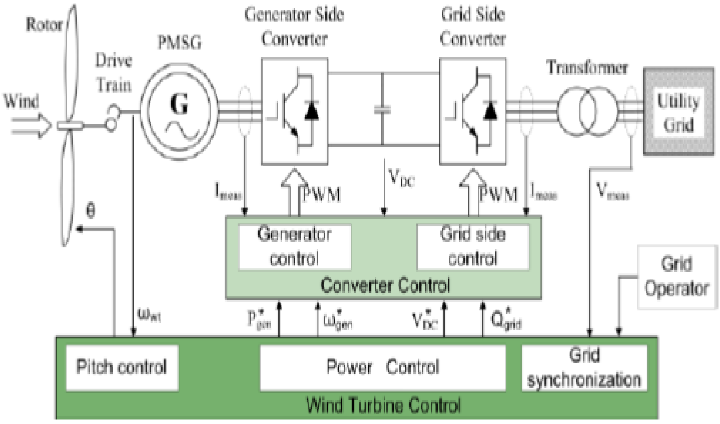


Fig. 7. Control scheme of WT

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:

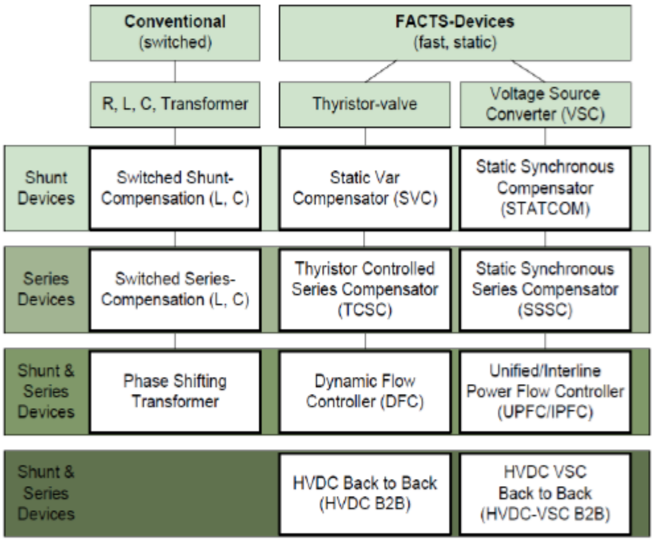
- Series FACTS Controllers
- Shunt FACTS Controllers
- Combined series-series FACTS Controllers
- Combined series-shunt FACTS Controllers

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.



	Conventional (switched)	**FACTS-Devices** (fast, static)	
	R, L, C, Transformer	Thyristor-valve	Voltage Source Converter (VSC)
Shunt Devices	Switched Shunt-Compensation (L, C)	Static Var Compensator (SVC)	Static Synchronous Compensator (STATCOM)
Series Devices	Switched Series-Compensation (L, C)	Thyristor Controlled Series Compensator (TCSC)	Static Synchronous Series Compensator (SSSC)
Shunt & Series Devices	Phase Shifting Transformer	Dynamic Flow Controller (DFC)	Unified/Interline Power Flow Controller (UPFC/IPFC)
Shunt & Series Devices		HVDC Back to Back (HVDC B2B)	HVDC VSC Back to Back (HVDC-VSC B2B)

Fig. 8. Overview of major FACTS controllers

The first column in Figure 8 contains the conventional devices build out of fixed or mechanically 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.

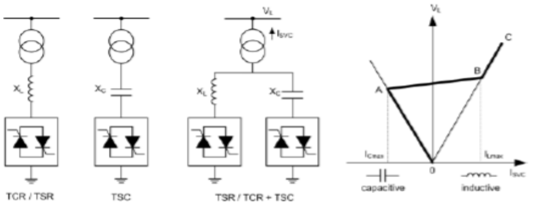


Fig. 9. Basic structures of Thyristor Controlled Reactor (TCR) and its characterizes

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.

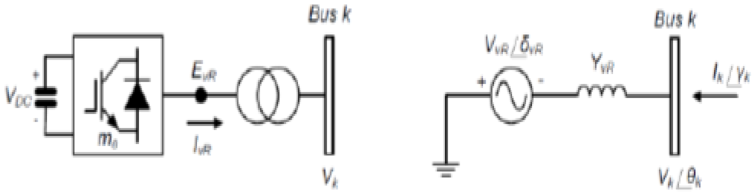


Fig. 10. STATCOM scheme with equivalent circuit representation.

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.

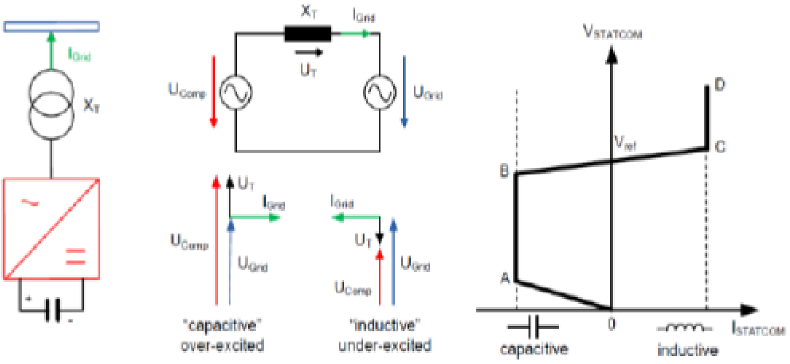
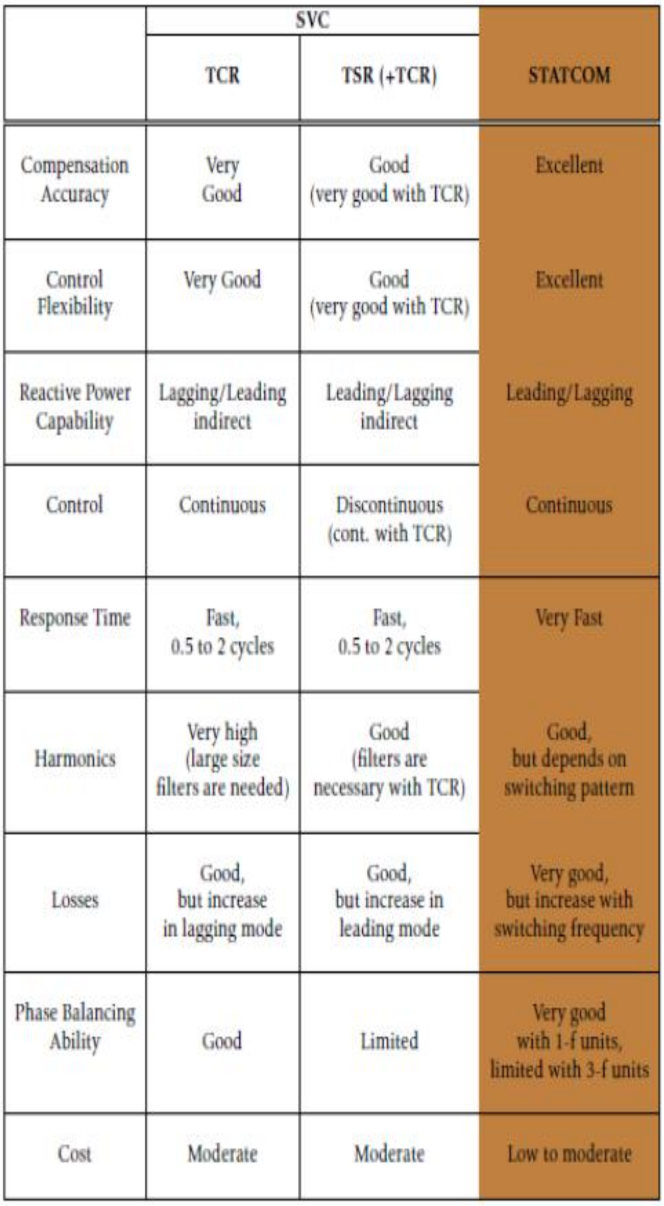


Fig. 11. Schematic representation of working principle of STATCOM



	SVC		
	TCR	**TSR (+TCR)**	**STATCOM**
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

Fig. 12. Comparison between SVC and STATCOM

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.

III. 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.

IV. 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:

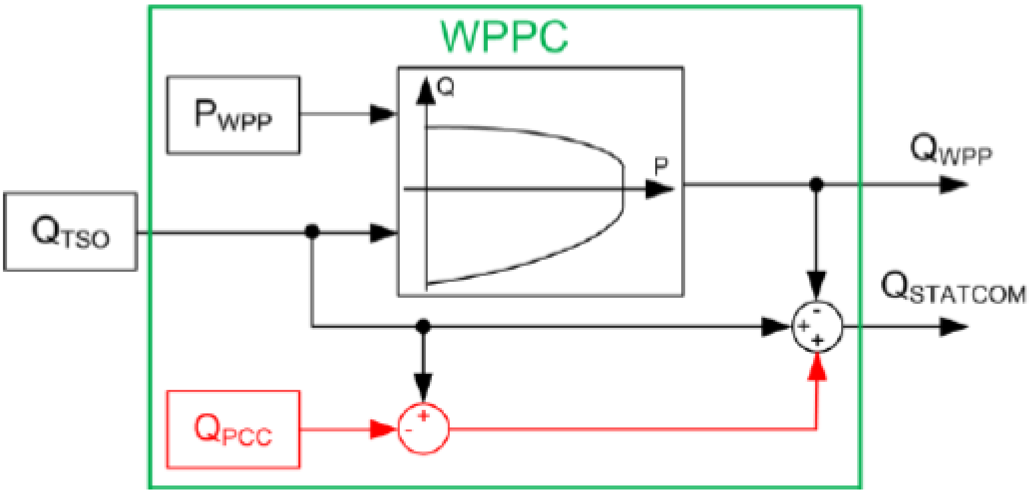


Fig. 13. Simple reactive power distribution algorithm for WPP with STATCOM.

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].

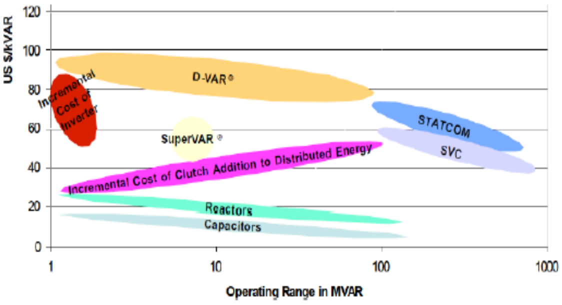


Fig. 14. Average Costs of Reactive Power Technologies

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.

V. Voltage Source Converter-Based FACTS Devices

Power-electronics-based FACTS devices have been widely recognized as powerful controllers to enhance the controllability of the ac transmission systems. Among various FACTS devices, those based on the VSC concept have some attractive features [8], such as rapid and continuous response characteristics for smooth dynamic control, allowing advanced control methodologies for high-performance operation, elimination or reduced requirements for harmonic filtering, ability to add energy storage devices, allowing simultaneous active and reactive power exchange with the ac system, etc. The VSCbased FACTS devices include the static synchronous compensator (STATCOM), the static synchronous series compensator (SSSC), and the unified power flow controller (UPFC).

A STATCOM [7], [9], [10] is a shunt FACTS device. The basic configuration of a STATCOM is shown in Figure 1.1. It consists of a gate turn-off (GTO), insulated gate bipolar transistor (IGBT), or integrated gated commutated thyristor (IGCT)-based VSC that uses charged capacitors as the dc source. The converter is connected in shunt to a

bus through a coupling transformer. The STATCOM generates a set of balanced threephase sinusoidal voltages in synchronism with the ac system, with rapidly controllable amplitude and phase angle. A typical application of the STATCOM is to provide smooth and rapid steady-state and transient voltage control at the point of common coupling (PCC) in the power network.

An SSSC is a series FACTS device, which uses a VSC to inject a controllable voltage in quadrature with the line current of the power network through a seriesconnected transformer, as shown in Figure 1.2.

This is equivalent to providing acontrollable capacitive or inductive impedance compensation which is independent of the line current [11]-[13]. A typical application of the SSSC is for power flow control. In addition, with a suitably designed damping controller, the SSSC has an excellent performance in damping low-frequency power oscillations in a power network [14]. By coupling an additional energy storage system to the dc terminal, the SSSC can also

provide simultaneous active power compensation, which further enhances its capability in power flow control, power oscillation damping, and improving transient stability [7],

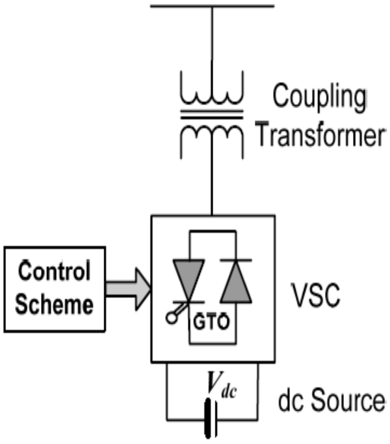


Figure 1.1: Single-line diagram of a STATCOM.

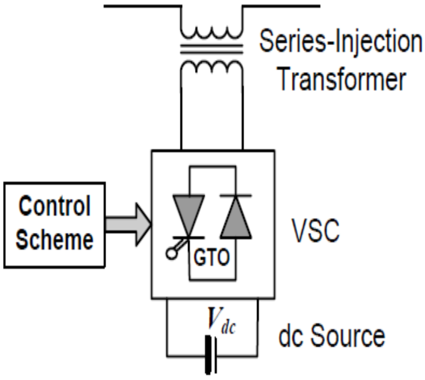


Figure 1.2: Single-line diagram of an SSSC.

Power systems containing generators and FACTS devices are large-scale, nonlinear, nonstationary, multivariable systems with dynamic characteristics over a wide operating range. Conventionally, linear control techniques are used to design the controllers of FACTS devices based on a linearized system model with fixed parameters around a specific operating point [9]-[15]. Final tuning of these controllers gains are typically made using field tests at one or two operating points. However, in practical applications, the FACTS devices and the associated power network cannot be accurately modeled as a linear system with fixed and known parameters. Therefore, at other operating points or in the event of a severe disturbance, these linear controllers may not able to provide an acceptable performance or stability.

Control, Operation, and Grid Integration of DFIG Wind Turbines

The basic configuration of a DFIG wind turbine is shown in Figure 1.3. The wind turbine is connected to the DFIG through a mechanical shaft system, which consists of a low-speed shaft and a high-speed shaft and a gearbox in between. The wound-rotor induction machine in this configuration is fed from both stator and rotor sides. The stator
is directly connected to the grid while the rotor is fed through a variable frequency converter (VFC), which only needs to handle a fraction (25-30%) of the total power to achieve full control of the generator. In order to produce electrical power at constant voltage and frequency to the utility grid over a wide operating range from subsynchronous to supersynchronous speeds [16], the power flow between the rotor circuit and the grid must be controlled both in magnitude and in direction. Therefore, the VFC consists of two four-quadrant IGBT PWM converters, namely, a rotor side converter

(RSC) and a grid side converter (GSC), connected back-to-back by a dc-link capacitor [17]. The crow-bar circuit is used to short-circuit the RSC to protect it from over-current in the rotor circuit during transient disturbances.

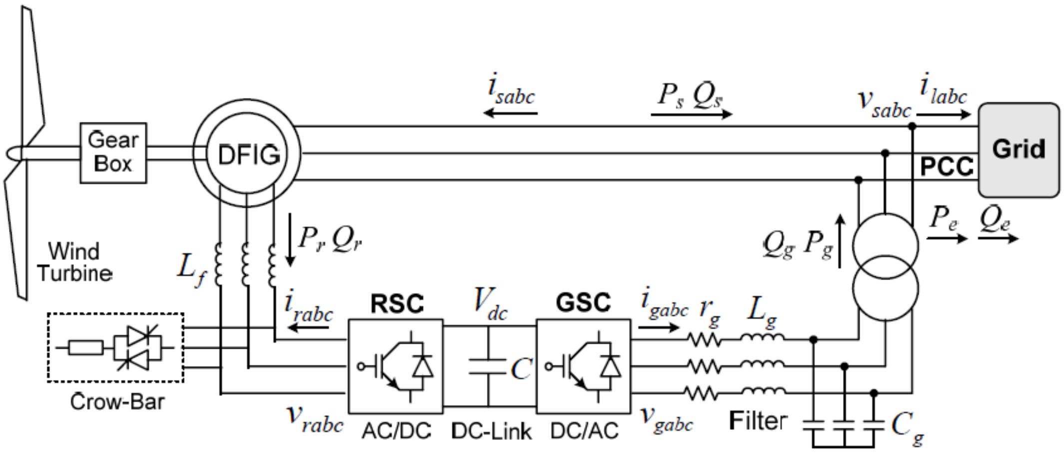


Figure 1.3: Configuration of a DFIG wind turbine.

By adjusting the shaft speed optimally, the variable-speed WTGs can achieve the maximum wind power generation at various wind speeds within the operating range. To implement maximum wind power extraction, most controller designs of the variablespeed WTGs employ anemometers to measure wind speed in order to derive the desired optimal shaft speed for adjusting the generator speed. In most cases, a number of anemometers are placed surrounding the wind turbine at some distance to provide adequate wind speed information. The anemometers are mechanical sensors. There are several problems of using anemometers. First, the use of anemometers increases the cost (e.g., equipment and maintenance costs) of the WTG system. Second, the anemometers are inevitably subjected to failure during lightning strokes, storms, and strong winds. This reduces the reliability of the WTG system. A mechanical sensorless control removes the need of using the anemometers, and therefore, reduces the cost and improves the reliability of the WTG system.

Another key issue related to the operation of the DFIG wind turbines is the grid fault or low voltage ride-through capability. When connected to the grid and during a grid fault, the voltage sags at the PCC of the WTGs can cause a high current in the stator windings of the DFIG. Because of the magnetic coupling between stator and rotor, this current will also flow in the rotor circuit and the VFC. Since the power rating of the VFC is only 25-30% of the DFIG power rating, this over-current can lead to the destruction of the converter. In order to protect the RSC of the DFIG from the over-current in the rotor circuit, it has to be blocked. In such a case, the generator becomes a conventional SCIG and starts to absorb reactive power; the GSC can be set to control the reactive power and voltage at the PCC. However, the reactive power control capability of the GSC is limited because of its small power capacity. Moreover, due to the unbalance between the mechanical shaft torque and the generator's electromagnetic torque, the induction generator speeds up and draws more reactive power from the grid. This contributes further to the PCC voltage collapse [2].

Moreover, many WTGs are installed in remote, rural areas. These remote areas usually have electrically weak power grids, characterized by low short circuit ratios and under-voltage conditions. In such grid conditions and during a grid fault, the DFIGs may not be able to provide sufficient reactive power support. Without any external dynamic reactive compensation, there can be a risk of voltage instability in the power grid [2]. It has been reported recently that incorporation of wind farms into the East Danish power system could cause a severe voltage recovery problem following a three-phase fault on the network [18]. To prevent such contingencies, utilities typically immediately disconnect the WTGs from the grid, and reconnect them when normal operation has been restored.

This is possible, as long as wind power penetration remains low. However, with the rapid increase in penetration of wind power in power systems, tripping of many WTGs in a large wind farm during grid faults may begin to influence the overall power system stability. Therefore, it will become necessary to require WTGs to support the network voltage and frequency not only during steady-state conditions but also during grid disturbances. Due to this requirement, the utilities in many countries have recently established grid codes [5], [19] that specify the range of voltage sags (in duration and voltage level) for which WTGs must remain connected to the power system, as shown in Figure 1.4, where V and Vn are the magnitudes of the actual and nominal voltages at the connection point of WTGs, respectively. According to this grid-fault/low-voltage ridethrough specification, the WTGs should remain connected to the grid and supply reactive power when the voltage at the point of connection falls in the gray area. The successful integration of WTGs into some weak power grids will therefore require dedicated local shunt FACTS devices, e.g., the STATCOM, to provide rapid, smooth, and step-less reactive compensation and voltage support [2], [20] in order to satisfy the relevant grid codes.

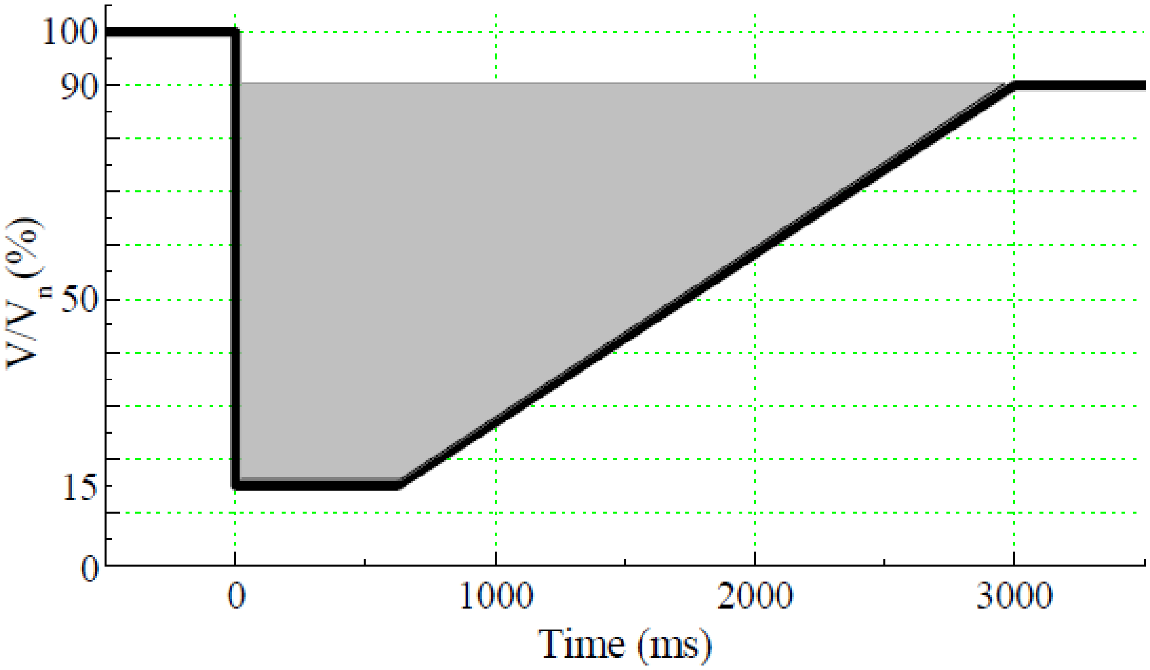


Figure 1.4: Typical grid-fault/low-voltage ride-through requirement of WTGs.

On the other hand, the VFC of the DFIG can be applied to control the reactive power and voltage. This reduces the demands of dynamic reactive compensation from the local FACTS devices. In order to achieve certain operational and economical benefits, it is necessary to coordinate the control actions of the wind farms and the local FACTS devices so that the WTGs will behave like other traditional sources of generations to assist in maintaining grid voltage and frequency stability, particularly during transient conditions. However, because of the stochastic and nonlinear nature of the power system, the traditional mathematical tools are not sufficient or too complicated to design such a coordinated control scheme based on the analytical models of the integrated system. ROWING concern for limited fossil fuels reserves and CO-2 emission reduction stimulated development of the renewable energy sector. Especially, wind energy sector experienced huge thrust in recent years. As an example, in EU in 2008 one third of the total 23.85GW newly installed power capacity were wind turbine generators (WTG) [1]. There was more installed capacity in wind power than in any other generation technology. Moreover, 8.48GW of installed wind power capacity represented two thirds of the total newly installed renewable energy capacity in 2008 in EU. EWEA
forecasts that by year 2030 total installed wind power capacity in EU will be in order of 300GW. In terms of share
of energy market, it means that in 2030 wind energy would cover from 20.8% to 28.2% of European electricity demand (depending on the scenario) [2]. Integration of wind energy into power systems on such a large scale is not straightforward. Power system and its operation, was designed and developed around conventional power plants (CPP) with synchronous generators directly coupled to the grid. Wind power plants (WPP) have different characteristics from the conventional ones. Thus, because amount of wind power has become significant, grid performance and stability is affected [3]-[5]. Therefore, transmission system operators (TSO) were forced to impose
new requirements for the connection of WTGs to the power network. This way, TSOs try to ensure that all regulatory actions, which are needed for maintaining grid stability, are still performed on a satisfactory level, when renewable energy is introduced into the picture. 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.

VI. GRID CODES AND WPP LIMITATIONS

TSOs requirements for all generation units are specified in formal documents called grid codes. However, nonconventional generation units are usually exempt from some of the general requirements and there is oftenadditional set of rules that apply only to wind power (UK, Germany). Beside ability to deliver contracted amount of power, generating unit is required to assist in maintaining power system transient and steady state stability, participate in voltage and frequency control, assist in post fault recovery and also have capability to survive through the system faults [6]-[8]. Therefore, grid codes specify active and reactive power profiles, that generating unit must perform under different grid conditions. In order to do so, first of all power plant must be able to continue its operation under off-nominal conditions. TSOs specify steady state voltage-frequency-time range in which generating unit must be able to operate without premature tripping. Around the nominal grid voltage and frequency continuous operation is required. For bigger conditions deviations power plant operation must be continued, but only for a limited time [6],[7]. Separate requirements are given for transients often referred as fault ride-through (FRT) requirements. TSOs specify time-voltage profiles, that show, when power plant is allowed to disconnect after fault occurrence [6],[7]. Active power control is required for maintaining the grid frequency. In most of the countries, WPPs are allowed to work at their maximum power point. Therefore they are exempt from primary and high frequency control requirement [7]. Normally, only active power down-regulation is required in case of over frequencies. Some TSOs specify minimum ramp-down and maximum ramp-up rates for active power [10],[11]. However, in the future higher requirements regarding WPPs contribution to active power and frequency regulation are expected. Draft of the new Spanish grid code for the wind power already mentions inertia emulation and power oscillation damping [12]. Voltage control and reactive power capability became a standard requirement for the Wind Power Plants. Grid codes specify minimal amount of reactive power (both lagging and leading) that in steady state WPP must be able to supply together with nominal active power [6],[7]. Special requirements are given for the disturbances, where the reactive current injection is prioritized over the active current, to support voltage stability. TSOs specify reactive current control characteristic that must be followed during transients [6],[7]. So far grid codes were specifying FRT characteristics based on symmetrical faults, since those would result in the highest voltage dips. However, in the future separate lowvoltage profiles would be given for unsymmetrical faults and negative sequence current injection might be demanded [12].

WTGs can comply with the grid codes in various degrees, depending on the technology. Capabilities of the oldest, fixed speed technology are highly limited [14]. Therefore fixed speed wind turbines on their own can be regarded as grid code incompliant. Much better performance can be expected from two variable speed wind turbine (VSWT) technologies: doublyfed induction generator (DFIG) based, and full-scale converter (FSC) based turbines. Because VSWT are fully or partially decoupled from the grid by frequency converters, they can quite easily tolerate small frequency and voltage deviations. Thus, voltagefrequency- time operation range can be met with proper converter control [21]. VSWT can comply with today's active power regulation requirement. Active power can be quickly limited by the converter control and with slower rate by pitch angle control [14]. VSWTs could even perform inertia emulation and participate in primary frequency control, if they would operate at de-loaded power curve (below maximum power point) [16]-[18]. However such solution is not cost efficient. Steady state reactive power capability is very good in case of FSC-WTs, but limited in case of DFIG-WTs. According to [16] reactive power capability of DFIG based wind farm might be not enough in case of in case of the weak grids and some external support might be needed. For FSC-WTs reactive power capability is only matter of proper sizing of grid side converter (GSC), that it would be capable of carrying extra current [19]. However, it must be remembered that due to cables and transformer impedances Q capability at point of common coupling (PCC) of the whole WPP in not a simple multiplication of Q capabilities of single WTGs [20]. Transient behavior requirement is challenging for DFIG technology. Fault occurrence excites high rotor currents and causes overvoltage in the DC-link [58],[59]. To protect machine side converter (MSC) active crowbar protection will be triggered and chopper resistors would be activated to limit DC-link overvoltage. Due to over current protection, DFIG for some time loses its controllability [16]. Then it behaves like an ordinary induction generator [16]. On the other hand, GSC can provide some reactive power support [58],[59]. However, its capabilities might be too limited for grid code compliance [16],[58]. Moreover, due to active power imbalance turbine WT is prone to over speeding. To prevent tripping, pitch angle controller might need to be activated [16]. Again, FSC-WTs show better FRT performance. They can survive through the faults up to several seconds even with 0 volts at WT terminals [21]. Over speeding problem is solved by employing braking resistor in the DC-link. FSCWTs can provide 1.0 p.u. reactive current during transients, as it is required by some of the grid codes [20].

VII. OVERVIEW OF FACTS DEVICES

Flexible AC Transmission Systems are represented by a group of power electronic devices. This technology was developed to perform the same functions as traditional power system controllers such as transformer tap changers, phase shifting transformers, passive reactive compensators, synchronous condensers, etc. [38]. Particularly FACTS devices allow controlling all parameters that determine active and reactive power transmission: nodal voltages magnitudes and angles and line reactance [42]. Replacement of the mechanical switches by semiconductor switches allowed much faster response times without the need for limiting number of control actions [38]. However, FACTS technology is much more expensive from the mechanical one [39].

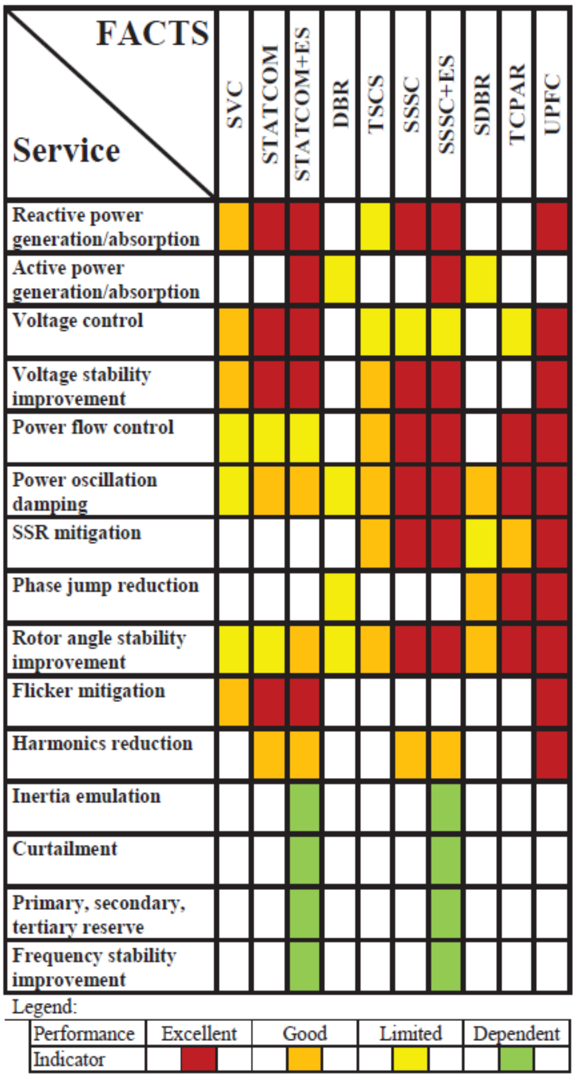
FACTS devices can be divided into two generations. Older generation bases on the thyristor valve, where newer uses Voltage Source Converters (VSC). In both categories there are corresponding devices performing similar services. Generally speaking, VSC technology offers faster control over a wider range [40]. Moreover, new generation does not need bulky reactors, thus size of these devices is considerably smaller than the thyristor controlled ones. However, VSC technology requires use of self commutating semiconductor devices which are more expensive, have higher losses and smaller voltage ratings when compared to the thyristors [41].

Another way of categorizing FACTS devices is by the way they are connected to power systems: shunt, series or shuntseries connection [41]. Main purpose of shunt devices is to provide reactive power compensation and dynamic voltage support of the lines or loads [40]. One of the shunt devices is the thyristor based Static VAR Compensator (SVC), which can be seen as a variable susceptance with a smooth control over a wide range from capacitive to inductive [43]. It is the oldest FACTS device and has the biggest number of applications [40]. VSC based Static Compensator (STATCOM) is another shunt connected device, which behaves like a synchronous voltage source which can inject or absorb reactive power [44]. Biggest advantage of STATCOM over SVC is the ability to maintain the reactive current output at its nominal value over a wide range of node voltages, where SVC has limited current capability when voltage is reduced. In conclusion SVC provides less support 3743when it is mostly needed [15]. Thyristor controlled braking resistor, known as Dynamic Braking Resistor (DBR), is also a shunt FACTS device, however its purpose is different from SVC and STATCOM. DBR is mainly used for consuming generator available active power that cannot be sent to the grid due to voltage depression in the post-fault period. In such a way DBR improves rotor angle stability of CPPs. Series devices have influence on the line effective impedance. Hence, they are basically used for controlling power flow and damping of power oscillations [40]. In this category of devices appears Thyristor Controlled Series Capacitor (TSCS), which can be regarded as adjustable reactance connected in series with the line reactance [40]. The same functions can be performed by a VSC based device, which is Static Synchronous Series Compensator (SSSC). It can be seen as series voltage source that compensates for the voltage drop on the line reactance [38]. However, SSSC offers better performance than TCSC, because its control characteristic is independent from the line current. Yet, due to the costs SSSC has not been applied yet on the transmission level. Another series FACTS device is Series Dynamic Breaking Resistor (SDBR). It offers similar functions as shunt DBR. But SDBR performance is better, since it is current not voltage dependent device [41].

It is worth pointing out, that STATCOM and SSSC topologies can be used to facilitate energy storage (ES) into the power system. It is feasible to install ES unit (super capacitor, battery, fuel cell, SMES, etc.) in parallel to the DClink capacitors of these FACTS devices [56],[59]. Depending on the storage size, STATCOM and SSSC could perform additional functions like inertia emulation or frequency regulation. In fact SSSC configuration with small size energy storage, known as Dynamic Voltage Restorer (DVR), is used on the custom power level [40]. However DVR control principles are different than for regular SSSC. Regarding shunt-series connection two devices should be mentioned Thyristor Controlled Phase Angle Regulator (TCPAR) and Unified Power Flow controller (UPFC).

TCPAR works as a Phase Shifting Transformer (PST), where mechanical switches are replaced by solid state thyristor switches. Hence, TCPAR is also often referred as Static Phase Shifting Transformer (SPST) and it can be represented as a variable phase angle in series with line [43]. Its basic purpose is to control line power flow and damp power oscillations. One of the most advanced FACTS devices is UPFC, which can be treated as STATCOM and SSSC sharing the same DC-link. Such configuration gives three degrees of freedom (control variables), where all of the FACTS devices described so far have only one (except the ones with storage, which have two degrees of freedom) [41]. UPFC can regulate both active and reactive power flow through the series connection, and additionally shunt connected converter can control reactive power at the point of its connection. Therefore, UPFC can perform almost all of the functions of previously described devices. Except the functions that are related to the energy storage. This is because UPFC does not contain real power source, it only transfers power from one

TABLE I
COMPARISON OF SERVICES PERFORMED BY DIFFERENT FACTS DEVICES



Service \ FACTS	SVC	STATCOM	STATCOM+ES	DBR	TSCS	SSSC	SSSC+ES	SDBR	TCPAR	UPFC
Reactive power generation/absorption	🟧	🟥	🟥		🟨	🟥	🟥			🟥
Active power generation/absorption			🟥	🟨			🟥	🟨		
Voltage control	🟧	🟥	🟥		🟨	🟨	🟨		🟨	🟥
Voltage stability improvement	🟧	🟥	🟥		🟧	🟥	🟥			🟥
Power flow control	🟨	🟨	🟨		🟧	🟥	🟥		🟥	🟥
Power oscillation damping	🟨	🟧	🟧	🟨	🟧	🟥	🟥	🟧	🟥	🟥
SSR mitigation					🟧	🟥	🟥	🟨	🟧	🟥
Phase jump reduction				🟨				🟧	🟥	🟥
Rotor angle stability improvement	🟨	🟨	🟧	🟨	🟧	🟥	🟥	🟧	🟥	🟥
Flicker mitigation	🟧	🟥	🟥							🟥
Harmonics reduction		🟧	🟧			🟧	🟧			🟥
Inertia emulation			🟩				🟩			
Curtailment			🟩				🟩			
Primary, secondary, tertiary reserve			🟩				🟩			
Frequency stability improvement			🟩				🟩			

Legend:

Performance	Excellent	Good	Limited	Dependent
Indicator	🟥	🟧	🟨	🟩

side to the other. Despite the very high costs there are already few UPFC applications [45],[46].There are even more advanced FACTS devices employing multiple VSCs, but they are out of this paper scope. Table 1 summarizes services and performance level, that different FACTS devices offer for the power system.

VIII. FACTS FOR WPPS – RESEARCH

Limitations of WPPs with respect to the grid codes were discussed in section II. The most modern WPPs equipped with the full scale converter turbines can meet all today's requirements, where FSWT based wind farms are to large extent not compliant. It will become common practice thatTherefore, lot of research has been done toward improvement of wind turbines behavior. Especially, the ones of old type. Grid codes requirements are aiming in securing electrical grid reliable and stable performance. As was discussed in section III one of the key features of FACTS devices is enhancement of the grid stability. Hence, one of the research paths is application of FACTS devices for WPP support.

However, research in not only limited to the compliance with existing grid codes. FACTS devices might introduced new features for WPPs, which yet might be not demanded by TSOs, but would be beneficial in terms of grid stability. Below, main research areas regarding FACTS solutions are reviewed.

A. Voltage stability

Grid code requirement for steady state and transient reactive power support originates in voltage stability problem.

Reactive power consumptions of the connecting lines and loads may lead to a voltage collapse in a weak heavily loaded system. Such situations are quite typical for wind generation, which is often placed in remote areas and connected with long lines.

If reactive power compensation provided by WPP is not sufficient, generated active power might need to be limited to avoid voltage instability [22]. It is especially likely for a wind farm employing FSWTs, which not only does not provide compensation but also consumes reactive power. Studies conducted in [22] show, that STATCOM applied at PCC of such plant greatly enhances system voltage stability, when connection to the main grid becomes weakened. Similar case was studied for DFIG based wind farm in [25]. Due to crowbar protection, WPP reactive power support is limited. In result, without a STATCOM voltage cannot be restored when one of the connecting lines was disconnected due to fault. [26],[27] also analyze transient voltage stability enhancement of DFIG-WT based farms by a STATCOM. [27] clearly shows proportional relation between STATCOM ratings and level of support. In [26] influence of STATCOM control strategy on post-fault voltage evolution was studied.

Optimized neural network controller allows faster voltage restoration with smaller overshoot and oscillations.

In [29] voltage stability of 486MW DFIG based offshore wind farm is indirectly addressed through the compliance

analysis with UK grid codes. Conclusion is made that for short connection (20km), DFIG can comply with grid codes without additional support. On the other hand, for 100km cable, STATCOM of at least 60MVAr would be needed to provide adequate voltage support from the wind farm. However, authors suggest that in both cases it could be beneficial, to cover whole reactive power demand by STATCOM, without relying on WTGs capabilities. Control is faster and less complicated in case of one centralized device, when compared to tens of turbines, distributed over a certain area. In such a light, more studies are needed, because in most of the publications usually WPP is modeled as one aggregated WTG (e.g. [25]-[27]).

B. Frequency stability

Active power control requirement stated in the grid codes is related to frequency stability. To maintain frequency close to the nominal value, balance between generated and consumed power must be provided. When there is surplus of generated power, the synchronous generators (which are the core of the power system), tend to speed up. In result synchronous frequency rises. On the contrary, when there is not enough power generation to cover consumption, overloaded synchronous machines slow down and grid frequency drops. There has been done lot of research on adding energy storage for wind turbines to improve active power control (e.g. [36],[37] discuss provision of frequency support, load leveling and spinning reserve). However, here particular interest is when energy storage is incorporated in FACTS device. Such studies have been done in [32], for STATCOM with Battery Energy Storage System connected in parallel to regular DC-link capacitors. According to simulation results,

5MWh storage helps 50MVA SCIG based wind farm to track ½ hour active power set point, which was based on wind prediction. Therefore need for balancing power is reduced and wind power can be better dispatched. It is clear that energy storage would bring benefits in terms of frequency control and inertia emulation. Still, primary STATCOM control functions are maintained.

C. Power oscillations

Grid codes do not specify requirements for power oscillation damping. However, this is one of the existing problems in power systems. In [26],[35] it is shown that additional control loop for STATCOM controller can help to damp power oscillations, while basic voltage support function is maintained. In [26] 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 [35]. 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. [35] 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 [35].

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. 3745 newly built wind farms would need to prove their compliance through certificates [13]. If TSO demands are not covered, some countries, like Spain, require retrofitting or repowering of already existing wind farms [33].

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D. Fault ride through

As was discussed fault ride through is a technical challenge for wind turbines, especially for SCIG and DFIG based. Employment of shunt compensation devices, SVC and STATCOM, at PCC was considered in [22] and [23] for Fig 2. Active power output from fixed speed turbine based wind farm (light blue trace – active power without storage, dark blue trace – ½ hour active power set point based on wind prediction, orange trace – active power with storage)[32] Fig 1. PV curves at PCC of FSWT farm for different conditions [22] Fig 3. Active power oscillations of DFIG wind farm after fault, for two STATCOM controllers (INC - interface neurocontroller) [26]improvement of FSWTs fault related speed stability. Both papers use as a stability measure critical fault clearing times (CCT) – maximum allowable fault duration times before turbines lose stability. In [22] CCT for base case is equal 0.260s. With 1 p.u. SVC and STATCOM compensation CCTs are 0.329s and 0.350s respectively. [23] also states STATCOM superior performance over SVC, however at the price of 30% higher installation costs. Similarly, satisfactory results were obtained in [24] and [25], where STATCOM were used as a solution for DFIG turbines FRT problems.

Different type of FACTS device was proposed in [47] for FRT of FSWTs – SDBR. Authors claim that 0.05p.u. SDBR is equivalent of 0.4p.u. dynamic reactive power compensation device. Totally different approach to FRT of FS- and DFIG-WTs was proposed by Gamesa in [33]. Instead of shunt compensation DVR was used. This device, by exchanging active power with the grid, injects series voltage between PCC and wind farm terminals to cover voltage reduction caused by grid fault (Fig. 4). In such a way fault is not seen from the wind turbine point of view. Thus, it might continue its operation uninterrupted. FRT concepts for DFIG-WTs are also discussed in [24] and [28].

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