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STATCOM AND SVC WITH WIND TURBINES

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ABSTRACT

Nouman Liaquat: STATCOM and SVC with Wind Turbines
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The large wind parks are the feasible solution in order to generate clean energy compared with conventional power plants. Therefore, the interest in the Wind Energy Conversion System (WECS) is quickly increasing to reduce the fossil fuels dependencies. While the penetration of the WECS increases into the grid, many of the technical challenges have appeared. Low voltage Ride Through (LVRT) is the new requirement which needs to be fulfill when the amount of wind power generation increases, to be able to guarantee the power system reliability and stability. The voltage dips that result from faults in the grid can lead to a loss generation unit. According to the LVRT, WTs are required to be always connect during the fault, and to support the power system by supplying reactive power to ensure grid stability.

The main purpose of the thesis was to investigate that how the LVRT of Doubly Fed Induction Generator (DFIG) based Wind Turbine Generator (WTG) can be enhanced using shunt connected Flexible AC Transmission System (FACTS) devices Static Synchronous Compensator (STATCOM) and Static Var Compensator (SVC). The theoretical background related to the LVRT enhancement using STATCOM and SVC is performed, and results are verified by the simulation model.

This thesis is constructed in 5 Chapters, Chapter 1 gives an overview about the problems related to wind power. Chapter 2 explains the different grid codes and different topologies of the wind turbine technologies. Chapter 3 explains the working principle, construction and applications of the STATCOM and SVC. A comprehensive comparison between the STATCOM and SVC is also explained in this chapter. The operation of DFIG wind turbine during voltage dip is analyzed by using the simulation model in the next Chapter. In the first case, the effect of a three-phase fault on the power system was analyzed without using any compensation device. The LVRT requirements were not fulfilled without any compensation device. Therefore, in the second case, SVC was added in the model. Some improvement was observed in this case, but it was not enough to fulfill very strict LVRT requirements such as German Grid Codes (GGCs).Therefore, in the third case, SVC is replaced by STATCOM to meet the LVRT requirement of GGCs. In the last case, three different ratings of STATCOM were utilized to see the effect on the grid voltage and reactive power support by STATCOMs. The key findings of this thesis work are reported by Chapter 5.

Keywords: DFIG, FACTS, German grid codes, LVRT, STATCOM, SVC

The originality of this thesis has been checked using the Turnitin Originality Check service.

PREFACE

This thesis was conducted at Tampere University Hervanta campus, in Faculty of Information Technology and Communication Sciences. The work started in June 2019 and eventually completed in November 2019.

I would like to thank my supervisor Dr. Jenni Rekola for her guidance, assistance and help during the whole thesis process. Throughout the thesis, she provided me ideas to make the thesis work better and achieve fruitful results.

I would like to thank my family and friends for their moral support and reminding me that it is important to indulge in extra curriculars along with working.

Tampere, 19 November 2019

Nouman Liaquat

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LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating Current
CSC	Current Source Converter
DC	Direct Current
DFIG	Doubly Fed Induction Generator
DSO	Distribution Operating System
EU	European Union
EWEA	European Wind Energy Association
FACTS	Flexible AC Transmission System
FRPC	Full Rated Power Converter
FRT	Fault Ride Through
GGCs	German Grid Codes
GTO	Gate Turn-Off Thyristor
HPFC	Hybrid Power Flow Controller
HV	High Voltage
Hz	Hertz
I	Current
IG	Induction Generator
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate-Commutated Thyristor
IPFC	Interlink Power Flow Controllers
kV	Kilovolt
LSC	Line Side Convertor
LVRT	Low Voltage Ride Through
MLP	Maximum Loading Point
MOC	Mos-Controlled Thyristor
ms	Millisecond
MVA	Mega Volt Ampere
MVAr	Mega Volt Ampere Reactive
MW	Mega Watt
MPPT	Maximum Power Point Tracking
PCC	Point of Common Coupling
PF	Power Factor
PLL	Phase Lock Loop
pu	Per Unit
PWM	Pulse Width Modulation
RSC	Rotor Side Converter
SCIG	Squirrel Cage Induction Generator
SCR	Short Circuit Ratio
sec	Second
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
TCR	Thyristor Controlled Reactors
TCSC	Thyristor Controlled Series Compensator
THD	Total Harmonic Distortion
TSC	Thyristor Switched Capacitors
TSO	Transmission System Operator
UPFC	Unified Power Flow Controller
V	Voltage
VSC	Voltage Source Converter
WRIG	Wound Rotor Induction Generator
WECS	Wind Energy Conversion System
WF	Wind Farm
WPP	Wind Power Plant
WT	Wind Turbine
WTG	Wind Turbine Generator

1. INTRODUCTION

Around the world, the use of renewable energy is increaing and these unconventional energy sources could help deal with climate change issues. Renewable energy is basically obtained from natural sources replenish themselves and are hardly exhausted. Over 80% of the entire energy consumed by humans is a result of fossil fuel utilization. Nonetheless, current observations have revealed that renewables are arguably the fastest-growing sources of energy around the world [1]. Renewable energy has abundant benefits. For instance, it is capable of combating issues related to the climate change since it leads to no direct greenhouse gas releases or emissions. Only indirect emissions are produced such as those resulting from installation operations, manufacturing parts as well as maintenance, all of which, are assumed to be minimal. Also, renewable energies may help reduce pollution and consequently minimize threats towards the environment and human health. Renewable energy is considered as a reliable source of power since its sources are overly renewable and they never run out once renewable facilities are established. Besides, these renewable sources of energy are cost-effective in terms of operation coupled with the fact that the fuel is usually free, making renewable energy prices be not only affordable but also stable over time.

Wind energy is the common type of renewable energy that can produce electricity without any pollution emission, and it will never run out. The installation of the Wind Farms (WFs) is quickly growing, it can be realized from this, between now and 2020 over 40 GW of the windmills will be installed in the US, which is enough for power 30 million homes [2]. The wind power of 280 GW has been added in the grid since 1996, which really makes this particular source of power an important contributor [3].

The expected increase in the EU’s share of the electricity provided by the wind power is shown in Figure 1-1. Based on Figure, according to the European Wind Energy Association (EWEA) the share of wind power generation in EU is expected to attain the 20% target in year 2020 and in 2050 it will reach 50% [4]. The offshore wind resources are particularly favorable since the intensity of the wind is pretty strong at sea. The EWEA is targeting 40 GW offshore wind power capacity until 2020 and 150 GW until 2030 [4].

The Clean Energy package of 2016 commission has laid the groundwork for better environment investment in order to achieve 2030's 33% target. Nonetheless, it is argued that failure to establish national targets is likely to threaten the achievements of the 2030s 32% target. If no new viable policies are established and no measures implemented during the period between 2020 and 2050, it is estimated that the use of renewable sources of energy will only increase by a mare 0.7% annually [5].

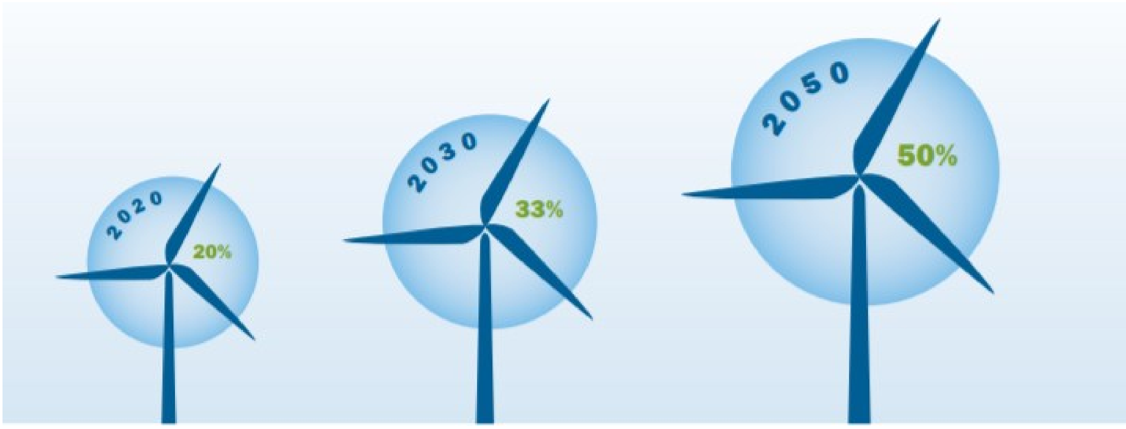

Figure 1-1. *Expected increase in the EU's share of electricity provided by wind power [4]*

The primary goal of this thesis is to understand the Low Voltage Ride Through (LVRT) enhancement of Doubly Fed Induction Generator (DFIG) based wind turbines using the Flexible AC Transmission Systems (FACTS) devices. The FACTS devices which are used in this thesis are shunt type controllers, Static Synchronous Compensator (STATCOM) and Static Var Compensator (SVC). The thesis is structured in five chapters; Chapter 2 gives an overview concerning the different grid codes as well as different wind turbines topologies. Shunt connected FACTS devices (STATCOM and SVC) are discussed in Chapter 3. Chapter 4 explains the simulation results of this thesis and finally Chapter 5 concludes the key findings of this thesis.

1.1 Grid Stability

Grid stability is defined as the system's aptitude to restore its operations to normalcy following a specific fault. Power system transitory stability is associated with the capacity to maintain synchronization when imperiled to a severe disturbance. Largely, system stability is related to faults within a power system in a network such as loss of production capacity, tripping of transmission lines and short circuits [6]. The aforementioned faults tend to disrupt the balance of power and consequently change power flow. Through the operating generators' capacity may be insufficient, large voltage drops can arise unexpectedly [7].

The redistribution and unbalance of reactive and real power in the network can cause variance in voltage beyond the stability's boundary [6]. Typically, voltage stability is related to the reactive power imbalance. When the system reaches or attains the Maximum Loading Point (MLP) or the voltage collapse point, reactive and real power losses tend to rapidly increase [6, 7]. Consequently, the reactive power support is essential.

1.2 Symmetrical Fault

A fault in a circuit is any failure which disturbs the normal flow of current. There are two types of faults which occur in the power system; the symmetrical fault and asymmetrical fault. Symmetrical faults are those faults where the power systems remain balance for instance three-phase line to ground fault or three-phase line to line fault [8]. Whereas, the asymmetrical faults are those faults which only involve one or 2 phases for example line to line fault, single line to ground fault and double line to ground fault. In this report, we will only discuss the symmetrical fault because the effect of three-phase symmetrical fault on the power system is being analysed in the simulation model.

The symmetrical fault can be produced by abnormal weather conditions, equipment failure or human error. These faults can cause the overflow of the current, severe short circuit, loss of equipment and blackout in the system. Lightning is one of the major causes of symmetrical faults on high voltage transmission lines. Lightening stroke ionizes the atmosphere around the conductor, which results in a low impedance path between conductor and supporting tower. This path allows the current to flow from the conductor to ground and through the ground to the grounded neutral of a transformer/generator. If symmetrical faults occur, the system remains balanced but results in severe damage to the electrical power system. Only 2 to 5 percent of system faults are symmetrical faults in high voltage transmission lines [8]. In our simulations, due to its severity, symmetrical fault has been considered in order to meet the requirement of the LVRT grid code.

Table 1 shows the probability of occurrence of most frequent kind of short-circuit faults in overhead transmission line.

Table 1. Relative probability of occurrence of most frequent kinds of short-circuit faults in overhead transmission line [8]

Type of Short Circuit Fault	Nature of Fault	Percentage of Occurrence
Single Line to Ground (L-G)	Unsymmetrical Fault	70
Phase to Phase (L-L)	Unsymmetrical Fault	15
Two-Phase to Ground (L-L-G)	Unsymmetrical Fault	10
Phase to Phase and Third Phase to Ground	Unsymmetrical Fault	2 to 3
All three phases to the ground (L-L-L-G)	Symmetrical Fault	2 to 3
All the three phases shorted	Symmetrical Fault	2 to 3

1.3 Problems Related to Variable Renewable Energy

However, economically and environmentally the wind energy placement has numerous benefits, but the wind farm propagation can also affect the stability and performance of the grid. Sudden changes in the wind speeds can lead to the disruption in the voltage on the network since wind energy is intermittent and non-dispatchable in nature, which really makes it difficult to provide align energy supply according to the demand. It frequently happens that wind speed is so high, load is low and wind speed is low, load is too high. This scenario results in grid instability and issues related to the power quality. For example, low Power Factor (PF), voltage drop , voltage unbalance, fluctuations, losses in the transmission line and consequently wind farm can be disconnected. Rapid changes in the voltage can result in grid instability and even unplanned outage can occur [3]. As the wind energy is intermittent in nature, wind turbines only generate power when the wind is blowing, batteries can store excess energy for later use, however they are often expensive.

2. NETWORK WITH HIGH PENETRATION OF THE WIND POWER

2.1 Grid Codes Overview

Grid codes are critically important, as they are required to ensure the safe, secure and proper function of the electrical system. The primary role of grid codes is to prevent the adverse effects of the WFs on the operation, reliability and power quality of the system. This chapter explores important grid codes, including reactive power control, Low Voltage Ride Through (LVRT)/ Fault Ride Through (FRT).

Grid codes are important technical specifications, which particularly define the key parameters for connecting facilities such as generation plants and consumer networks to public electric grids. For example, they can be used for specifying the technical requirements of the components to use in the connections [11]. Conventional power generation has a tendency of deploying synchronous generation equipment which is often directly connected to the power grid. An outcome of the process is that the rotational inertias of the turbines and generators generally contribute towards stabilizing the frequencies of the networks.

The grid connection of renewables differs from the grid connection of conventional power generation. Two differentiating factors are; the rate of change in renewable energies is higher and Wind Energy Conversion System (WECS) contain converters for example Full Rated Power Converter and DFIG WTs; that produce different transients in the system, these transients' harmonics can affect the power system stability.

As the renewable energy generators become modular and penetration of nonlinear loads is increasing day by day. Thus, in order to achieve technical and economical optimization these grid codes need to be renewed.

The importance of renewing the grid code requirement can be reflected from the incident occurred in Northwest Germany on 4th November 2006 leading to a blackout affecting 16 million European household. Two main reasons for this disturbance were identified during the investigation which are following; non fulfillment of N-1 criterion (grid should operate in steady state following the loss of a transformer, generating unit or transmission line) and insufficient inter-Transmission System Operator (TSO) coordination. An investigation committee was appointed instantly for finding the root causes of this blackout. The adequacy of present standards and practices were assessed by the committee as well as improvements to these standards and practices were proposed by them [14]. In depth analysis of the investigation can be found from reference [14].

2.2 Important Grid Codes

Grid code requirements aim to ensure that the grid is not adversely affected by the wind farms in relation to supply, security, power quality, and reliability. As such, essential requirements are related to voltage, frequency, and wind turbine behavior in case of grid faults. Some of the grid codes are following [12, 15]:

LVRT capability

Low voltage ride-through (LVRT) is a recent addition in the grid codes, which is considered to be the most vital requirement for wind farm operation [18]. It is necessary for the reliable and vital operation of power supply networks, more in regions where the penetration of the wind power is high. The voltage dips that result from faults in the grid can lead to a loss in generation units. Reactive power is the component of energy that is generated on the grid. This reactive power can be used to regulate the system voltage; the voltage levels of the grid can be boost by adding the reactive power.

According to this requirement, WTs are required to be always connected. During the fault, if the grid voltage amplitude reduces adequate reactive power must be supplied by the wind park in order to increase this voltage drop and to ensure the grid stability.

Reactive Power Control

WTs are required by grid codes to perform voltage control as conventional power plants, by controlling the reactive power. Presently, the wind power plants must be able to fulfil reactive power and voltage control demand because of the increasing penetration of wind power into the grid. Wind power plant should interchange the reactive power with the grid, level and exchange rate is defined by the TSOs.

Active Power Control

The active power control emphasizes that the deviation of active power around actual output must remain as per voltage or frequency diagram which is stated in grid codes. Numerous regulation methods are defined in grid codes. The slope of the active power production is controlled by the droop characteristics or by power and frequency characteristics. That control will be adjusted in accordance with the demand of TSO.

Frequency Control

The frequency of the power system should be constant, and this is defined in standards. In some grid codes, WTs are required to participate in frequency control, just like the conventional plants. Ordinarily, frequency is kept within acceptable limits with the aim of securing supply, preventing equipment overload, and thus fulfilling power quality standards.

2.3 German Grid Codes (GGCs)

As discussed, different Transmission System Operators (TSOs) in various countries issue different requirements for the grid connection. In the simulation model, the LVRT enhancement of DFIG-WTG was assessed using the STATCOM and SVC. The LVRT requirement of the German Grid Code (GGC) was taken as a reference. The LVRT grid code of Germany was chosen due to the fact that stringent LVRT is imposed by them.

The LVRT requirement is able to fulfill by producing the reactive power by the generator. Therefore, in this section we will discuss the LVRT requirement and reactive power control in accordance with the GGC.

2.3.1 LVRT capability

The German Grid Code provides two border lines to meet LVRT requirement [17]. These requirements must be followed by WTG to remain interconnect with the grid as shown in Figure 2-1. In this study borderline 2 has been selected as reference because it is widely being used.

Previously, the WTs used to separate from the network during the fault in the network. However, presently, the separation of WTs for voltage value less than 80 percent of the nominal voltage during the grid fault has been shown to affect power generation [18]. Therefore, the E.on German grid code utilities now demand FRT/LVRT capability as shown in Figure 2-1. It is now a requirement for the WTs to remain connected even when there is a voltage drop to zero. As shown in Figure 2-1, 150ms accounts for the time of the normal operations for protection relays. The red solid line indicates the lower voltage boundary. Under specific circumstances, short term interruption (STI) is allowed (area 3), which requires resynchronization within 2s, and at least 10% in power increase rate. Area 2 shows the interruption time allowed, which is less than a few hundred milliseconds. At this period, reactive power supply by wind turbines is required. GGCs further require that WTs provide voltage support whenever there is a dip.Figure 2-2 gives a summary of the corresponding voltage control characteristics. Here, wind turbines are mandated to supply a minimum of 1.0 pu reactive current as the voltage goes below 50%. Undesirable control actions are avoided by the introduction of a 10% dead band.

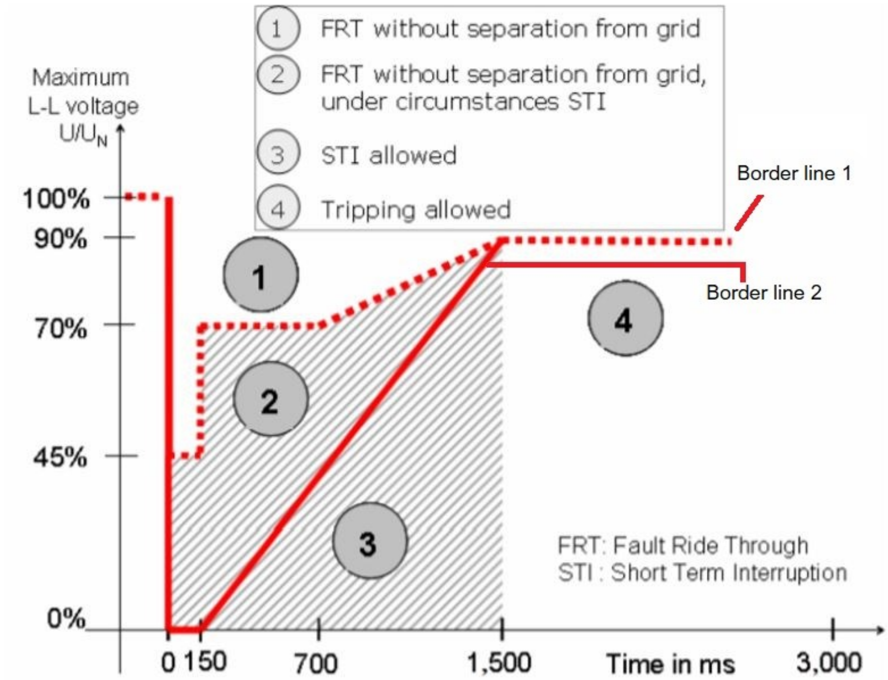

Figure 2-1. *LVRT requiement in accordance with E.on [18]*

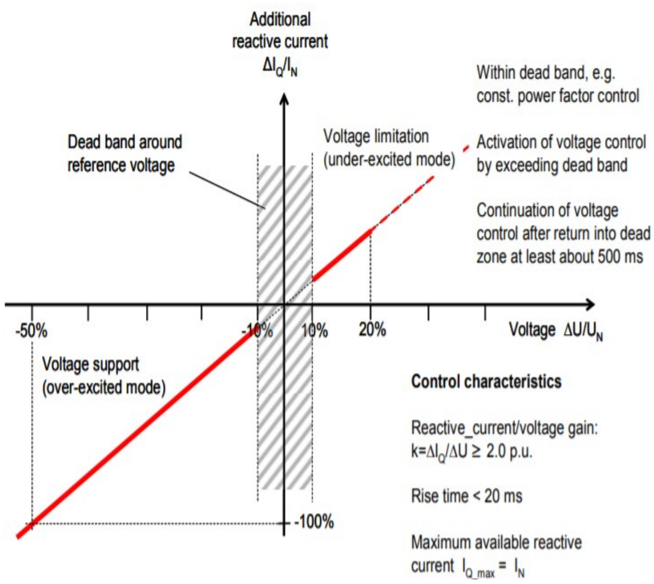

Figure 2-2. *Voltage support characteristics in accordance with E.on [19]*

The recent grid codes require that WFs must remain connected during and after a fault [19]. They ought to withstand dips in voltage up to a set percentage for the specified period. Above the borderline, disconnection is not permitted. Grid codes require voltage control while the voltage is decreased below 90 % of the nominal voltage. As such WFs are supposed to supply reactive current to the grid, depending on the depth of the dip. Currently, in Europe, the GGCs are the most demanding since they set the rated reactive current at 20% of the set rating.

2.3.2 Reactive Power Control

LVRT requirement is able to fulfil by producing reactive power with generators by utilizing capacitors/reactors and at certain times FACTS devices toward feeding in reactive power at the connecting points at a time of the fault. The required reactive power is defined in Figure 2.3. Every new generating unit which connects to the network in Germany should be able to meet the requirement in accordance with this Figure. One of the three possible variants of TSO demand for reactive power from the Wind Power Plant (WPP) are shown in Figure. One of the versions is selected by the TSO depending on the relevant network characteristics. It can be noted that if the grid voltage drops to 96kV while being supported with the normal active power of a 110kV wind turbine, it is able to produce a maximum range of +0.33 pu to +0.48 pu reactive power. If the voltage of the grid is increased to 127 kV, more than -0.228 pu reactive power will be consumed by the Wind power plant [21].

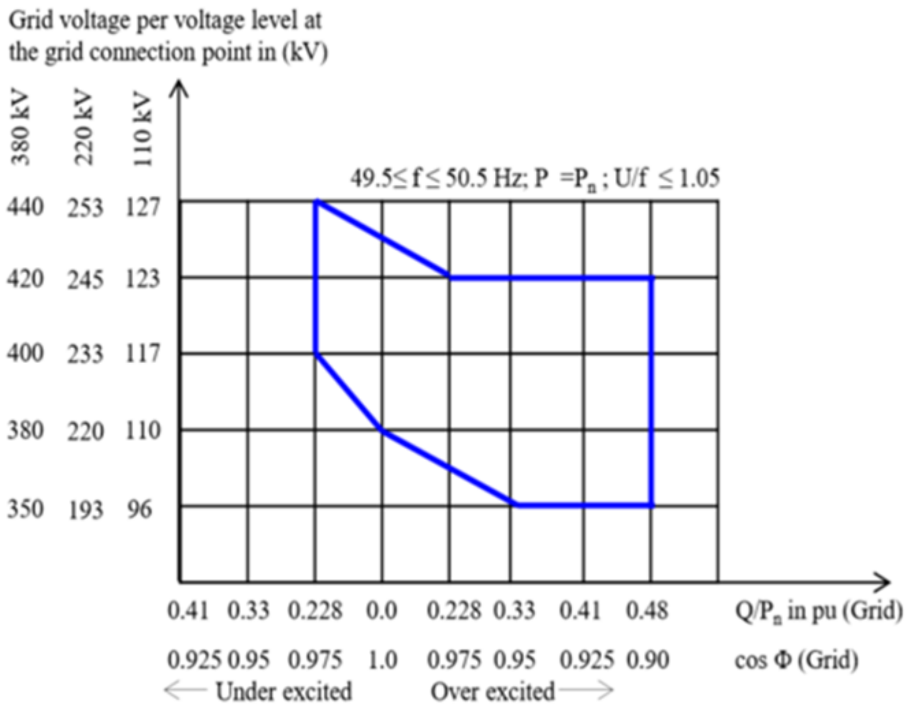

Figure 2-3. *German TSO reactive power demand for wind power plant as a function of voltage at active power [21]*

Furthermore, the GGCs require that the wind power plant interchange the reactive power with the network even when the wind power plant is working at the de-rated power. The largest reactive power range that must be covered along with the associated voltage band is presented in Figure 2.4. The y-axis denotes the instant active power relative to the existing installed active power in percentage while the x-axis denotes the reactive power which is relative to the operational installed active power in percentage [21]

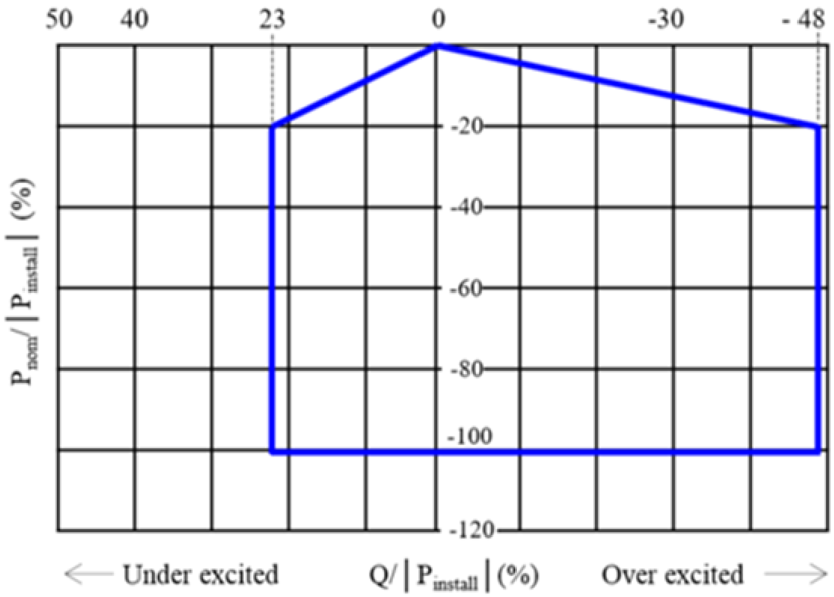

Figure 2-4. *German TSO reactive power requirement for wind power plants as a function of the active power when the WPP is working at de-rated power [21]*

2.4 WTs Capabilities Respecting the Grid Codes

Four different types of WTs are available, these WTs are categorized either in variable speed or fixed speed WTs. Mostly fixed speed wind turbines were used during a few past years of the WECS. Presently, the unique concept is being utilized which is the use of power electronics and generators in variable speed WTs. This power electronics-based technology is dominating the WT market. Figure 2-3 gives an overview of the various configurations of WECS [24].

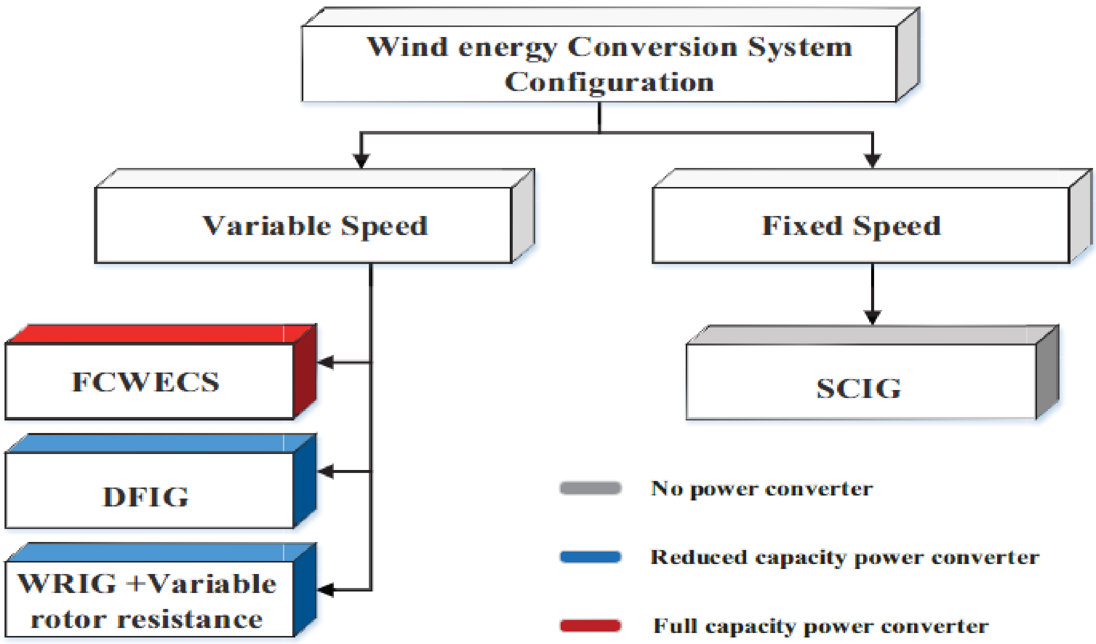

Figure 2-3. *WECS types*

2.4.1 Fixed Speed WT

The configuration of the fixed speed WT is shown in Figure 2-4. This type uses squirrel cage induction generator (SCIG) that is an asynchronous generator. SCIG is directly connected to the grid in this configuration via a coupling transformer, thus the WT speed is fixed by the grid frequency.

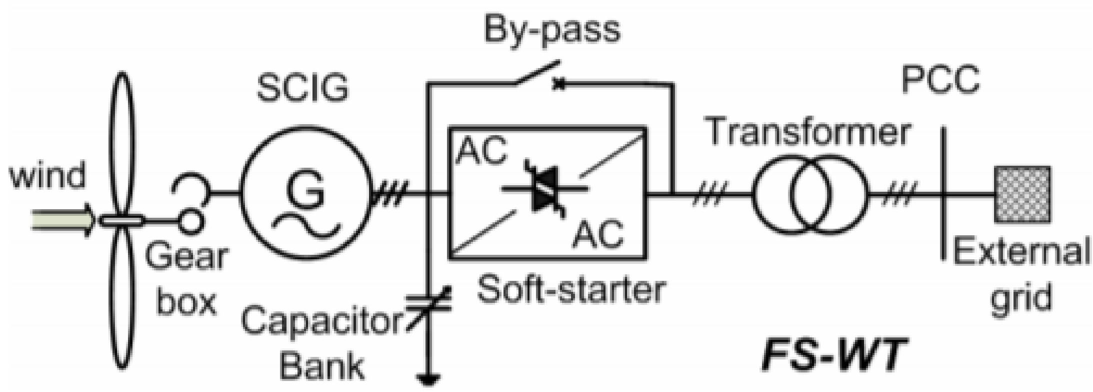

Figure 2-4. *Fixed Speed WT [30]*

In this WT technology, reactive power compensation is done through the capacitor bank. In addition, a soft starter is used in order to achieve smooth grid connection [26]. Fixed speed WTs do not have any power electronics devices; therefore, the capacitor bank is used with each turbine for reactive power compensation. Due to the absence of power electronics devices control of reactive power is not possible [23]. These capacitors only compensate the reactive power of the generator and not able to control depending on the grid conditions.

This induction generator based WTs cause some more problems for example low power quality as well as mechanical stress [27, 28]. The fluctuations of the wind are converted into the fluctuations of power because of its fixed speed, and if the grid is weak this scenario can lead to the flicker on the PCC [26]. Consequently, it is very difficult for the fixed speed WTs to meet the grid code requirement without any exterior support like FACTS devices [23].

Some of the advantages of this configuration are following; the fixed speed wind turbines are very simple and robust, the cost of the equipment is not very high, and these kind of WTs are designed to achieve full efficiency at a specific speed of the wind [29].

2.4.2 Restricted Variable Speed WT

This type of wind turbines is similar to the fixed speed WTs with some additional features. This particular type is shown in Figure 2-5, it consists of a Wound Rotor type Induction Generator (WRIG) which is connected to the grid via a coupling transformer. The main purpose of this transformer is to transform the low voltage into the medium voltage level and the soft starter is used similar to the fixed speed WTs.

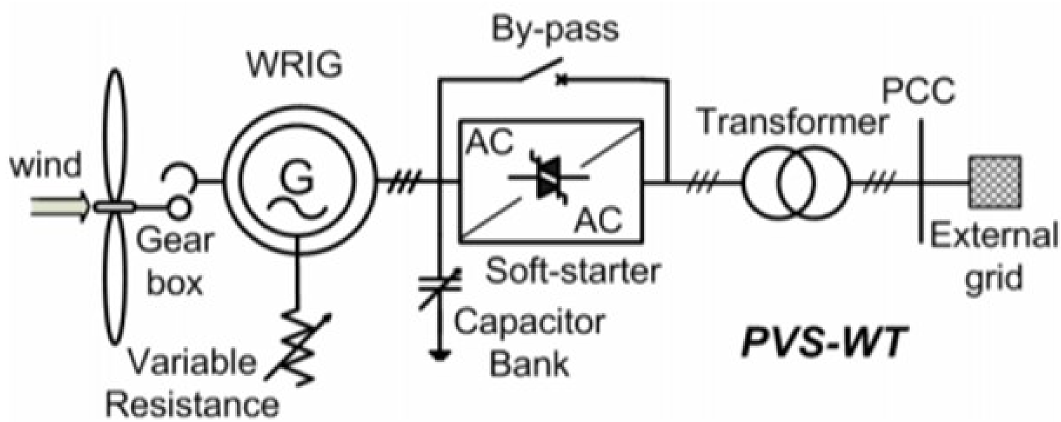

Figure 2-5. *Restricted variable speed WT [30]*

In terms of construction, WRIG is like the SCIG but the main difference is that a variable resistance is added to the generator’s rotor side. The minor development has been noticed in the case of grid disturbance by adding this kind of variable resistance that changes the rotational speed of the WT in a narrow range. Almost 10 percent of speed can be increased above than synchronous speed by using this resistance [23]. Rotor variable resistance also has heat losses which is the drawback of this configuration.

Similarly, to the fixed speed WTs, capacitor banks are used for reactive power compensation. Consequently, restricted variable speed WTs offer low performance regarding the grid connection codes. The flickers are the major concerns in the first 2 types of the WTs when the WPPs are coupled with the weak power grid. These flickers are caused because of the so-called tower shadow effect.

2.4.3 DFIG-WT

A WECS is shown in Figure 2-6, which comprises a DFIG. In this concept the rotor circuit is coupled to the grid via a partial scale back to back Voltage source converter (VSC). While, the stator circuit is directly coupled to the grid via a coupling transformer.

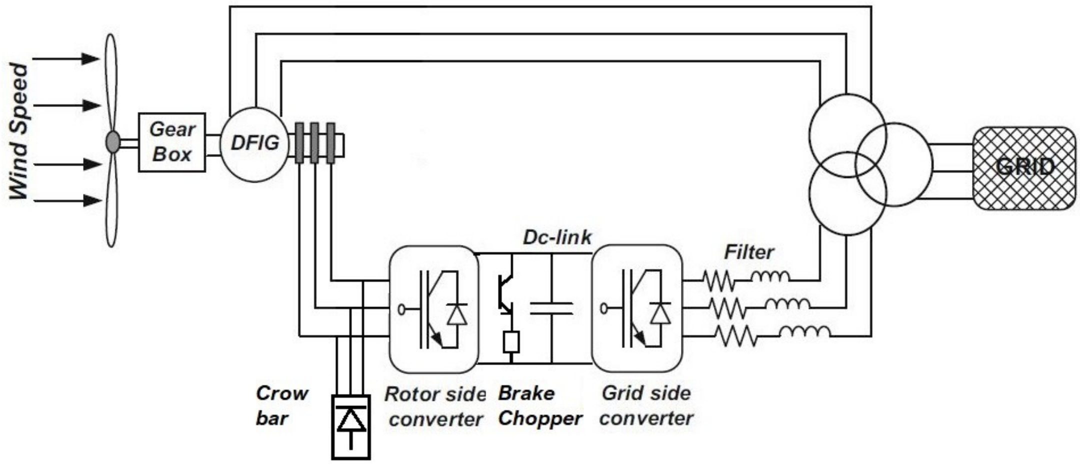

Figure 2-6. *DFIG-WECS [31]*

Typically, the Rotor Side Converter (RSC) controller is used to regulate electromagnetic torque; a specific part of the reactive power is supplied by the RSC in order to maintain the machine magnetisation. While, the Grid Side Converter (GSC) controller keeps the DC link voltage at a desire value and controls the PF of PCC. In this type of the WTG, all power is not controlled by the power electronics converter, almost 25-30 percent of all power passes via the converter [32].

As it can be noticed from Figure 2-6 a brake chopper is connected to the intermediate circuit. The purpose of this device is to provide the protection to the DC-link. When a specific threshold of DC- link voltage is exceeded, this brake chopper shorts the DC-link through a power resistor [33].

The over current protection is established by the DFIG crow bar in order to protect the RSC during any power network disturbances when the stator connects to the grid [32]. The RSC can handle only a certain amount of current flowing through it during the FRT condition. In this situation there is also an overvoltage risk on the DC-link capacitor. Therefore, the crow bar disconnects the RSC, this scenario further leads to the disconnection of the DFIG rotor from the grid. The RSC is reconnected by the crowbar when the fault clears.

The GSC is connected to the network through the low pass filter; it could be either LC or LCL low pass filter. This filter is required for removing the Pulse Width Modulation (PWM) frequency components [33].

In this topology, there are two dedicated operation modes; super synchronous mode and sub synchronous mode. The mode in which the rotor of the DFIG rotates above the synchronous speed is known as super synchronous mode. The slip is negative in this mode, both the rotor and stator can deliver the power to the network. However, when the generators operate under synchronous speed this mode of operation is known as sub synchronous mode. The slip is positive in that mode and the power is delivered by the stator winding to both the rotor winding and grid [34].

The control of the DFIG-WTG usually contains two parts; RSC control and GSC control. In this report only the GSC control will be discussed since grid side parameters are being controlled in the simulation model. The maximum produced power for example Maximum Power Point Tracking (MPPT) and pitch control are controlled by the RSC which does not affect in our case because in the simulation model we supposed that the speed of the wind is constant.

A very well-known vector control theory is used for the electric drives. This control theory can be applied on DFIG control [35]. The rotor circuit power from/to the grid connection is transmitted by the GSC, the main objective of GSC is to maintain the voltage of the DC-link. The following measurements are used by the vector controller; the exchange of reactive power between the grid and converter, DC- link voltage and stator voltage as well as converter currents in order to control the voltage of DC-link.

The space vector of the grid-side current is stated in equation 2.1; it defines the current direction as it flows from the converter to the network.

$$\bar{\boldsymbol{i}}_{\boldsymbol{c}} = \frac{\bar{\boldsymbol{V}}_{\boldsymbol{s}} - \bar{\boldsymbol{V}}_{\mathbf{GSC}}}{\boldsymbol{Z}_{\mathbf{filter}}} \tag{2.1}$$

Reference frame aligned with supply voltage, steady state values become constant;

$$\overline{V}_s^e = |V_s| \therefore \overline{i}_c^e = \frac{|V_s| - \overline{V}_{GSC}^e}{Z_{filter}} \quad (2.2)$$

It is assumed that inductance of the filter is not large, equation 2.3 can be utilized as a simple feedbacked current control law. The equation's feedforward term on the right hand is optional, however it can help the converter to respond to step changes in stator voltage.

$$\overline{V}_{GSC}^{e\ \otimes} = \mathrm{PI}\left(-\overline{i}_c^{e\otimes} + \overline{i}_c^e\right) + \overline{V}_s^e \quad (2.3)$$

PI is the gain of error controller and values with symbol '$\otimes$' represents controller demand value. The reactive as well as real powers to the GSC can be expressed by the equations 2.4 and 2.5;

$$P_c = |V_s| i_{cd}^e \quad (2.4)$$

$$Q_c = -|V_s| i_{cq}^e \quad (2.5)$$

The reactive and real power inputs are controlled by the reactive and real current components independently. The DC voltage is directly affected by the real power; the energy which is consumed by the converter goes to the DC-link which raises the DC voltage. Therefore, simple version of feedback power control expresses as;

$$i_{cd}^{e\ \otimes} = \mathrm{PI}\left(V_{dc}^{\otimes} - V_{dc}\right) \quad (2.6)$$

$$i_{cq}^{e\ \otimes} = \mathrm{PI}\left(-Q_c^{\otimes} + Q_c\right) \quad (2.7)$$

The control configuration of the GSC is given in Figure 2-7. The output signal of the current controller multiplies by the reciprocal of DC- link voltage in order to ensure the correct pu modulation output and the negative effect because of the DC-link variations on the controller performance can be reduced.

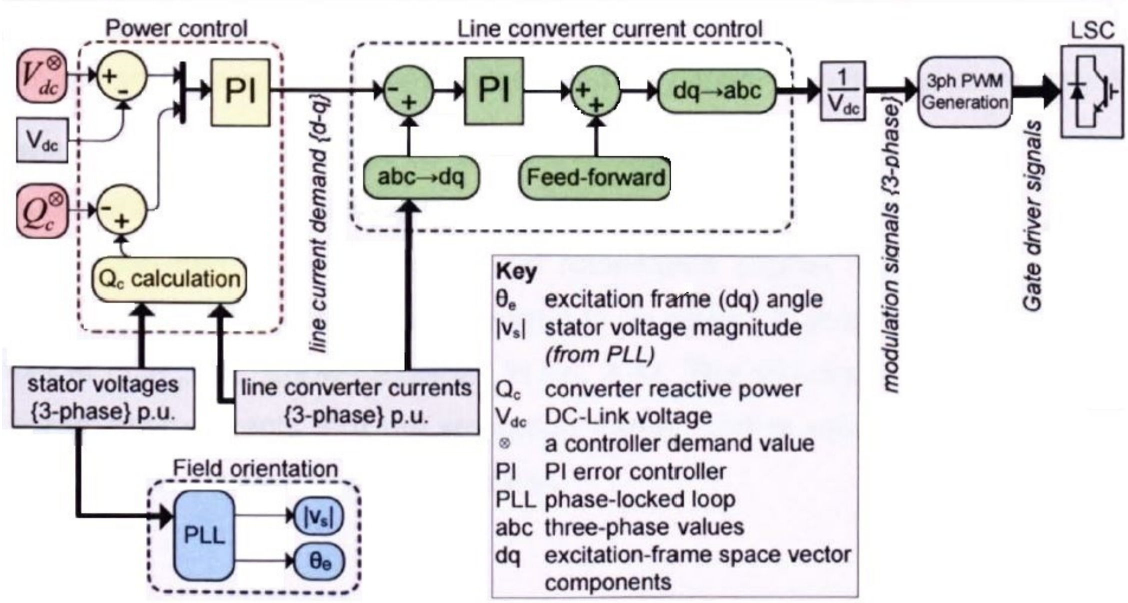

Figure 2-7. *GSC Vector control scheme [33]*

The fast-acting current controller in order to respond to the current errors instantly for maintaining steady output is enabled by the grid side converter. It is possible to tune the controller of GSC in such a way that it can respond faster than controller of the RSC. It is usually done for achieving the decent DC- link voltage control [33].

The major advantages which are offered by the DFIG are; the reduced cost of the inverter since as we know the rating of the DFIG inverter is around 25 percent to 30 percent of total power of system, the inverter filter cost reduces, it provides steady response in case of minor external disturbance.

One of the drawbacks of this topology which has been approved via the simulation model as well; these WTGs are not able to produce enough reactive power for supporting the grid in case of the fault in the grid. Therefore, external devices are required in order to fulfil the grid requirements. Gear boxes are used in the DFIG which might cause maintenance issues.

2.4.4 Full Rated Power Converter-Based WT (FRPC-WT)

The last type of WT is the variable speed WT with the full power converter. The generator which is used in this type could be either synchronous or asynchronous and usually it is used without the gear box as shown Figure 2-8. The use of the synchronous machine with FRPC-WT could be a good option although it is expensive as compared to the induction generator but the synchronous machines do not draw magnetizing reactive current from the grid [26]. The reactive and active power can be controlled in the extensive range, consequently, much-improved controllability is offered by this WT topology.

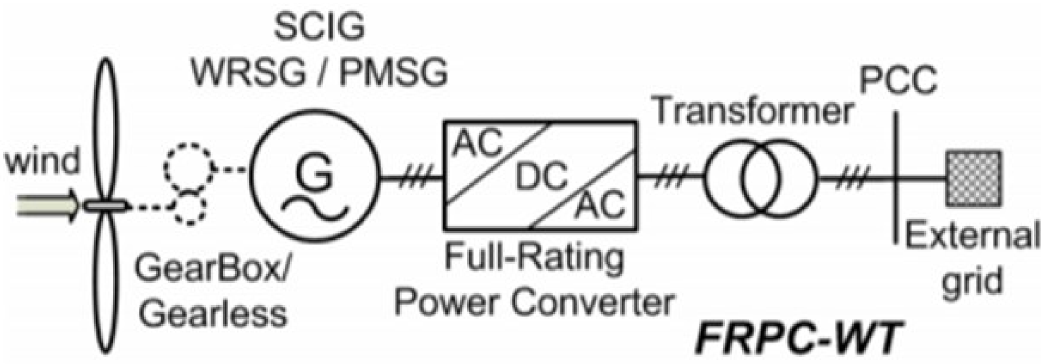

Figure 2-8. *Full Rated Power Converter Wind Turbine [30]*

During all probable voltage dips, these VSC based WTs with fast acting power electronics switches remain connected and provide support to the grid. Generators provide current to the grid at controllable PF after a specific transient period of the controller readjustment. The large power imbalance can be formed across the converter as the power export is limited. A protective power sink should be fitted with the converter for maintaining the nonstop working or WT mechanical input power should be decreased rapidly. Whereas, the second option is conceivable through WT's blade pitch control, the available mechanical power may be limited by this immediately during the fault [33].

Compared with the DFIG-WT, 30 percent of all power passes via the converter in DFIG based WTG but in FRPC based WTG all the power passes through the converter which means the size of the converter used in this topology is larger than DFIG based WT. FRPC-WT topology is more attractive due to the fact that it is not very complex and has better FRT capability as compared to the DFIG-WTs [30]. The energy buffer exists (DC-link) between the grid and generating unit, thus, the flicker is not a problem in these WTs. Power converters are used in variable speed WTs; therefore, filtering devices are required since these power converters are the source of harmonics [8]. As a conclusion, during the fault the FRPC-WTGs can contribute positively in order to maintain the grid stability.

3. FACTS DEVICES FOR WIND TURBINES TO FULFIL GRID REQUIREMENT

First-generation WFs used fixed-speed induction generators. These induction generators consumed reactive power and had limited controllability of real power. As the size of WFs increased, grid operators developed more stringent grid code requirements, such as FRT, active and reactive power control capability. It is very essential to fulfill the grid requirements that are imposed by the TSO. Sudden changes in the wind speeds can lead to the disruptions in voltage on the network. Rapid changes in voltages can result in grid instability and even unplanned outages can occur. Reactive power is the component of energy that is generated on the grid. Too much reactive power can lead to inefficient power flows and too little can create unstable conditions. Reactive power can be used to regulate the system voltage. Adding reactive power can boost voltage levels, whereas, absorbing reactive power can correct voltage spikes. Placing FACTS devices at the PCC can help wind park control reactive power and safely integrate into the grid. FACTS devices are helping wind farms meet reactive power standards and grid codes requirements. A point to note, that these FACTS devices are not needed with the FRPC-WTs [36].

Multiple FACTS devices exist such as STATCOM, SVC, Unified Power Flow Controller (UPFC), Interlink Power Flow Controllers (IPFC), Hybrid Power Flow Controller (HPFC); that can be used with the wind farms [37]. This chapter presents STATCOM and SVC in detail.

FACTS concept was firstly introduced in the 1980s [38]; different power electronics devices are used in FACTS in order to control both voltage and power at a specific location of an electrical grid during any disturbance. Generally, these devices were developed in order to enhance the existing capacity of the transmission line as well as for providing the controllable flow of power for a nominated transmission direction [39].

FACTS devices consist of two prominent features; static and dynamic [35]. The term "dynamic" expresses the fastest controllability of FACTS devices which is provided the courtesy of power electronics. The other term "static" Indicates that the devices do not have any moving elements such as mechanical switches to act dynamic controllability

[35]; these differences make the FACTS devices prominent among the conventional devices.

Figure 3-1 gives an overview concerning the FACTS and the conventional (switched) devices, on the left column, conventional devices consist of mechanically/fixed switchable elements for example inductance, capacitance or resistance with the transformer. The FACTS devices also consist of those parts but extra power electronics devices are used in order to switch these parts quickly [40].

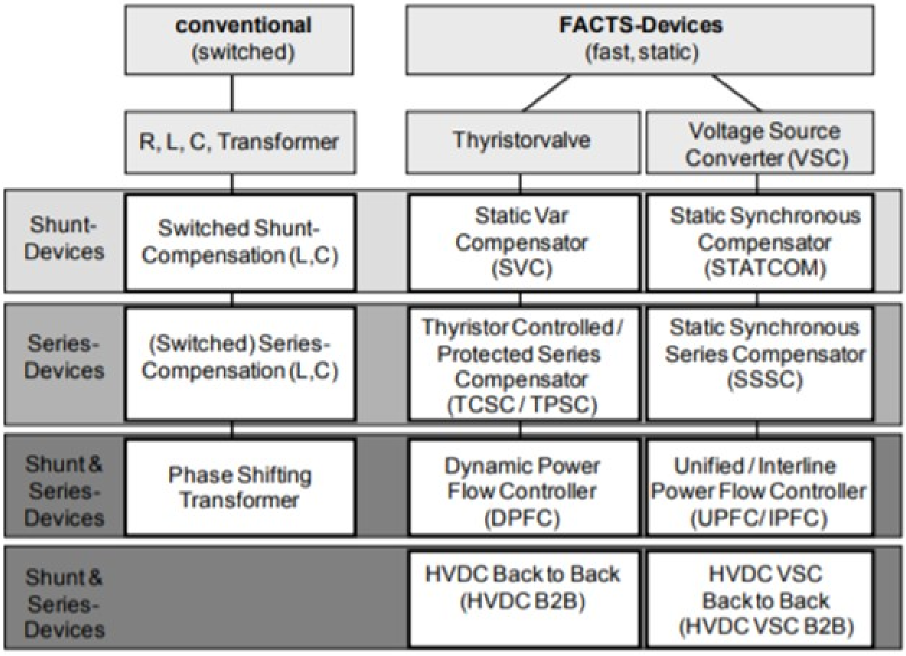

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Figure 3-1. *Major FACTS Devices [40]*

As mentioned in Figure 3-1, FACTS- devices can be divided into two subcategories, thyristor valve and VSC based technologies respectively. Thyristor controlled series compensator (TCSC), Dynamic power flow controller (DPFC) and SVC were introduced by the thyristor valve-based technology. The interline power flow controller (IPFC), Static synchronous series compensator (SSSC), STATCOMs were resulted by the VSC based technology.

Both generations of the FACTS devices have their own characteristics but the second type which is categorized by VSC and based on the force commutated devices is more superior since they provide faster response and better control range. The VSC based FACTS devices do not need low pass filters in order to filter out low-frequency harmonics because the switching frequencies are high [41]. Furthermore, the size of the VSC based

FACTS devices is significantly smaller as compared to the thyristor-controlled ones since bulky capacitors and reactors are not needed [36].

As debated in Chapter 2, according to the new grid codes for WPPs; reactive power compensation during normal and abnormal conditions and FRT are some of the important requirements imposed by TSO. Shunt connected controllers (STATCOMs and SVCs) have been proved as a reliable solution to fulfill these requirements [40]. In the following sections, shunt type compensators are discussed in detail.

3.1 Static Var Compensator- SVC

3.1.1 Introduction

SVC is the 1st generation FACTS device that does not have any rotating element [42].In 1972, it was commercially installed for the arc furnace whereas, in 1979 SVC for the very first time used for the transmission line [40]. The SVC is the shunt device that has been used for improving the transmission line span by resolving the problems related to the voltage variations [43]. The voltage on the power system is adjusted by the SVC that supplies/absorbs reactive power at PCC [44].

3.1.2 Configuration of SVC

The thyristor valves (series-connected anti-parallel thyristors) are the most significant part of SVC, which provide controllability. High voltage AC capacitors and reactors (air-cored) are utilized with the thyristor valves. These elements are connected to the grid via a step-down transformer for protecting the SVC equipment because they cannot bear high voltage [40, 45]. This transformer is also seen as a small inductive source of power which can contribute to the SVC reactive power output [46]. Furthermore, the fault currents can also be limited at the SVC side using this transformer [46]. The components that can be included in the configuration of SVC are shown in Figure 3-2.

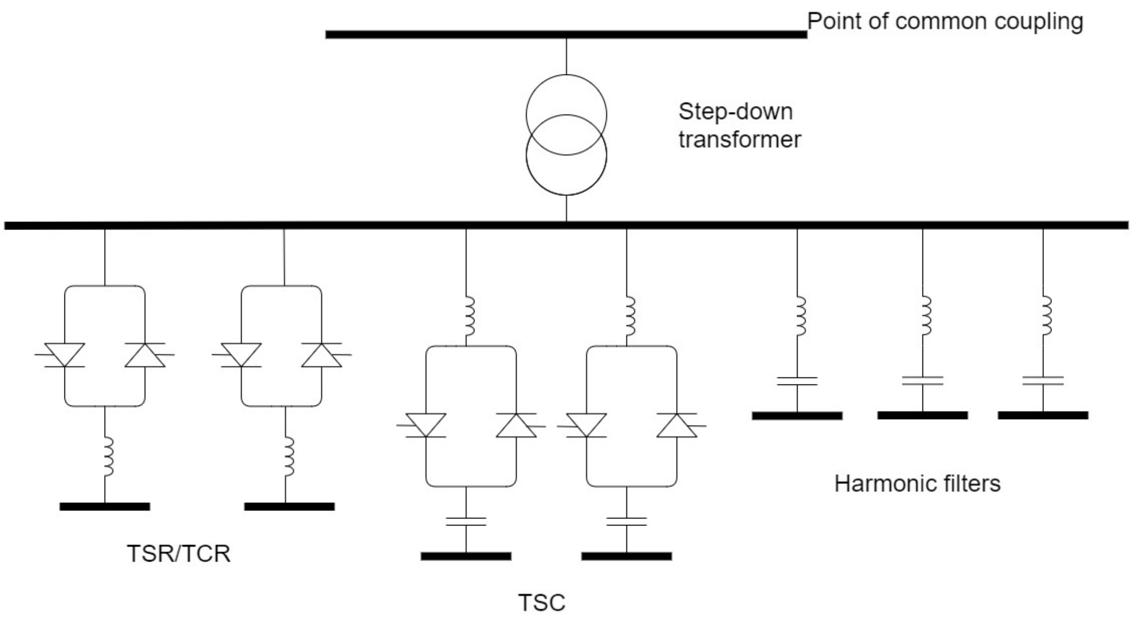

Figure 3-2. *Blocks of SVC*

The SVCs consist of Thyristor Controlled Reactors (TCR) and Thyristor Switched Capacitors (TSC), harmonics filters. SVC can also include Thyristor Switched reactors (TSR) [40]. These elements are connected in parallel to dynamically compensate the reactive power of an electrical network. The firing angle control is utilized by the TCR for continuously increasing/ decreasing the inductive current. On the other hand, the inductors which are connected in TSR are stepwise switched on and off due to the absence of the firing angle control [47].

3.1.3 Operational Principle of SVC

The thyristor valve conduction period is adjusted by the SVC for providing the required reactive power (absorption or generation) in the system. The SVCs which are used with the WPPs usually consist of TSC and TCR as shown in Figure 3-3. Assuming the capacitor and reactor both have the same rating then;

- When the capacitor leg switch is on and the thyristor valve on the reactor leg is in no/partial conduction mode then the reactive power will be generated by the SVC.
- When the capacitor leg switch is off and the thyristor valve on the reactor leg is fully/partially conducting. In this case, the reactive power will be absorbed by the SVC.
- When the capacitor switch is off as well as the thyristor valve does not conduct then reactive power will not be produced/consumed by the SVC.

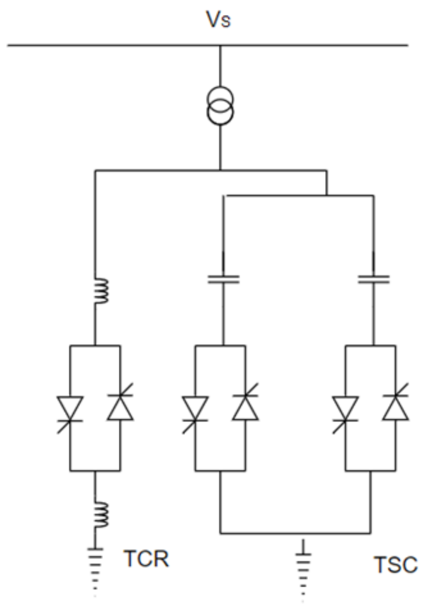

Figure 3-3. *SVC for wind power plant [48]*

3.1.4 SVC Control System

As discussed, by controlling the amount of reactive power consumed or supplied into the grid; the terminal voltage is regulated by the SVC. The reactive power is generated by the SVC when the voltage of the system is low. On the other hand, reactive power is absorbed by the SVC when the voltage of the system is high. Figure 3-4 presents the control system of the SVC [49].

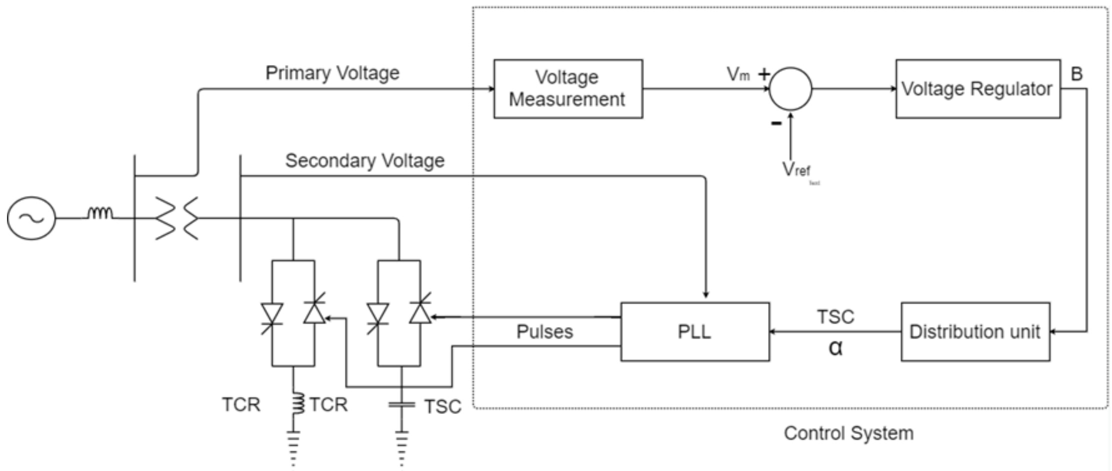

Figure 3-4. *Control of SVC with WT*

The SVC control system comprises the measurement system that measures the positive-sequence voltages. The voltage regulator is used that utilizes the voltage error in order to find the difference between the reference voltage V_{ref} and measured voltage V_m. According to this difference, the needed susceptance of SVC (B) is determined for keeping the system voltage constant. The purpose of the distribution unit is to determine the TSCs (and eventually TSRs) that should be switched out and in, and TCRs firing angle α is computed [50]. A synchronizing system utilizing a phase-locked loop (PLL) synchronized on the secondary voltages and a pulse generator that sends suitable pulses towards the thyristors [49].

This thyristor valve-based technology is obsolete because of its low dynamic performance i.e. long response time. Nowadays, the substitution of the SVC is STATCOM and it is discussed in the next section.

3.2 Static Synchronous Compensator (STATCOM)

3.2.1 Introduction

The dynamics stability of the WPP can also be enhanced by using STATCOM which delivers or absorbs reactive power during any grid disturbance. STATCOM is an advanced version of SVC and it was firstly introduced in 1999 Japan [40]. It is the 2nd generation FACTS device which either consists of VSC or current source converter (CSC) instead of thyristors [51]; from a general cost perspective, VSC appears to be preferred [38].The STATCOM controller can be recognized as a controlled source of current that has the ability to provide any kind of reactive current waveform in real-time. The inductive and capacitive output currents are controlled without depending on each other [52].

STATCOM can also be integrated with the energy storage system [53].A small DC capacitor is utilized when only the reactive power is supposed to be controlled. The active power can also be controlled if large energy storage is added to the DC side, for example, super-capacitor or battery. Though it is not possible to exchange real power with the SVC [24]. This scenario is beneficial where fluctuating active power causes issues related to power quality, particularly in weak grids [52].

3.2.2 Structure of STATCOM

The STATCOM is a pure power electronics device which consists of a voltage source converter that is based on Gate Turn-off Thyristor (GTO), Insulated Gate Bipolar Transistor (IGBT), Integrated Gate-Commutated Thyristor (IGCT) [24] for generating or controlling reactive current [54]. It also consists of a capacitor which is installed on the converter DC side, a coupling transformer and LCL filter. The structure of a STATCOM is shown in Figure 3-5.

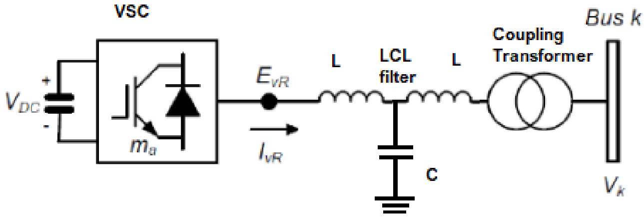

Figure 3-5. *STATCOM configuration*

The main purpose of the VSC is to flow the power in both directions. The phase angle, magnitude as well as the frequency of the voltage on the output is controlled with the VSC [55]. The stabilization of the DC voltage is ensured by using the DC capacitor [45]. This DC capacitor operates as energy storage. The square wave of the VSC contains harmonics; these harmonics can be removed by using the LCL filter [45].

3.2.3 Operating Principle

STATCOM is seen as a controlled or variable source of voltage which is based on VSC instead of a variable shunt susceptance [45]. One of the best approaches, in order to comply with the grid codes, is to install STATCOM either at the PCC or at wind park collector grid [2]. The reactive power amount can be automatically controlled by connecting the STATCOM at the wind park collector grid and the events concerning the voltage stability are addressed. The STATCOM device has the ability to respond rapidly and automatically to voltage stability events. There are two ways in which STATCOM can be used; the voltage control mode and reactive power control mode.

Voltage Control Mode

Assuming active power is not being interchanged between the grid and STATCOM then;

- The reactive power is absorbed from the grid by the STATCOM if the magnitude of the voltage is higher at the connection point than the reference value and in this case, STATCOM acts like an inductor or under excited generator and absorbs reactive current and decreases the grid voltage [40, 56].
- The reactive power is delivered to the grid by the STATCOM if the amplitude of the voltage is lower than the reference value into the connection point. In this case, STATCOM will act as a capacitor or overexcited generator and injects reactive current for supporting the voltage of the grid [40, 56]. The schematic demonstration of the STATCOM working principle with the phasor diagram is shown in Figure 3-6.

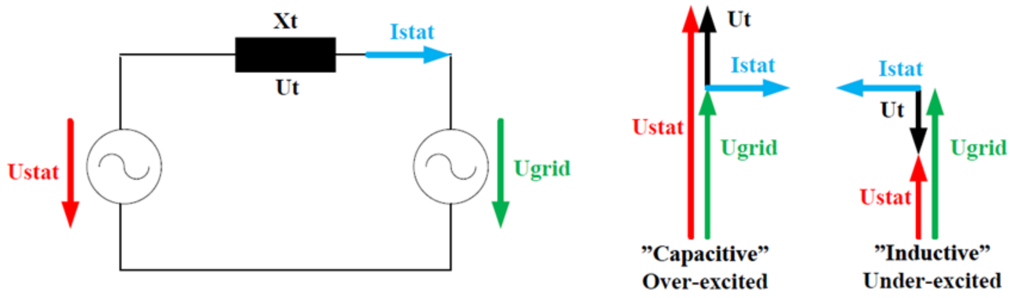

Figure 3-6. *STATCOM Working Principle [40]*

Reactive Power Control Mode

In the control mode of reactive power, the reactive power is compensated by using STATCOM at the PCC in accordance with the set reference reactive power by the wind park controller [21, 40]. Whenever, the fault happens in the grid and the voltage dips appear (LVRT); the adequate reactive power must be delivered (capacitive reactive power) by the STATCOM for reducing these voltage dips according to the standards. In case of voltage sag (HVRT), the reactive power must be absorbed (inductive reactive power) by the STATCOM to reduce this voltage sag in accordance with the grid codes. STATCOM has the ability to compensate the reactive power without depending on grid parameters.

3.2.4 STATCOM Control System

STATCOM control block diagram with its single line diagram is shown in Figure 3-7

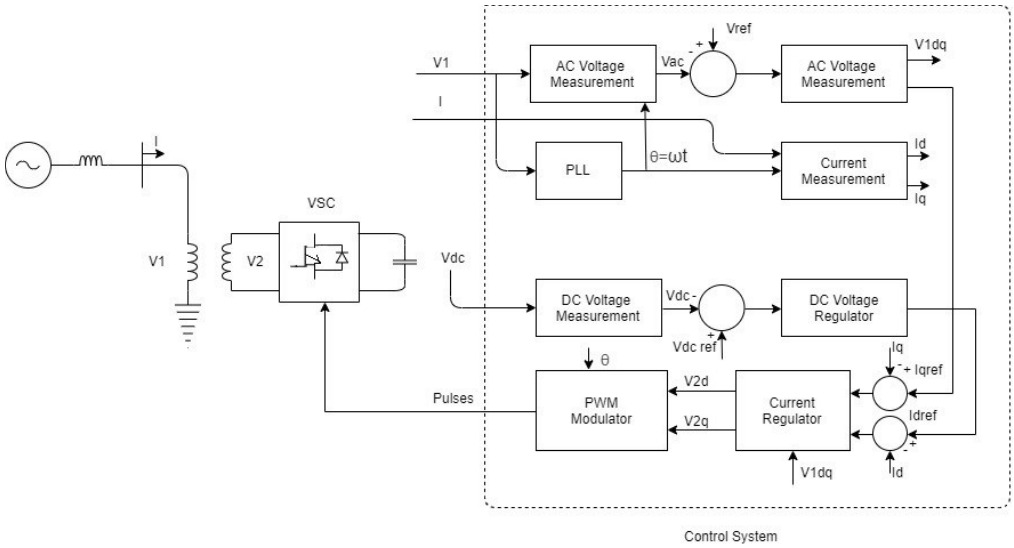

Figure 3-7. *STATCOM control block diagram*

STATCOM control system comprises PLL that is synchronized on the positive sequence primary three-phase voltage component V1. The quadrature axis components as well as direct axis components of three-phase AC current and voltages (I_q, I_d and V_q, V_d) are computed by the output of PLL (angle $\theta = \omega t$). As shown in the block diagram some measurement systems are used in order to measure the q and d components of positive sequence AC current and voltages to be controlled, and DC voltage (V_{dc}).

Two regulation loops are also used; outer regulation loop and inner regulation current loop. DC and AC voltage regulators are used in the outer regulation loop. The AC voltage regulator output is the I_{qref} (reference current) for current regulator (I_q indicates quadrature current with voltage which is used to control the flow of reactive power). Whereas, the DC voltage regulator output is the I_{dref} (reference current) for current regulator (I_d indicates the current in phase with voltage which is used to control the flow of active power).

The current regulator is used in the inner current loop. The phase as well as the magnitude of voltage that is generated by the Pulse width modulation (PWM) converter is controlled by the current regulator. The reference current I_{qref} is generated by the AC voltage regulator whereas, the I_{dref} is generated by the DC voltage regulator (in the mode of voltage control). The feedforward assists the current regulator, the feedforward is used to predict V2 voltage output ($V2_d$, $V2_q$) from the measurement V1 ($V1_d$, $V1_q$) and transformer leakage reactance [21].

3.3 Performance Comparison between STATCOM and SVC

Promising FACTS controllers have the ability to improve the issues related to the power quality and voltage stability of the grid that connects to WFs. FACTS controllers prevent the faults, as well as the after-effects of the faults, can also be mitigated by the use of FACTS devices in order to improve the reliability of the electrical network. For example, a large load is injected which can cause the overvoltage of overhead lines that leads to the outage. This overvoltage is opposed by the STATCOM and SVC in order to avoid tripping [57]. Both the shunt type controllers are adopted for the integration of the wind farms as well as for large WPPs which are placed far away from the electrical grid. These compensation devices have become the optimum solution in order to fulfill essential grid code conditions [58]. Table 3 gives an overview about the comparison of the STATCOM and SVC.

Table 2. Comparison between STATCOM and SVC

Features	**Technology**	
	STATCOM	**SVC**
VI Characteristics	Good performance in under voltage conditions	Limited performance in under voltage condition
Response Time	Fast	Lower than STATCOM
Active power control	possible	Not possible
Cost	High	Low
Size	Compact	Larger in size
Losses	High	Low

STATCOM has the ability to produce a prominent amount of reactive power even when the voltages of the system are extremely low. Figure 3-8 shows the V-I characteristics of the STATCOM and SVC, in accordance with that even when the voltages are reduced, the rated current can be produced by the STATCOM. Whereas, the current which is injected by the SVC decreases linearly with the voltages and hence the amount of the generated reactive power is quadratically decreased. Based on that feature, STATCOM has been observed as a better option than SVC in transient conditions as well as when the system voltage is low (LVRT) [51].

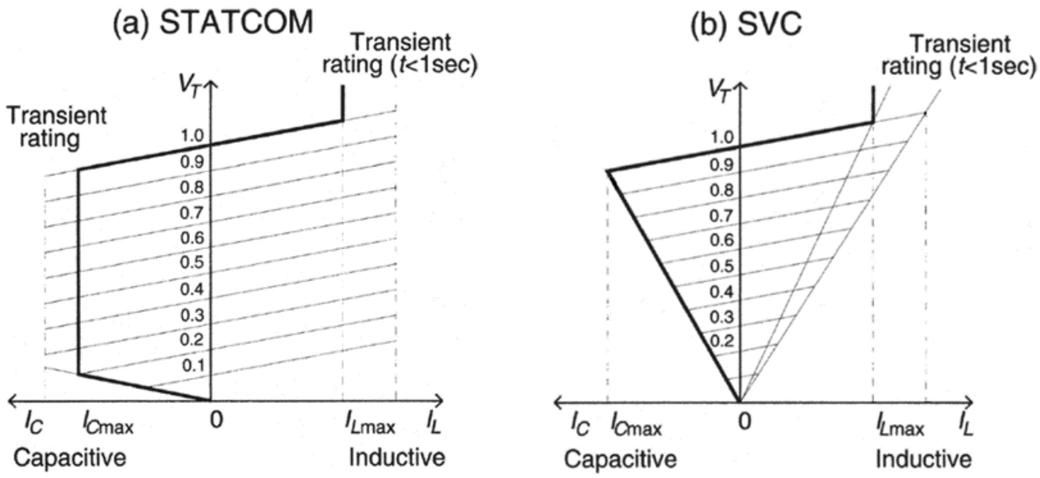

Figure 3-8. *STATCOM and SVC voltage-reactive power characteristics [31]*

Compare to the typical SVC large inductive and capacitive elements are not required in STATCOM for providing the inductive and capacitive reactive power. Therefore, the size of the STATCOM is smaller than SVC [51]. As discussed in the STATCOM section, this device can also be interfaced with the energy storage system (E-STATCOM) in order to interchange the active power. E-STATCOM is used where the power quality issues are caused by the fluctuating real power. Though it is not possible to exchange real power with the SVC [24].

STATCOM device offers much faster response as compare to the SVC, courtesy of the VSC technology that does not have any delays related to the firing of the thyristors. STATCOMs have higher losses than SVCs. Currently available semiconductor power devices that have internally turn off capabilities possess more conduction losses as compared to the conventional thyristors [37].

Based on the above analysis it can be concluded that the STATCOM device is superior than SVC because of the features include; compact size, wide range operating conditions for stabilization and regulation of voltage, high reliability and flexibility.

4. SIMULATION MODEL AND RESULTS

4.1 Introduction

The literature review has shown that the DFIG is able to support the grid voltage to some extent depending on the rating of the converter. In severe faults i.e. three-phase line to line to ground fault, it has been observed that normally DFIG based WTG could not provide enough reactive support to meet the LVRT requirement of the grid. As debated in the literature review, all power is not controlled by the power electronics converter; 30 percent of all power passes via the converter in DFIG based WTG. In the case of a FRPC based WTG, all the power passes through the converter. Therefore, it provides better performance than DFIG. There are two FACTS devices that are STATCOM and SVC, that can be utilized in order to enhance the LVRT capability of DFIG based wind turbines.

In this chapter, simulation has been made to compare reactive power support by DFIG with SVC and DFIG with STATCOM under severe fault cases. The LVRT requirement of the German Grid Code (GGC) has been taken as a reference. MATLAB Simulink tool is used to simulate the system. The following sections present the details of the system model and the following four cases;

- Reactive power support by DFIG under symmetrical fault;
- DFIG with SVC to meet LVRT requirement;
- DFIG with STATCOM to meet LVRT requirement;
- Effect of different ratings of STATCOM on grid voltage.

4.2 System Modeling

Three-phase symmetrical fault conditions are analyzed by using a simulation model as shown in Figure 4-1. The model represents a 1.5 MW DFIG-type WT connected to the 120-kV transmission grid. The 120-kV transmission grid contains a DFIG based WT, transmission line, resistive load, inductive load, and two 25 kV distribution transformers.

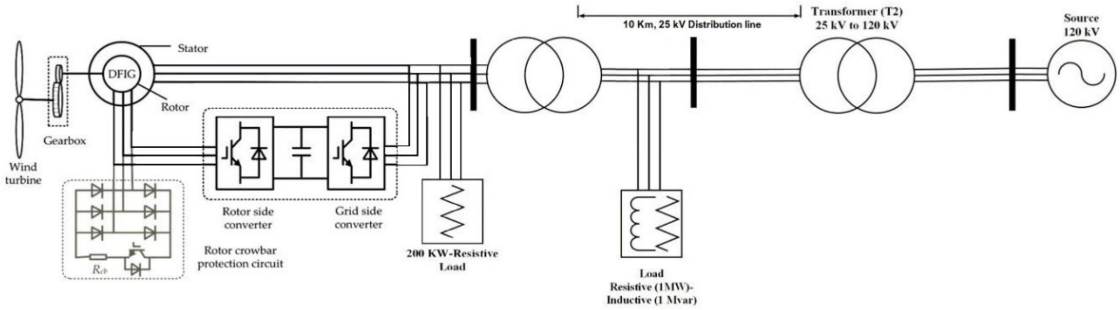

Figure 4-1. *System Model*

The power source used in the simulation is a programmable source and the fault was introduced using this programmable power source. Figure 4-1 contains two sources, one is DFIG based WTG and the other is the programmable source. Both sources are connected to the transmission line via two transformers. A resistive load is connected directly to the output of WTG. The load that is connected to the transmission line contains resistive and inductive elements. To analyze the measurement of different parameters of the system, a measurement block converts measured quantity in phasor representations that is the magnitude of quantity. In order to check the LVRT capability of the connected system, the nominal voltage of the programmable source is set to 120 kV with a voltage dip of 0.8 pu at 2 seconds. The dip in the voltage lasts for two seconds and the voltage becomes normal at 4 seconds. This will act as a 3-phase symmetrical remote fault that will occur at 2 seconds and lasts for 2 seconds.

DFIG consists of a WRIG and an IGBT-based converter. The stator of DFIG is connected directly to the grid while the power from the rotor is supplied through IGBT based power electronics converter to the grid. In this simulation, the wind speed has remained constant at 8 m/s. The pi-model of the transmission/distribution line has been utilized. Variable step size was used to simulate the model and the maximum step size is set to 1/60 s. The same model will be used for observing the integration effect of SVC and STATCOM. The summary of different parameters is shown in Table 3.

Table 3. *Ratings of different elements of the power system*

Component	Power	Voltage
DFIG based WTG	1.5 MW	575 V
Converter Rating of DFIG	0.45 MVA	1500 V (DC link capacitor)
Resistive Load 1	200 kW	575 V
Resistive Load 2	1 MW	25 kV
Inductive Load	1 MVAr	25 kV
Transformer (T1)	2 MVA	0.575/25 kV
Transformer (T2)	4 MVA	25/120 kV

The objective of this report is to analyze the fundamental operation principle of DFIG, SVC, and STATCOM during the three-phase symmetrical fault. In the simulation, 60 Hz frequency has been considered, however, the German power system is operated at 50 Hz. The step size is so large that only fundamental frequency phenomena (60 Hz) is analyzed. Harmonics are not included in the LVRT requirement, hence not analyzed [18]. To analyze the voltage response of the grid, 25 kV is considered as 1 pu and for source voltage analysis, 120 kV is considered as 1 pu.

4.3 Case I: Reactive Power Support by DFIG Under Symmetrical Fault

In the beginning, the effect of three-phase fault to the power system is examined without any additional compensation device and measurements have been made as shown in Figure 4-2.

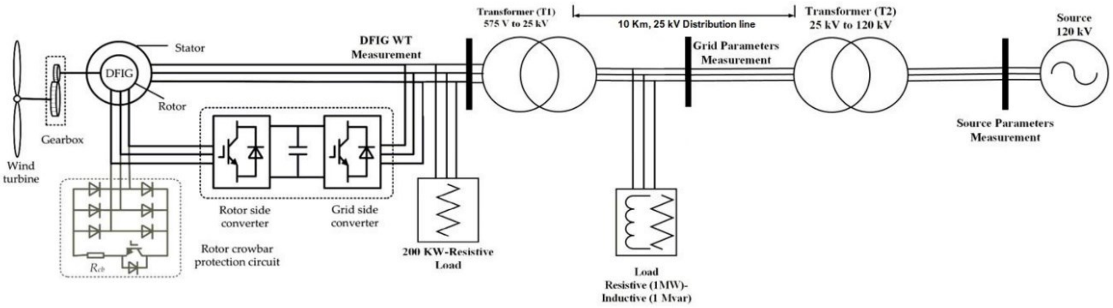

Figure 4-2. *DFIG without FACTS device*

DFIG is set to voltage regulation mode and converter rating of DFIG is 0.45 MVA. During normal operation, DFIG is controlled in order to retain the PF closer to unity in PCC. In the simulation, reactive power support by DFIG was analyzed during the fault. The simulated voltage and power values are shown in Figure 4-3.

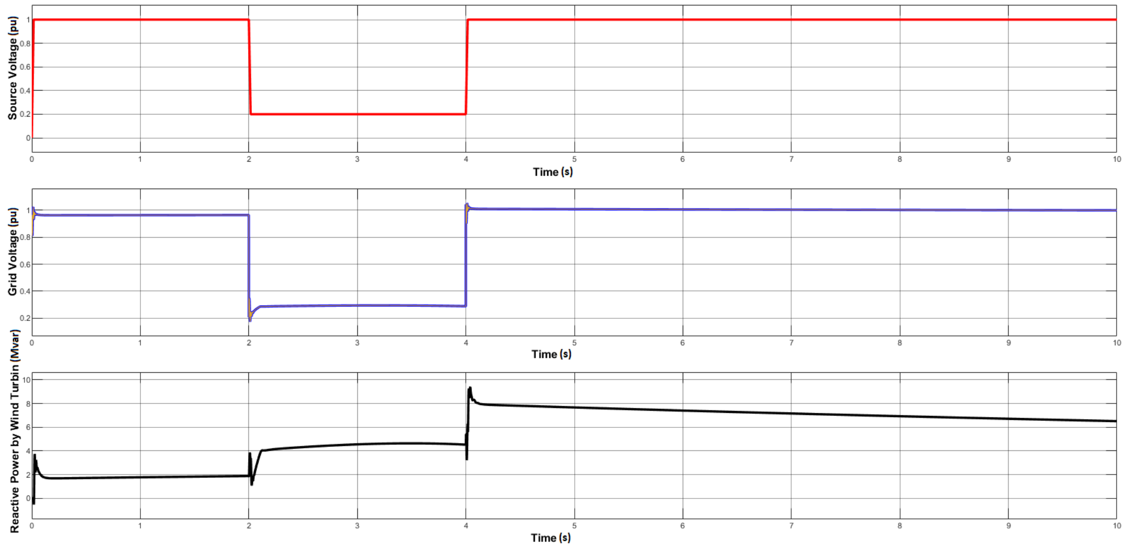

Figure 4-3. *Reactive power support by DFIG WTG under symmetrical fault*

As shown in Figure 4-3, reactive power generated by DFIG based WTG is increased from 2 MVAr to 4 MVAr during the fault time. The injection of reactive power raised the grid voltage from 0.2 pu to 0.3 pu. After the fault, the reactive power gradually decreases to its normal value. According to the GGCs, the voltage must be raised at least 0.8 pu in 1500 ms but It can be noticed that the LVRT requirement was not fulfilled by the DFIG based WTG. An SVC has been added in the next case to enhance the LVRT meeting capability of the grid.

4.4 Case II: Reactive power support by DFIG WTG with SVC under symmetrical fault

The grid code requirement was not able to fulfill as shown in Figure 4-3. Therefore, SVC is added in the model as shown in Figure 4-4.

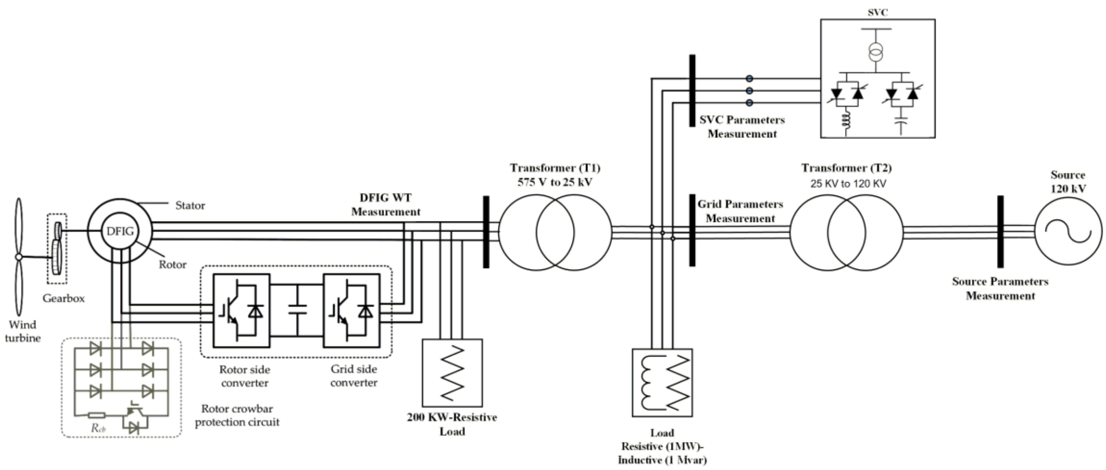

Figure 4-4. *Reactive power support by DFIG WTG with SVC under symmetrical fault*

The SVC is used as a shunt compensator element in order to maintain grid voltage at the desired level. SVC regulates bus voltage by compensating reactive power to the grid. SVC consist of capacitors, reactors, and thyristors. The firing angle of the thyristor is controlled to generate or absorb desired reactive power by the capacitor and reactor. Multiple proportional-integral controllers are utilized to maintain the bus voltage at the desired level. The limit of reactive power support of the SVC is set to 50 MVA. The nominal voltage is set to 25 kV. Fault time, fault interval and fault level are the same as in the previous case. The model is simulated for 10 seconds and subsequent results are shown in Figure 4-5 and Figure 4-6.

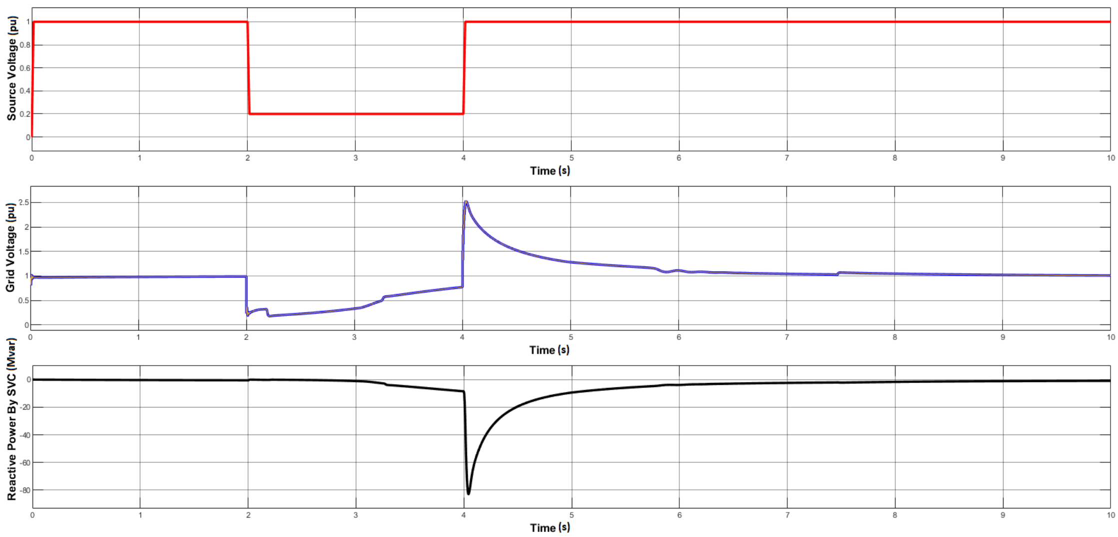

Figure 4-5. *Reactive power support by SVC under symmetrical fault*

Fig. 5 represents the voltage profile of the grid and reactive power support by the SVC during the fault period. It has been observed that by installing SVC, partially grid code requirements have been met. A more detailed voltage profile of the grid is shown in Figure 4-6. It is observed that the obtained slope of the voltage of grid is much lower than the GGC LVRT requirement. According to the LVRT requirement, voltage must raise to 0.80 pu in 1500 ms. In our case, the voltage of the grid raised to 0.6 pu in 1500 ms with the slope lower than required that is below the second borderline presented in GGC requirement. According to the result, grid voltage raised to 0.8 pu in 2100 ms, which is beyond the LVRT requirement. In comparison with the result presented in the last case, SVC has provided much better reactive power support.

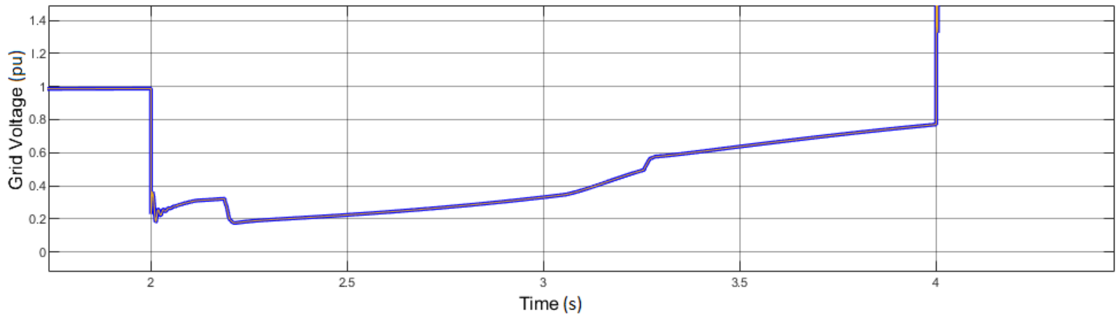

Figure 4-6. *Reactive power support by SVC under symmetrical fault*

In comparison with the grid code presented in the literature, the conclusion can be made that the LVRT requirement has not been fulfilled. However, much better results obtained than the previous case in which DFIG was operated alone. If we further increase the nominal rating of SVC, the LVRT requirement might be fulfilled. In this study, the minimum possible power rating of the converter for all three cases has been considered. Converter rating for the SVC and STATCOM have been set to 50 MVA.

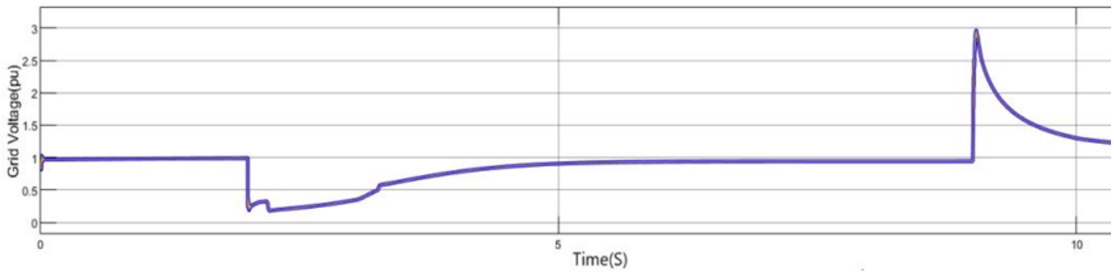

Figure 4-7. *Grid voltage after the integration of SVC under long duration fault*

In Figure 4-7, the fault duration has increased from 4 seconds to 9 seconds. According to Figure, the grid voltage is able to increase to be nominal with SVC if the fault exists for longer. In some other countries, the grid codes are not so strict as in Germany for example in Spain and Italy. Hence, SVC can be used. Also, SVC with a higher nominal power would be an option. The third option would be a combination of SVC and STATCOM or the combination of STATCOM and passive compensation devices (capacitors and inductors).

To fulfill the GGC LVRT requirement, SVC is replaced with STATCOM in the next case. Simulation and results are presented in case III.

4.5 Case III: LVRT requirement and reactive support by STATCOM under symmetrical fault

In the third case, SVC has been replaced by STATCOM to meet the requirement of LVRT of the GGCs. The same model has been utilized with the replacement of SVC by STATCOM as shown in Figure 4-8. STATCOM is a power electronic device that utilizes force commutated devices like GTO and IGBTs. STATCOM is a shunt connected device. It continuously supports variable reactive power that depends upon the magnitude of the voltage at PCC. STATCOM is set to the voltage-controlled mode in order to get desired reactive power support. In the model converter rating of STATCOM is set to 50 MVA. Nominal voltage is set to 25 kV whereas, the reference voltage is taken as the 1 pu.

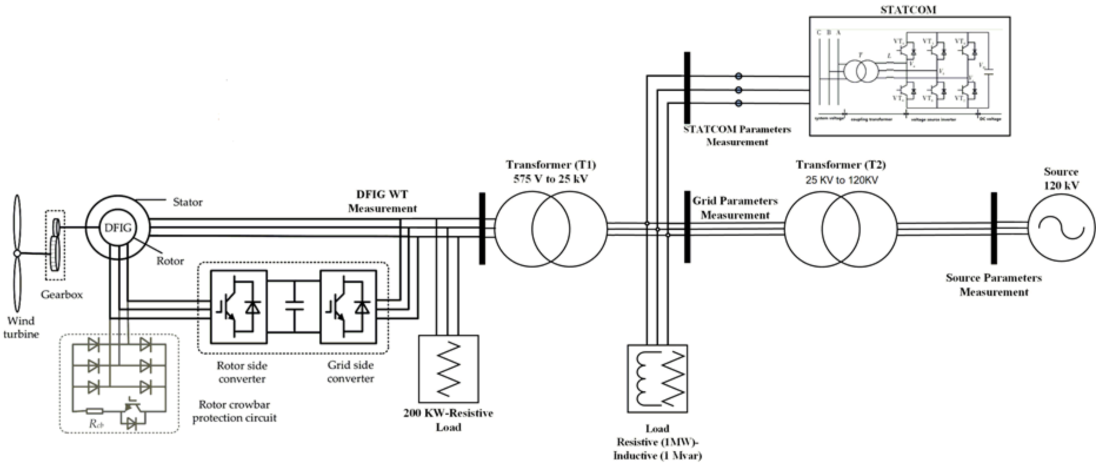

Figure 4-8. Reactive power support by DFIG WTG with STATCOM under symmetrical fault

Fault time, fault interval and fault level are the same as in the previous cases. The model is simulated for 10 seconds and subsequent results are shown in Figure 4-9 and Figure 4-10.

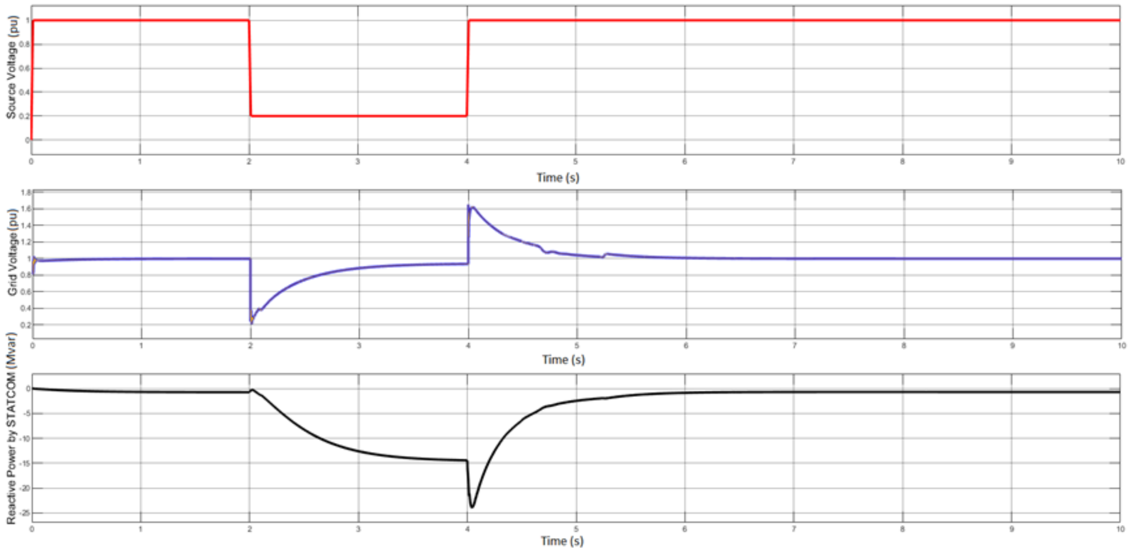

Figure 4-9. *Reactive power support by STATCOM under symmetrical fault*

Figure 4-9 represents the voltage profile of the grid and reactive power support by the STATCOM during the fault period. A more detailed voltage profile of the grid is shown in Figure 4-10. It is observed that the obtained slope of the voltage of grid meets the GGC LVRT requirement. In the simulated results shown in Figure 4-10, the voltage of the grid raised to 0.9 pu in 1500 ms while the slope of voltage is much higher than required that is above the second borderline presented in GGC LVRT requirements.

In comparison with the result presented in the last case, STATCOM has provided enough reactive power support to meet the requirement. It has been observed that by installing STATCOM, the GGC LVRT requirement is fulfilled efficiently.

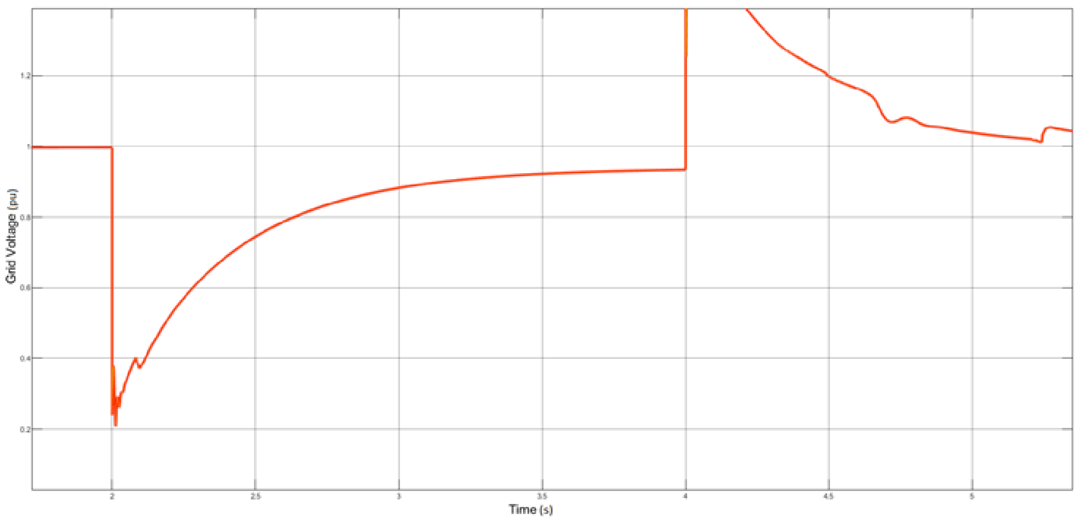

Figure 4-10. *Grid Voltage after integration of STATCOM*

The conclusion can be made that with the same converter rating of SVC and STATCOM, the LVRT requirement has been fulfilled by DFIG with the support of STATCOM.

The capability of meeting the LVRT requirement can be increased or decreased by utilizing STATCOM with different ratings. In the next case, the effect of different ratings of STATCOM on the grid has been observed.

4.6 Case IV: Effect of converter ratings of STATCOM on the grid voltage

In this simulation, three different ratings of STATCOM have been utilized to see the effect on the grid voltage and reactive power support by STATCOM respectively. The converter rating of DFIG is 0.45 MVA and the converter rating of STATCOM has been changed in each case. Figure 4-11 shows the voltage profile of the grid. Reactive power that is produced by STATCOM is shown in Figure 4-11b.

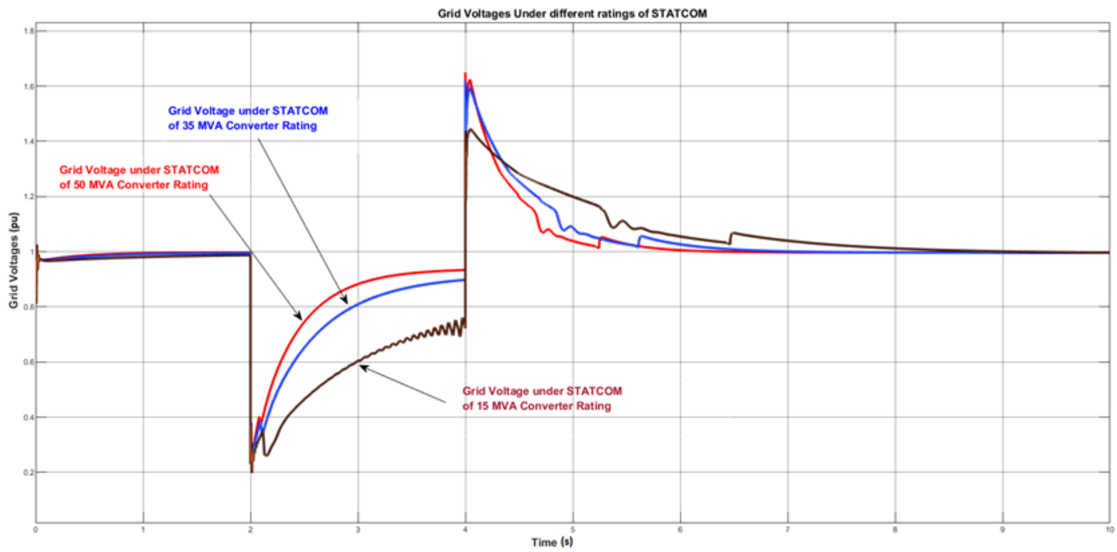

Figure 4-11 *Grid Voltage under different power ratings of STATCOM*

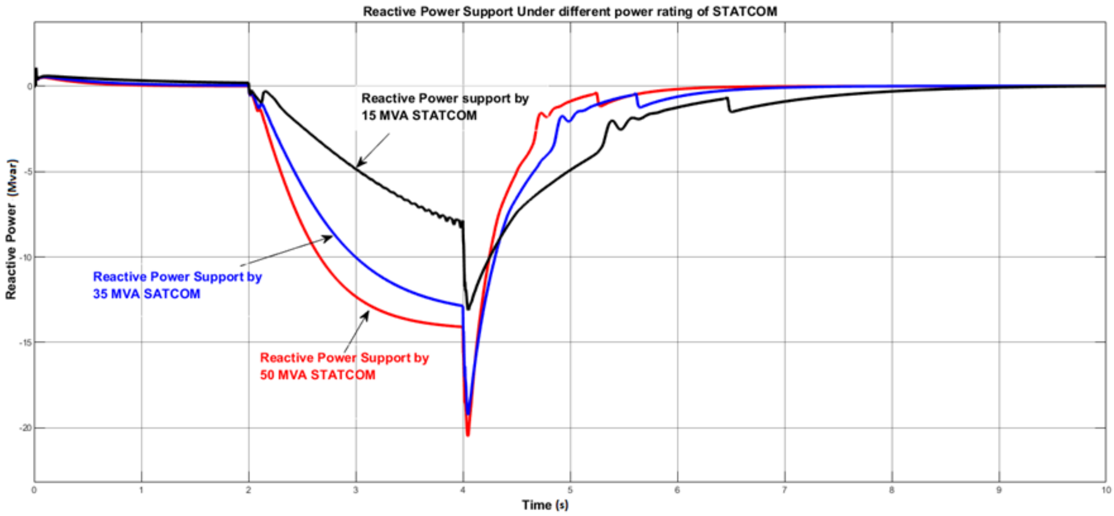

Figure 4-12 *Reactive power support by STATCOM under different power ratings*

According to Figure 4-11, when the simulation was carried out with STATCOM of 15 MVA rating, the grid voltage profile could not meet the LVRT criteria. It is categorized as below the second borderline. As the power rating of STATCOM increased to 25 MVA, voltage profile partially touches the second borderline but LVRT criteria do not achieve. In the case of 50 MVA, it is observed that LVRT criteria have been achieved successfully. As we increased the power rating of STATCOM, reactive power support increased accordingly as shown in Figure 4-12.

4.7 Summary of Simulation Work

In this simulation, the LVRT capability of the power system with different scenarios has been assessed. LVRT of the GGC was taken as a reference to assess the power system. In the simulation, the severe fault of 0.8 pu in the grid voltage was created to test different cases. Three cases were modeled and presented in the thesis. In the first case, the capability of DFIG based WTG was assessed without the integration of any FACTS device. It was observed that DFIG based WTG can support the grid voltage under normal faults from 0.1 pu to 0.3 pu. Under severe fault, DFIG based WTG cannot provide enough reactive power support to meet the requirement of the LVRT GGC. SVC and STATCOM are FACTS devices that are widely used in the power grid to fulfill LVRT requirements of the grid.

To meet the LVRT requirement, two other cases were studied. In the second case, the DFIG-WTG in integration with SVC is modeled. In the third case, SVC was replaced by STATCOM with the same converter rating. The converter rating of SVC and STATCOM kept the same in both cases. It was found in the second case that SVC supported the grid with reactive power to raise the voltage up to 0.6 pu but the LVRT requirement was not met. When SVC is replaced by STATCOM, it was found that with the same converter rating, STATCOM met the criteria of the LVRT GGC effectively. Simulations have also shown that if we increase the converter rating of STATCOM, reactive support increases accordingly.

5. CONCLUSION

The purpose of this thesis was to address the reactive power compensation significance for the wind power plants. The role of reactive power compensation with external devices regarding the selected grid codes was investigated in this thesis. The shunt connected FACTS devices (STATCOM and SVC) were chosen for this study. These shunt connected FACTS devices were used with the DFIG based WT in order to provide the support to the grid during the fault.

The demand of the LVRT issued by the TSOs is increasing significantly. To limit the voltage drop and keep the power system reliability and stability, the LVRT requirements are set for wind turbines. This requirement is fulfilled by generating reactive power. The DFIG based WT topology does not have sufficient capacity to provide enough reactive power during the severe faults. Therefore, FACTS devices are installed in parallel with the wind parks. These FACTS devices provide additional reactive power to fulfill the grid requirement.

Four different cases were analyzed in MATLAB Simulink based work. The LVRT of German grid code was taken as reference. In the first case, DFIG based WTG was connected to the grid without any compensation device. During the three-phase symmetrical fault of 0.8 pu, it was observed that DFIG could not raise the grid voltage in accordance with the grid requirement. Therefore, SVC was added with WT in order to provide more reactive power. In this case significant improvement was examined but, it was not according to the grid requirement imposed by German TSO. Due to the fact that LVRT requirement was not achieved by SVC thus, SVC was replaced by STATCOM. After adding the STATCOM the grid voltage profile was exactly according to German grid codes. In the last case, STATCOM of different ratings were utilized and it was found that STATCOM of 50 MVA rating is reliable to fulfill the German LVRT.

The penetration of the wind power into the grid is considerably increasing, according to the EWEA 50 percent of electricity will be produced by the wind energy in Europe [4]. It means LVRT requirement will be more stringent in future. STATCOM will be reliable solution to fulfill the LVRT requirement of DFIG-WT. Another solution is to fulfill the LVRT requirement without any compensation device is to use FRPC based WTG.

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