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Application of STATCOM for improved dynamic performance of wind farms in a power grid

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APPLICATION OF STATCOM FOR IMPROVED DYNAMIC PERFORMANCE OF WIND FARMS IN A POWER GRID

by

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ABSTRACT

When integrated to the power system, large wind farms pose stability and control issues. A thorough study is needed to identify the potential problems and to develop measures to mitigate them. Although integration of high levels of wind power into an existing transmission system does not require a major redesign, it necessitates additional control and compensating equipment to enable recovery from severe system disturbances.

This thesis investigates the use of a Static Synchronous Compensator (STATCOM) along with wind farms for the purpose of stabilizing the grid voltage after grid-side disturbances such as a three phase short circuit fault, temporary trip of a wind turbine and sudden load changes. The strategy focuses on a fundamental grid operational requirement to maintain proper voltages at the point of common coupling by regulating voltage. The DC voltage at individual wind turbine (WT) inverters is also stabilized to facilitate continuous operation of wind turbines during disturbances.

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1. INTRODUCTION

A pressing demand for more electric power coupled with depleting natural resources has led to an increased need for energy production from renewable energy sources such as wind and solar. The latest technological advancements in wind energy conversion and an increased support from governmental and private institutions have led to increased wind power generation in recent years. Wind power is the fastest growing renewable source of electrical energy. Total wind power installation in the US was 11,603 MW in 2006 and it increased by 26% in the year 2007 [1]. Figure 1.1 illustrates the total amount of installed wind power in the U.S. power system from the years 2000 to 2007.

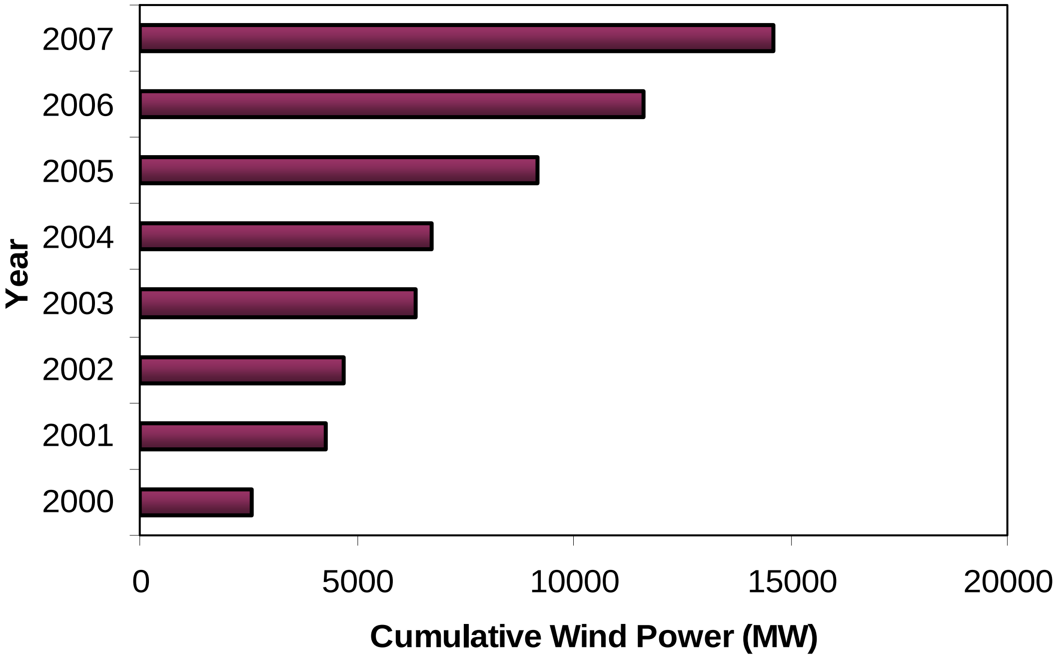

Figure 1.1. Cumulative wind power production in the United States

The wind power penetration has increased dramatically in the past few years, hence it has become necessary to address problems associated with maintaining a stable electric power system that contains different sources of energy including hydro, thermal, coal, nuclear, wind, and solar. In the past, the total installed wind power capacity was a small fraction of the power system and continuous connection of the wind farm to the grid was not a major concern. With an increasing share derived from wind power sources, continuous connection of wind farms to the system has played an increasing role in enabling uninterrupted power supply to the load, even in the case of minor disturbances. The wind farm capacity is being continuously increased through the installation of more and larger wind turbines. Voltage stability and an efficient fault ride through capability are the basic requirements for higher penetration. Wind turbines have to be able to continue uninterrupted operation under transient voltage conditions to be in accordance with the grid codes [2]. Grid codes are certain standards set by regulating agencies. Wind power systems should meet these requirements for interconnection to the grid. Different grid code standards are established by different regulating bodies, but Nordic grid codes are becoming increasingly popular [3].

One of the major issues concerning a wind farm interconnection to a power grid concerns its dynamic stability on the power system [4]. Voltage instability problems occur in a power system that is not able to meet the reactive power demand during faults and heavy loading conditions. Stand alone systems are easier to model, analyze, and control than large power systems in simulation studies. A wind farm is usually spread over a wide area and has many wind generators, which produce different amounts of power as they are exposed to different wind patterns.

Flexible AC Transmission Systems (FACTS) such as the Static Synchronous Compensator (STATCOM) and the Unified Power Flow Controller (UPFC) are being used extensively in power systems because of their ability to provide flexible power flow control [5]. The main motivation for choosing STATCOM in wind farms is its ability to provide busbar system voltage support either by supplying and/or absorbing reactive power into the system.

The applicability of a STATCOM in wind farms has been investigated and the results from early studies indicate that it is able to supply reactive power requirements of the wind farm under various operating conditions, thereby improving the steady-state stability limit of the network [6]. Transient and short-term generator stability conditions can also be improved when a STATCOM has been introduced into the system as an active voltage/var supporter [5, 7].

The methods used to develop an equivalence of a collector system in a large wind power plant are described in [8]. The requirements, assumptions and structure of an aggregate model of a wind park with constant speed turbine and variable speed turbines are discussed in [9].

This thesis explores the possibility of enabling wind farms to provide voltage support during normal conditions, as well as under conditions when system voltages are not within desired limits. The transient behavior of wind farms can be improved by injecting large amounts of reactive power during fault recovery [10]. This thesis examines the use of STATCOMs in wind farms to stabilize the grid voltage after grid disturbances such as line outages or severe system faults.

The wind turbines (WTs) considered in this thesis are Doubly Fed Induction Generators (DFIGs) that are capable of variable speed operation. A DFIG has a power electronic converter by which both real power and reactive power can be controlled. A STATCOM was employed to regulate the voltage at the bus, to help maintain constant DC link voltages at individual wind turbine inverters during disturbances. This feature will facilitate the continuous operation of each individual wind turbine during disturbances, thus enabling the wind farm to participate in the grid side voltage and power control.

The dynamic DFIG model available in DIgSILENT PowerFactory Version 13.2 [11] was used for the simulations. The STATCOM with a higher rating capacity was developed based on the study of an available low capacity STATCOM model. The complete power grid studied in this thesis is a combined case study of interconnected two wind turbines, a synchronous generator, a STATCOM and a typical load all forming a four bus system.

Power control is vital for transient and voltage stability during faults and is required to meet the connection requirements of the wind turbines to the grid which vary mostly with the short circuit capacity of the system considered. Reactive power is required to compensate for the additional reactive power demand of the generator and the matching transformers so that the wind power installation does not burden the system. Low Voltage Ride Through (LVRT) is a recently introduced requirement that transmission operators demand from wind farms. A STATCOM is being evaluated for its performance to effectively provide LVRT for wind turbines in a wind farm.

The European electrical power system contains larger amounts of wind power and the share of embedded wind generation is increasing in other power systems as well. The significant size of new wind power installations requires realistic modeling capabilities of wind generators for assessing the power system planning and to perform stability studies with increased wind power share.

DIgSILENT version 13.6 was used for the simulation studies on the modeled test system. DIgSILENT is an acronym for "**Dig**ital **Si**mu**l**ation and **E**lectrical **Net**work calculation program" is one the most powerful power system software with an integrated graphical one-line interface. DIgSILENT has faster simulation time when compared to PSCAD, SimPower systems in MATLAB. In terms of accuracy of the results and implementation of the models, all the softwares are similar in nature. This is becoming popular in DFIG model was used to model the turbines in a wind farm and the STATCOM model was developed specific to this application.

This thesis is presented in five sections. Section 2 is about the wind power statistics, types of wind turbines, wind farm modeling requirements, stability and reliability considerations, and fault studies on the WTs, and the performance of WTs with faults on the system. Section 3 deals with the need for voltage control in the presence of wind energy. Also, the reactive power capability of wind turbines, the need for reactive power support along with the applicability of FACTS devices, and the reasons for choosing STATCOM are presented. Section 4 deals with the methodology including the capabilities, ratings, location of STATCOM, and the total reactive power available with faults on the system. Section 5 describes the test system and explains the simulation results obtained. The dynamic performance of the test system is analyzed for three cases, viz. three phase impedance faults, tripping of a WT in the wind farm and sudden temporary load changes. Section 6 consists of conclusions drawn from the simulation study.

2. WIND ENERGY IN THE POWER SYSTEM

2.1. WIND ENERGY

Wind is a continuously varying source of energy and so is the active power generated by the wind turbine. If a WT is connected to a weak grid (which has low short circuit power), the terminal voltage also fluctuates, producing flicker, harmonics and interharmonics due to the presence of power electronics.

For a set of connected wind turbines forming a wind farm, there exist certain grid codes or specific requirements with which each wind turbine must conform with in order to be allowed to be connected to the grid [12]. Most wind power systems are based in remote rural locations and are therefore prone to voltage sags, faults, and unbalances. These unbalanced grid voltages can cause many problems such as torque pulsations, unbalanced currents and reactive power pulsations [13].

When wind farms are connected to a strong grid, that is closer to a stiff source, voltage and frequency can be quickly re-established after a disturbance with the support of the power grid itself. To wait for the voltage to re-establish after the fault has been cleared in the case of a weak grid interconnection is not reliable because there is always a risk of voltage instability initiated by the disturbance. Hence, reactive power and voltage support that can be provided by mechanically switched capacitors, SVC or STATCOM is needed to help improve the short term voltage stability and reinforce the power network. This is also true for wind farms with all fixed speed wind turbines with no dynamic control or reactive power compensation.

There are many wind turbine manufacturers who produce different wind turbine technologies. Table 2.1 gives a list of all the MW range WTs manufactured by various producers and their technical specifications. The high power MW range WTs are typically the DFIGs which are becoming increasingly popular with their increasing number of installations.

Wind generators are generally of two types: fixed and variable speed. Fixed speed generators are induction generators with capacitor bank for self-excitation or two-pole pairs or those which use rotor resistance control. Variable speed generators are either DFIG (which is a round rotor machine) or full power converters such as squirrel cage induction generators, permanent magnet synchronous generators, or externally magnetized synchronous generators. Variable speed wind turbines are connected to the grid using power electronic technology and maximize effective turbine speed control.

Table 2.1 Types of wind turbines produced by various wind generator manufacturers

Wind Turbine	***Rated Speed***	***Cut out speed***	***Generator***	***Power Control***
GE 1.5 MW	13 m/s	25 m/s	DFIG	Active blade pitch
GE 2.5 MW	12.5 m/s	25 m/s	PM generator	Active blade pitch
GE 3.6 MW	14 m/s	27 m/s	DFIG	Active blade pitch
VESTAS 1.65 MW	13 m/s	20 m/s	Asynchronous	Active Stall
VESTAS 1.8 MW	15 m/s	25 m/s	Asynchronous with Optislip	OptiSlip / Pitch
VESTAS 3 MW	15 m/s	25 m/s	Asynchronous with Optispeed	OptiSpeed and OptiTip Pitch regulation
NORDEX 2.5 MW	15 m/s	25 m/s	DFIG	Pitch
NORDEX 3 MW	13 m/s	25 m/s	DFIG	Pitch
SUZLON 0.95 MW	11 m/s	25 m/s	Asynchronous	Pitch
SUZLON 1.25 MW	14 m/s	25 m/s	Asynchronous	Pitch

Variable speed wind turbines such as DFIGs are the most popular wind turbines being installed today because they perform better than the fixed speed wind turbines during system disturbances. DFIGs are the only class of wind generators capable of producing reactive power to maintain unity power factor at the collector bus. Figure 2.1 shows the DFIG model used in the simulations.

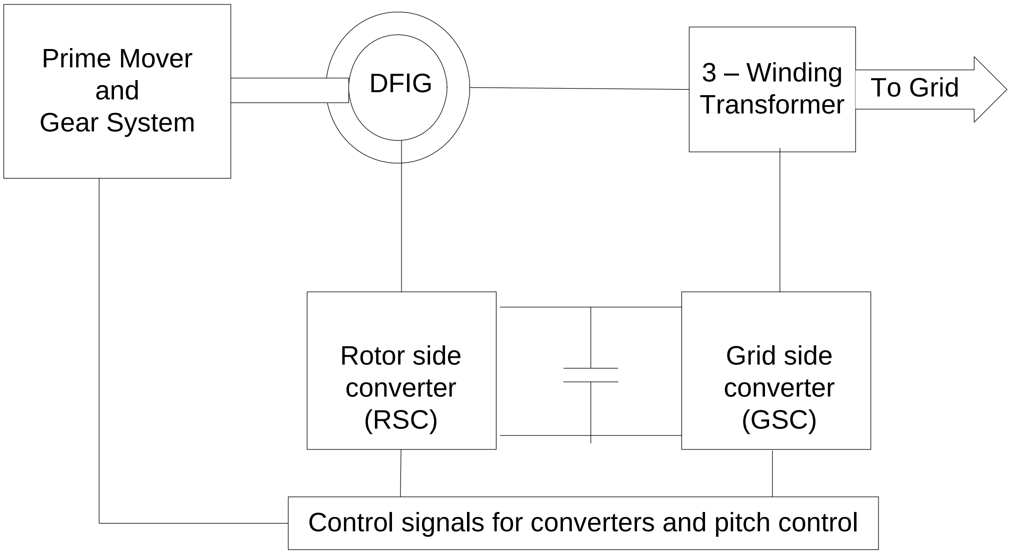

Figure 2.1. Block diagram of a Doubly-fed induction generator

A back-to-back converter is connected between the rotor and stator of the DFIG. The main objective of the GSC is to keep the DC link voltage constant. The reactive power supplied by this converter can be controlled by maintaining the power factor of this converter at unity. The GSC works as supplementary reactive power compensation though the reactive power capability of this converter during the fault is limited as it is rated just about 25% of the wind turbine power ratings. RSC controls the stator active and reactive powers. The RSC is also used to control the machine speed and the stator reactive power. The stator of the DFIG is directly connected to the grid and the slip-rings of the rotor are fed by self-commutated converters. The magnitude and phase of the rotor voltage can be controlled using these converters which makes active and reactive power control possible. By controlling the reactive power generated or absorbed by the RSC, voltage or reactive power at the grid terminals can be controlled.

The main components of the DFIG model are: the prime mover consisting of the pitch angle controller, the wind turbine and the shaft, the DFIG, control system regulating active and reactive power of the DFIG through the RSC and a protection system. Crowbar protection is also being increasingly used in wind turbines to short circuit (with small impedance) the rotor side converter in case of faults to protect the RSC from over currents. Crowbar protection is specific to DFIGs and protects the RSC against over-currents. The converter is blocked and bypassed through additional impedance, when the rotor current exceeds the rotor converter current ratings. The additional impedance reduces the amount of reactive power absorbed by the machine and, thus, improves the torque characteristic during voltage sags [11].

In DFIGs, the size of the converter is related not to the total generated power, but to the selected speed range and, hence, to the slip. As speed range requirements around the synchronous speed increases, the size and cost of the converter increases. Typical high power wind turbine generators are mostly DFIGs that allow more speed control of about 25% synchronous and an effective reactive power control with a small size rotor that is only about 25% of the total power rating of the turbine.

2.2. WIND FARM MODELING

When many wind turbines are added to the system, the grid becomes weaker as these types of generators require additional control equipment since they do not have any self recovery capability like the conventional generators. This requires a thorough study of the normal and dynamic performance of the wind turbines during and after a disturbance. Before integrating large amounts of wind power with the conventional generating units, a comprehensive analysis of the power system stability and reliability issues has to be studied. A simulation study is the best known method to understand the system dynamics for operation under normal conditions and during contingencies. Smaller wind farms are easier to model and study while larger wind farms require more effort and complex modeling.

A very large wind farm contains hundreds of wind turbines which are connected together by an intricate collector system. Though each WT of a wind farm may not critically impact the power system, a wind farm has significant impact on the associated power system during severe disturbances [14]. It is not practical to represent all wind turbines to perform a simulation study; a simplified equivalent model is required. It also helps that there is no mutual interaction between wind turbines with well-tuned converters in a wind farm (apart from the conditions of the power grid) [15].

2.3. RELIABILITY AND STABILITY CONSIDERATIONS

Power quality problems to the associated power system due to the presence of WTs are continuous power variations, voltage variations, flicker, harmonics, and transients. Likewise, the kind of power quality issues that the wind farm encounters due to the associated network are voltage dips, interruptions, voltage imbalances and frequency variations. In the past, wind power was exempted from some grid interconnection requirements like voltage regulation and frequency regulation. The wind power systems were allowed to disconnect on system events like three phase faults and blackouts. Only recently, after the increase in wind power penetration, have some stringent interconnection rules, known as “grid codes” with which these wind plants have to conform been developed. These grid codes require that wind turbine generators be treated more like conventional generating units and participate in grid voltage and frequency regulation. To facilitate WT participation in frequency control there are two major controls: turbine-based control and substation-based control. In turbine-based control systems, each turbine has to have some specific control capabilities, such as power factor or reactive power (Q) control. In substation-based control, some kind of reactive power compensation is either provided by switched capacitors (manual or static compensation) or FACTS devices. [16].

2.4. POWER AND VOLTAGE PERFORMANCE

Effective power control is essential for transient and voltage stability during system faults such as a 3-phase short circuit fault. When a three phase short circuit fault occurs in the system, the voltage at the terminal drops to a value that depends on the fault’s location. In this case, the WT will not be able to transfer all its generated power leading to an acceleration of the wind turbine due to an imbalance between input mechanical power and output electrical power. This imbalance makes it more difficult for the WT to recover after the fault has been cleared because more reactive power is required by the system.

Power control is necessary for all connection requirements for wind turbines, which vary widely according to the short circuit capacity of the system. The relative impedance for weak grids is high, so the impact of Q support is usually significant. If wind turbines are connected to a weak system, more power control is required to keep the system stable during and after a fault.

A turbines Low voltage ride through (LVRT) capability is its ability to survive a transient voltage dip without tripping. Wind turbines’ LVRT capability is vital for wind farm interconnection because the tripping of a wind farm due to a fault on a nearby power line results in the loss of two major system components (the line and the wind farm).

2.5. PERFORMANCE OF A WT WITH FAULTS ON THE SYSTEM

Generators are the major components in the power system that reacts to system disturbances. The reaction of the conventional synchronous generators to all kinds of grid disturbances has been studied extensively; however wind turbines are generally not equipped with synchronous generators. Wind turbine generators interact differently with the grid when there are faults on the system. The grid voltage has to be controlled inevitably, irrespective of the capabilities with which a wind farm’s generators might be equipped.

The most popular type of wind turbines installed today are variable speed wind turbines that feature improved power quality and speed control and reduced mechanical stresses. Under the same circumstances, the power generated by variable speed wind turbines is greater than that generated by the fixed speed wind turbines [17]. Recently-developed grid codes require that wind turbines be able to withstand voltage disturbances without disconnection, which is known as the LVRT capability of the wind turbine [10]. Figure 2.2 shows the LVRT requirement for wind generation facilities per FERC order 661 and power electronic based FACTS controllers such as STATCOM can be used to hold the line voltage to a specific value to help the WT ride-through the fault. The LVRT requires that a WT does not trip even if the voltage drops to 0.15 per unit for about 0.625 seconds. If due to a fault, the voltage drops below this value, the wind turbine can be tripped until the system restores and the wind turbine can be resynchronized. A WT can take a maximum of 2.375 seconds to restore to about 0.9 per unit voltage after the fault has been cleared. These rules are more stringent for some grids which are derived based on grid reliability requirement.

Order No. 661 issued by FERC (Federal Energy Regulatory Commission) on June 2, 2005, sets specific wind power requirements, namely, low voltage ride through, power factor design criteria (reactive power), and Supervisory Control and Data Acquisition (SCADA) capability. The grid codes are specific to a particular power zone and they vary with respect to the voltage profile requirement during system disturbances.

This thesis focuses mainly on the low voltage ride through requirement for wind turbines. Several studies have been performed to understand the behavior of the wind generators, the voltage profile and the reactive power in the system, to various system disturbances. The transient behavior of the wind turbines during and after fault in the presence of different compensation techniques and their dynamic performance has been studied.

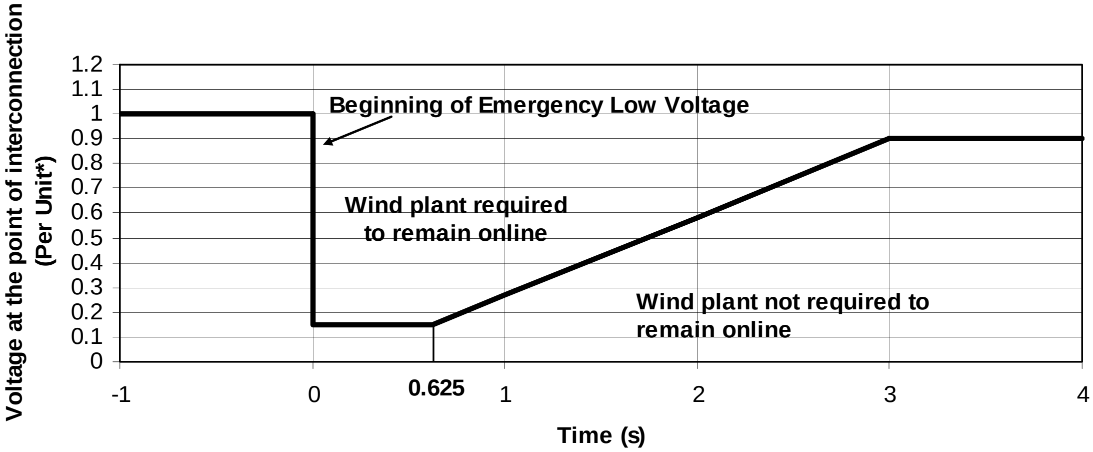

Figure 2.2. LVRT requirement for wind generation facilities per FERC Order No. 661

3. VOLTAGE CONTROL IN THE PRESENCE OF WIND ENERGY

3.1. WIND TURBINE REACTIVE POWER CAPABILITY

A majority of the wind turbines installed in the past were induction generators that absorb reactive power from the system even during normal operating conditions. As WTs are a sink for reactive power, an effective dynamic reactive power management system is required to avoid low-voltage issues in the wind power system. Recently a large number of wind turbines installed are of the variable speed type fitted with DFIGs. Under normal operating conditions the DFIGs operate at close to unity power factor and may supply some reactive power during system disturbances such as a three phase fault close to the wind farm in order to meet the LVRT grid code requirement. Mechanically switched capacitors are used in wind farms containing asynchronous generators to provide reactive power support during system disturbances. However, limited support provided by these small wind generators is required to meet the interconnection standards such as to ride through a fault. Hence, additional compensating equipment is needed by the system in order to restore quickly after the fault has been cleared so as to maintain system stability and to avoid generator tripping. In some instances, the collector bus of the wind farm may have some reactive power compensation, which is typically lower than that required for critical contingencies in the system.

3.2. FACTS DEVICES AND CAPABILITIES

Recently, FACTS-based devices have been used for power flow control and for damping power system oscillations. They can also be used to increase transmission line capacity; steady state voltage regulation; provide transient voltage support to prevent system collapse; and damp power oscillations. FACTS devices can be used in wind power systems to improve the transient and dynamic stability of the overall power system. The STATCOM is from the family of FACTS devices that can be used effectively in wind farms to provide transient voltage support to prevent system collapse. In other words a STATCOM is an electronic generator of reactive power. Figure 3.1 show the various STATCOM installations on the map of the United States. Table 3.1

shows these STATCOM installations and their voltage levels along with their reactive power control ranges.

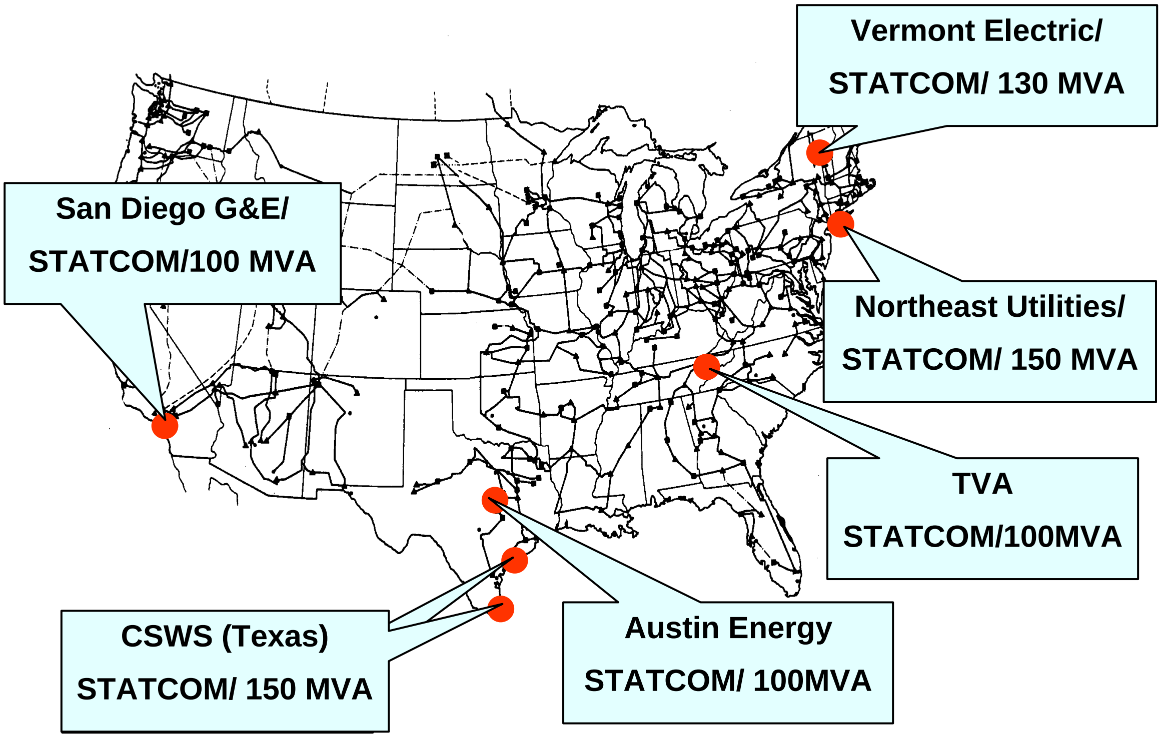

Figure 3.1. US STATCOM installations [18]

Transmission of power 'S' ($P + jQ$) over a power line with impedance 'Z' ($R + jX$) results in a voltage drop (ΔV) (1)

$$\Delta V = \frac{R.P + X.Q}{V} \qquad (1)$$

For larger wind farms connected to transmission systems X>>R and, from equation 1, ΔV is directly proportional to the reactive power (Q) transferred. From equation 1, it is clear that for efficient voltage control an effective reactive power strategy is required. FACTS devices can provide dynamic and steady state support. They can improve dynamic and transient stability, control dynamic overvoltages and undervoltages and also support against frequency and voltage collapses.

Table 3.1 US STATCOM installations [19]

No.	Year	Customer	Location	Voltage	Control range	Supplier
1	1995	Tennessee Valley Authority (TVA)	Sullivan Substation (Johnson City, Tennessee)	161kV	±100MVar	Westinghouse Electric Corporation
2	2001	Vermont Electric Power	Essex station (Burlington, Vermont)	115kV	-41 to +133MVar	Mitsubishi
3	-	Central & South West Services (CSWS)	Laredo and Brownsville stations (Texas)	-	±150MVar	W-Siemens
4	2003	San Diego Gas & Electric (SDG&E)	Talega station (Southern California)	138kV	±100MVar	Mitsubishi
5	2003	Northeast Utilities (NU)	Glenbrook station (Hartford, Connecticut)	115kV	±150MVar	Areva (Alstom)
6	2004	Austin Energy	Holly (Texas)	138kV	-80 to +110MVar	ABB

3.3. SVC/STATCOM/UPFC COMPARISONS

The thyristor protected series compensation (TPSC), Thyristor Controlled series compensation (TCSC) are those FACTS devices that have a strong influence on the system stability and small or no influence on the voltage quality. The SVC and STATCOM have a strong influence on voltage quality improvement and show medium performance with respect to overall system stability. The unified power flow controllers (UPFC) have shown efficient performance in terms of load flow support, stability and voltage quality. The main objective in this thesis is to look for solutions to provide voltage stability to the system in order to operate wind turbines in accordance with the grid codes. The STATCOM is the best option available for providing efficient voltage quality in the power system.

A STATCOM is a shunt-connected reactive power compensation device that is capable of generating and/or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system. The STATCOM is a static compensator and is used to regulate voltage and to improve dynamic stability [20]. A STATCOM can supply the required reactive power under various operating conditions, to control the network voltage actively and thus, improve the steady state stability of the network. The STATCOM can be operated over its full output current range even at very low voltage levels and the maximum var generation or absorption changes linearly with the utility or ac system voltage.

The maximum compensating current of the SVC decreases linearly with the ac system voltage and the maximum var output decreases with the square of the voltage. This implies that for the same dynamic performance, a higher rating SVC is required when compared to that of a STATCOM. For an SVC, the maximum transient capacitive current is determined by the size of the capacitor and the magnitude of the ac system voltage. In the case of a STATCOM, the maximum transient capacitive overcurrent capability is determined by the maximum turn-off capability of the power semi-conductors employed. [19]

Figure 3.2 shows the schematic of SVC and its VI characteristics. Figure 3.3 shows the schematic of the STATCOM and its VI characteristics. The main function of a STATCOM is to provide reactive power support and thus improve voltage stability. The main objective of using a UPFC in a system is to be able to control both active and reactive power in the associated line in which it is placed. The STATCOM has better reactive power control than an SVC as seen in Figures 3.2 and 3.3.

Mechanically switched capacitors do not have a better performance at lower voltages and hence a higher rating device is needed for the same performance. Also, the reactive power support provided by the SVC is dependent on the ac system voltage and hence its capability is de-rated at lower voltages. The UPFC is not very economical and requires more complicated control techniques for exploiting its complete capabilities.

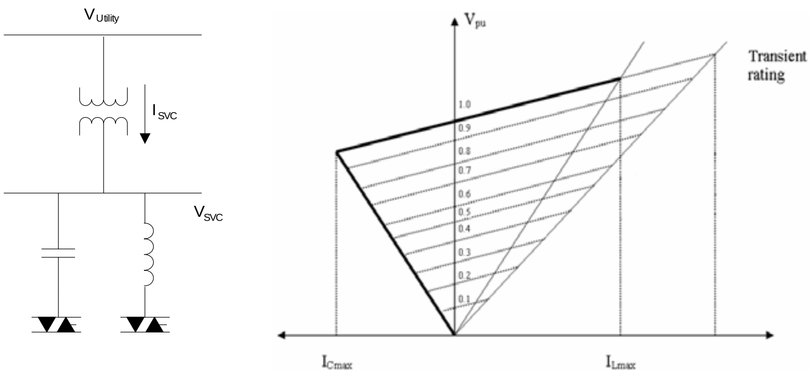

Figure 3.2. SVC and its VI characteristics

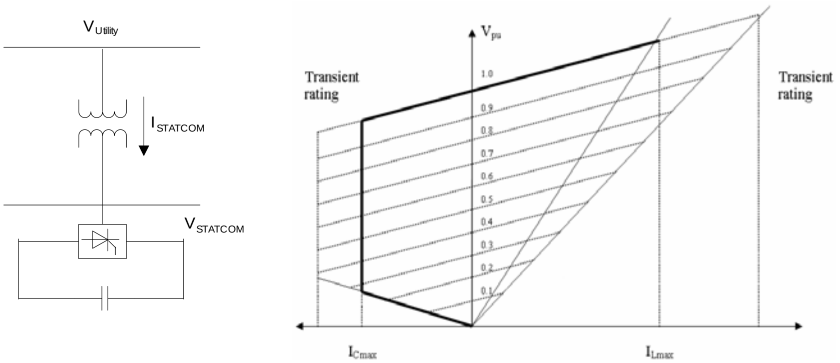

Figure 3.3. STATCOM and its VI characteristics

3.4. REASONS FOR CHOOSING A STATCOM

Capacitors are usually connected to fixed speed wind turbines to enhance the system voltage because they are a sink of reactive power. Mechanically switched fixed shunt capacitors can enhance the system's voltage stability limit, but is not very sensitive to voltage changes. Also, voltage regulated by the wind generators equipped with only fixed capacitors can become higher than the voltage limit of 1.05 pu. Hence, a fixed capacitor cannot serve as the only source of reactive power compensation.

One of the most important advantages of using STATCOM over a thyristor based SVC is that its compensating current is not dependent on the voltage level at the connection point which means that the compensating current is not lowered as the voltage drops [3].

The output of the wind power plants and the total load vary continuously throughout the day. Reactive power compensation is required to maintain normal voltage levels in the power system. Reactive power imbalances, which can seriously affect the power system, can be minimized by reactive power compensation devices such as the STATCOM. The STATCOM can also contribute to the low voltage ride through requirement because it can operate at full capacity even at lower voltages.

In this thesis, a voltage source converter (VSC) PWM technique based STATCOM is proposed to stabilize grid connected DFIG based wind turbines.

4. THE STATCOM

4.1. STATCOM MODEL

Figure 4.1 shows the basic model of a STATCOM which is connected to the ac system bus through a coupling transformer. In a STATCOM, the maximum compensating current is independent of system voltage, so it operates at full capacity even at low voltages. A STATCOM's advantages include flexible voltage control for power quality improvement, fast response, and applicability for use with high fluctuating loads.

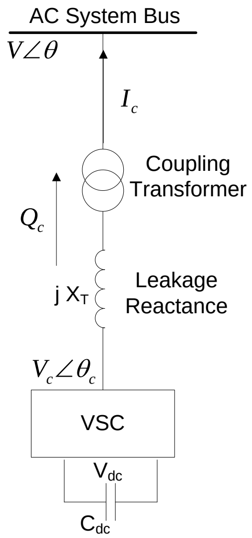

Figure 4.1. Basic model of a STATCOM

The output of the controller Q_c is controllable which is proportional to the voltage magnitude difference $(V_c - V)$ and is given by (2)

$$Q_c = \frac{V(V_c - V)}{X} \tag{2}$$

The shunt inverter, transformer and connection filter are the major components of a STATCOM. The control system employed in this system maintains the magnitude of the bus voltage constant by controlling the magnitude and/or phase shift of the voltage source converter's output voltage. By properly controlling i_q, reactive power exchange is achieved. The DC capacitor voltage is maintained at a constant value and this voltage error is used to determine the reference for the active power to be exchanged by the inverter.

The STATCOM is a static var generator whose output can be varied so as to maintain or control certain specific parameters of the electric power system. The STATCOM is a power electronic component that can be applied to the dynamic control of the reactive power and the grid voltage. The reactive output power of the compensator is varied to control the voltage at given transmission network terminals, thus maintaining the desired power flows during possible system disturbances and contingencies.

STATCOMs have the ability to address transient events at a faster rate and with better performance at lower voltages than a Static Voltage Compensator (SVC). The maximum compensation current in a STATCOM is independent of the system voltage. Overall, a STATCOM provides dynamic voltage control and power oscillation damping, and improves the system's transient stability. By controlling the phase angle, the flow of current between the converter and the ac system are controlled

A STATCOM was chosen as a source for reactive power support because it has the ability to continuously vary its susceptance while reacting fast and providing voltage support at a local node. Figure 4.2 show the block diagram of the STATCOM controller. The values for all the variables in the figure are presented in the appendix.

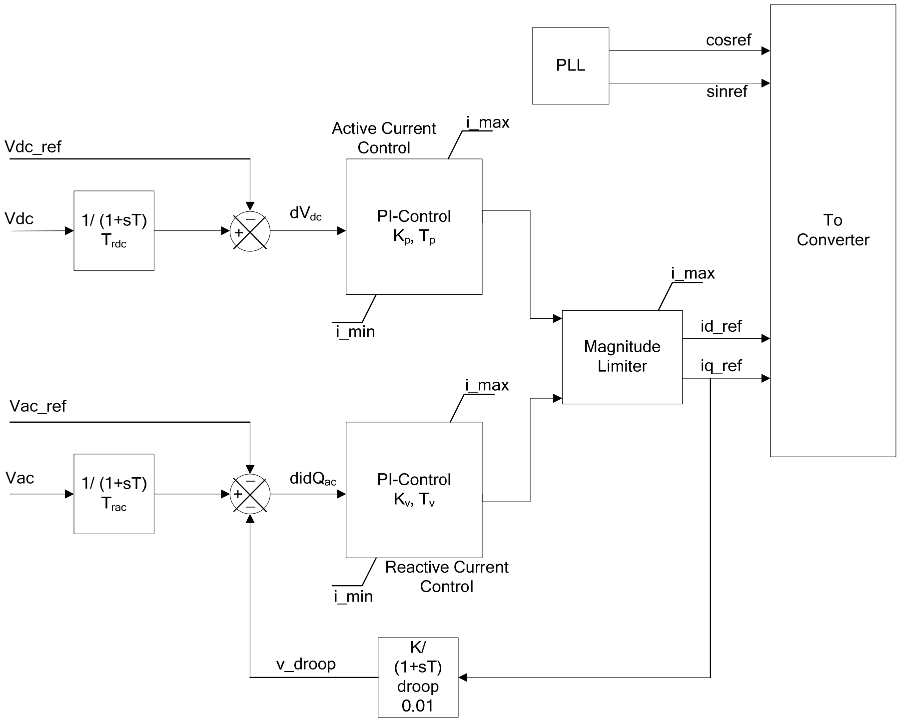

Figure 4.2. Control scheme of the STATCOM [DIgSILENT version 13.6]

By controlling the phase and magnitude of the STATCOM output voltage, the power exchange between the ac system and the STATCOM can be controlled effectively. The outputs of the controller are id_ref and iq_ref which are the reference currents in the dq coordinates which are needed to calculate the power injections by the STATCOM as in (3) and (4).

$$P_{inj} = V_i \left(i_d \cos\theta_i + i_q \sin\theta_i \right) = v_d i_d + v_q i_q \tag{3}$$

$$Q_{inj} = V_i \left(i_d \sin\theta_i - i_q \cos\theta_i \right) = -v_d i_q + v_q i_q \tag{4}$$

where i_d and i_q are the reference d and q axis currents of the ac system. The control variables are the current injected by the STATCOM and the reactive power injected into the system.

The STATCOM ratings are based on many parameters which are mostly governed by the amount of reactive power the system needs to recover and ride through typical faults on the power system and to reduce the interaction of other system equipment that can become out of synchronism with the grid. Although the final rating of the STATCOM is determined based on system economics, the capacity chosen will be at least adequate for the system to stabilize after temporary system disturbances. The type of faults that the system is expected to recover from also determines the size of the STATCOM. For example, a three phase impedance fault of low impedance requires a very high rating STATCOM while a high impedance short circuit fault needs a lower rating device to support the system during the fault and help recover after the fault. The converter current ratings and the size of the capacitor also decide the capability of the STATCOM.

The STATCOM can be connected to the system at any voltage level by using a coupling transformer. The devices in a voltage source converter are clamped against over-voltages across the DC link capacitor bank to minimize losses and not have to withstand large spikes in reverse over-voltage.

4.2. LOCATION OF STATCOM

Simulation results show that STATCOM provides effective voltage support at the bus to which it is connected to. The STATCOM is placed as close as possible to the load bus for various reasons. The first reason is that the location of the reactive power support should be as close as possible to the point at which the support is needed. Secondly, in the studied test system the location of the STATCOM at the load bus is more appropriate because the effect of voltage change is the highest at this point.

The location of the STATCOM is based on quantitative benefits evaluation. The main benefits of using a STATCOM in the system are reduced losses and increased maximum transfer capability. The location of STATCOM is generally chosen to be the location in the system which needs reactive power. To place a STATCOM at any load bus reduces the reactive power flow through the lines, thus, reducing line current and also the I^2R losses. Shipping of reactive power at low voltages in a system running close to its stability limit is not very efficient. Also, the total amount of reactive power transfer available will be influenced by the transmission line power factor limiting factors. Hence, sources and compensation devices are always kept as close as possible to the load as the ratio $\left|\frac{\Delta V}{V_{nom}}\right|$ will be higher for the load bus under fault conditions.

4.3. REACTIVE POWER SUPPORT FROM STATCOM

The amount of reactive power supplied by any compensating device depends on the voltage drop at the bus and its capabilities. For example, a STATCOM can supply its maximum rated compensating current even at lower voltages. The rating of the STATCOM also decides the maximum reactive power that can be supplied, but usually they have some extra capability called the transient capability which is available to the system for a short period of time. The reactive power supplied is also dependent on the immediate reactive power sources in the system. The size of the wind turbine and the synchronous machine also influences on the reactive power capability.

5. TEST SYSTEM AND SIMULATION RESULTS

5.1. TEST SYSTEM

To evaluate the voltage support provided by a STATCOM which is connected to a weak grid, simulations have been performed in DIgSILENT Version 13.6. Figure 5.1 shows the test system that includes a load supplied by the local synchronous generator as well as from the installed wind turbines (DFIG). The power system is studied to evaluate the system performance under different transient conditions such as a three phase fault, a sudden load change, and temporary tripping of a wind turbine in a wind farm.

The values and ratings of system components are presented in the Appendix. The system voltage rating is 30 kV and every transmission line has an impedance of 0.06+j0.6 ohms. Two DFIGs operating under similar conditions are connected to a common bus called the collector bus. The system is connected to an external grid whose short circuit capacity is 50 MVA, i.e., it is a weak grid and cannot respond to system disturbances. The total system has a load of 18 MW and 2 Mvar connected at bus 3 (the load bus). The DFIG WTs operate at close to unity power factor and hence the reactive power generated from these machines is almost zero. The total demanded reactive power is therefore mostly generated by the synchronous generator. The active power of the load is shared by the WTs and the synchronous generator. As per the previous analysis, a STATCOM, an active voltage supporter, is connected to the load bus and the mechanically switched capacitors (MSC) will also be connected to the same bus. The STATCOM is connected to the system via a 0.4 kV/30 kV transformer. MSC with a 30 Mvar capacity is connected to the system during contingencies.

Synchronous generators respond immediately to system disturbances while due to their complex control it is difficult to make wind turbines respond in a similar fashion. Hence, additional system equipment is required to help maintain the power grid to be stable during and after a disturbance. The proposed test system has two types of generators - a DFIG and a synchronous generator. Under normal operating conditions, the synchronous generator is not operating at its full capacity to accommodate for power reserve in the system.

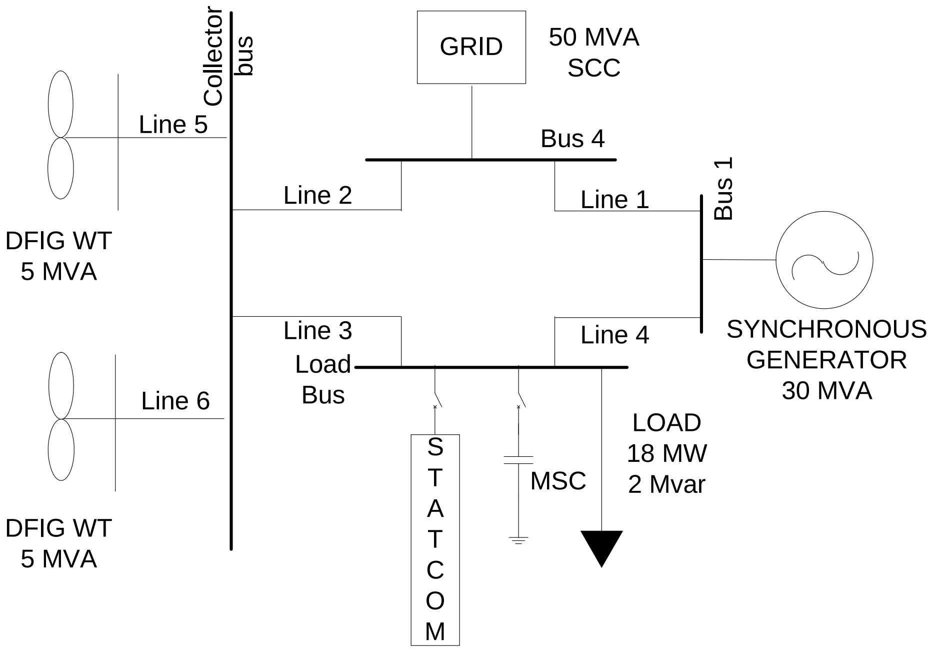

Figure 5.1. Test system

The grid represents an external system which is connected to the system of interest through a weak link. The intent to force the generator and STATCOM only, and not the grid to respond to faults in the area of interest. The low short circuit capacity of the connected electric power grid implies that this is a weak grid and thus requires a compensating device of a higher rating. One of the objectives of this thesis is to evaluate the specific needs of the system to restore to its initial state as quickly as possible after fault clearing.

The source of reactive power is always connected as close to the point where it is required and this is the main motivation for connecting the STATCOM at the load bus. This is specifically done to facilitate the effective operation of the STATCOM and to avoid excessive interaction of the connected power system. Also, mechanically switched capacitors are relatively inexpensive and are used for slow changes in the reactive power but ideally reactive power requirement changes continuously and hence a controller is required to adjust the reactive power level.

The different cases studied on this test system are (i) small duration high impedance three phase faults, (ii) a sudden temporary change in the load, and (iii) tripping of a wind turbine. The results are presented in the corresponding sections and discussions are mentioned therein.

5.2. SIMULATION RESULTS

5.2.1. Three phase impedance ground faults.

The effect of a three phase high impedance (X_f=5Ω) short circuit fault at the load bus is studied. The ground fault is initiated at t=0.4 sec and cleared at t=0.6 sec. The system is studied under five different conditions at the load bus: (i) without a compensating device, (ii) with mechanically switched capacitors, (iii) with a STATCOM with a rating of 25 MVA, (iv) with an MSC and a STATCOM, and (v) a STATCOM with a rating of 125 MVA. The study evaluates voltages during the fault, voltage recovery time, voltage overshoot at recovery, and the settling time.

Figure 5.2 shows the voltage at the load bus or the fault bus for the five different operating conditions discussed earlier. Without any compensating device, the voltage takes a long time to recover after the fault has been cleared - a condition that does not meet some stringent grid codes for certain transmission operators. Figure 5.3 shows the zoomed version of the load bus voltages where it is observed that the voltage during the fault, and overshoot at recovery is the highest in the case of system using 125 MVA STATCOM. It also has the fastest response time.

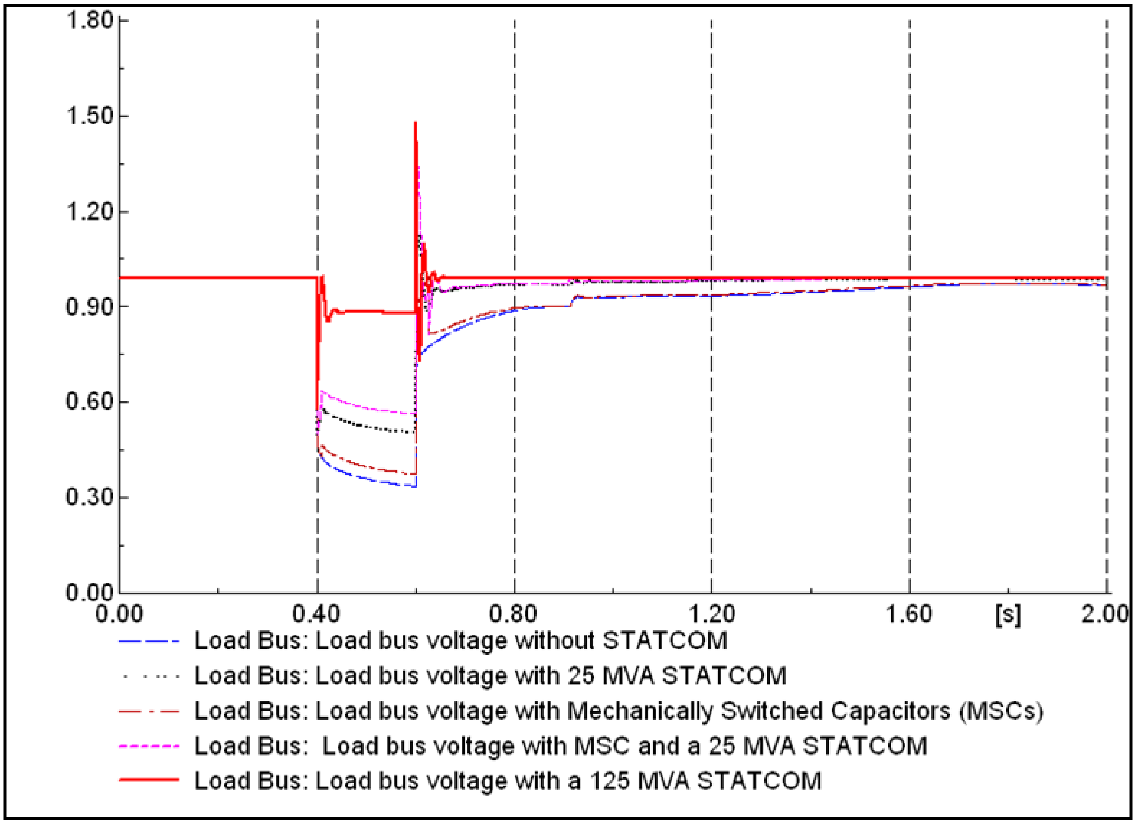

Figure 5.2. Voltage at the fault bus (Load bus)

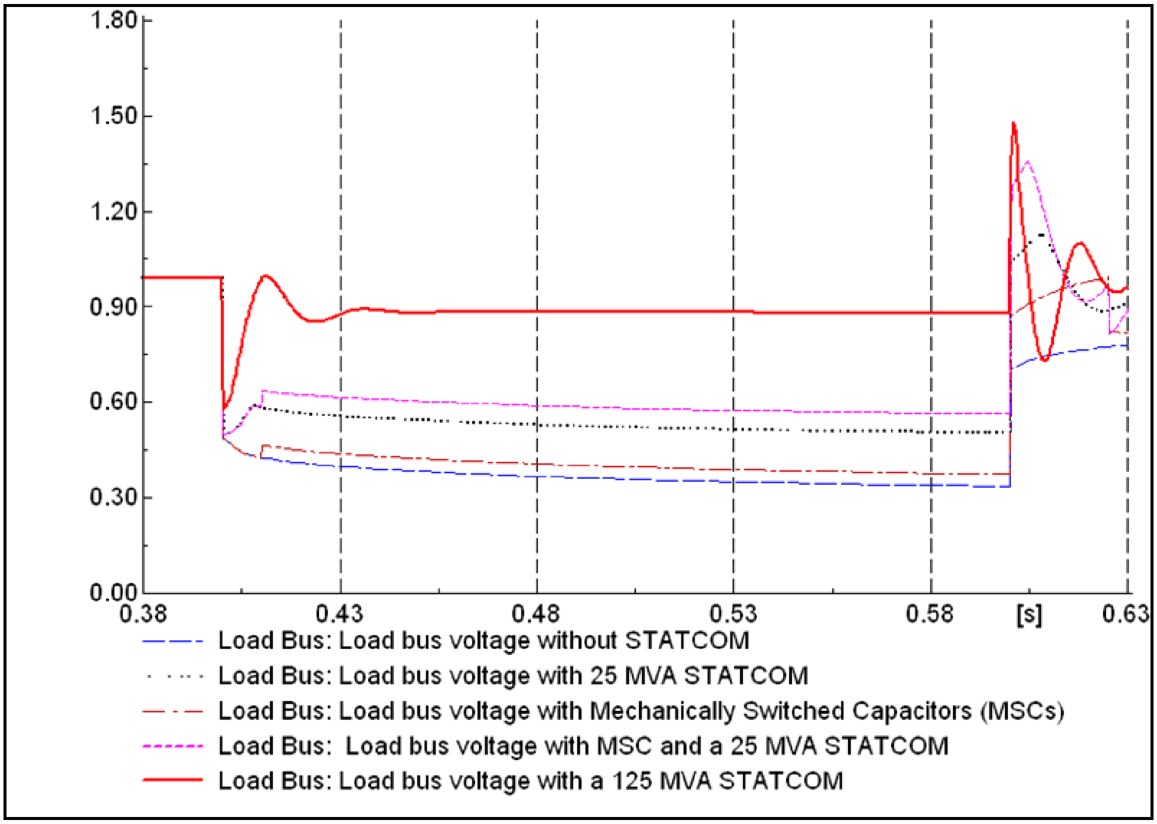

Figure 5.3. Voltage at the fault bus (Zoomed version)

Figures 5.4 and 5.5 shows the synchronous generator bus voltage and its zoomed version respectively under the same five distinct conditions. The time that this voltage takes to recover is longer than that of the load bus voltage as it has to supply some reactive power to the system to help stabilize the voltages at different buses of the system. The case with the high rating STATCOM yields the best performance. The DFIG operates normally even during the faulted conditions as the total reactive power demand is provided only by the STATCOM and the system is not overly stressed. In the other cases, the synchronous machine also has to respond to supply some of the reactive power required. DFIG protection is triggered if the rotor side converter currents exceed a threshold value, thus shorting the RSC connections by impedance so that it becomes an induction generator. The rotor protection scheme called "crowbar" protection is removed once the rotor currents return to normal. Figures 5.6 and 5.7 show the collector bus voltage and its zoomed version respectively under the same five conditions. It can be observed that there is a voltage overshoot at recovery for every case where a STATCOM is used. The case with only mechanically switched capacitors does not exhibit any overshoot during recovery but they do have a longer recovery time.

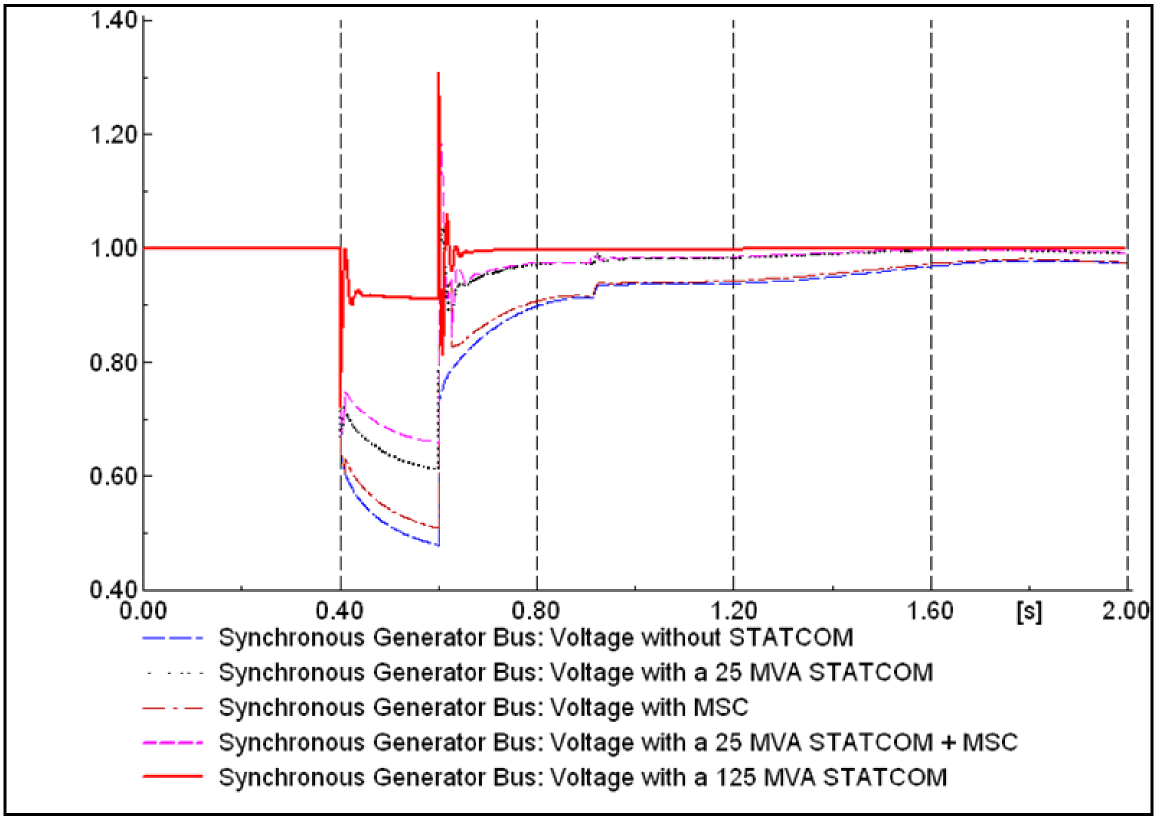

Figure 5.4. Voltage at the synchronous generator bus

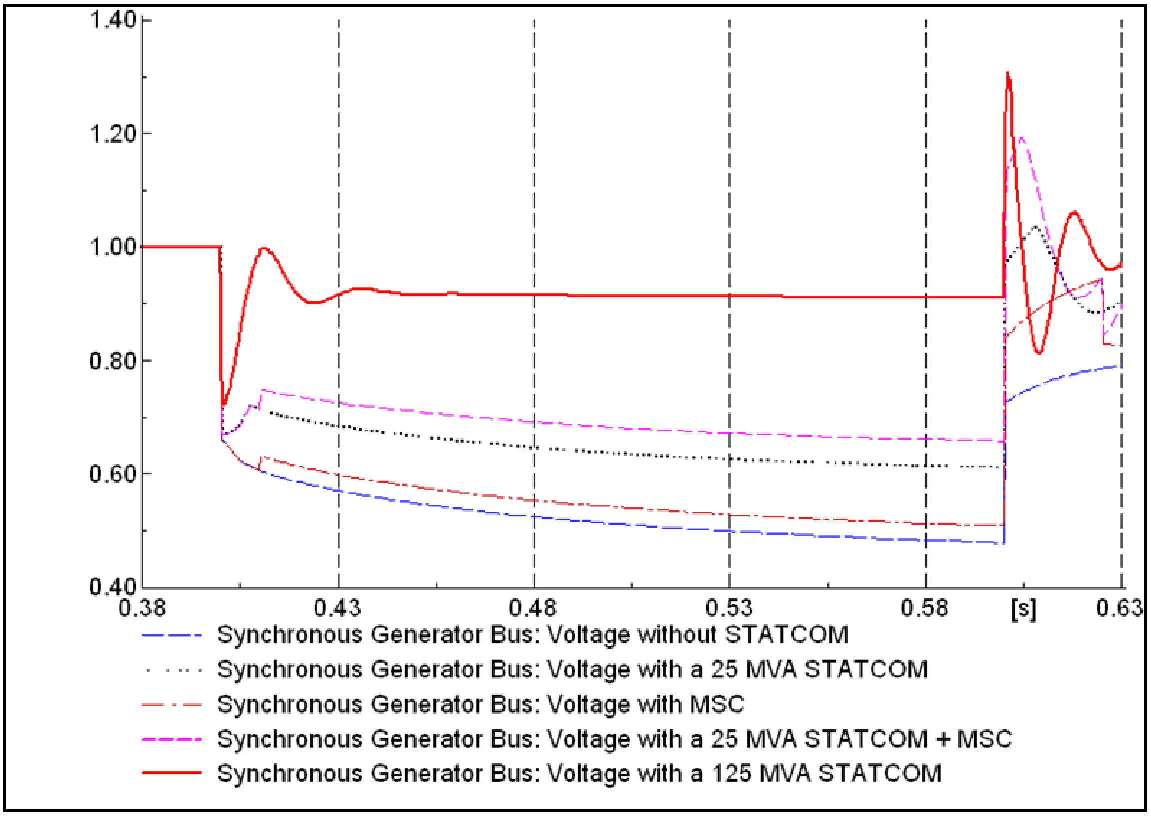

Figure 5.5. Voltage at the Synchronous generator bus (Zoomed version)

The compensating devices will be connected to the load bus as the ratio $\left|\frac{\Delta V}{V_{nom}}\right|$ is the maximum for this bus. The voltage at the generator terminals (both the synchronous generator and the DFIG) is also depressed due to the voltage drop at the load bus with the reactive current flowing into the load bus. Table 5.1 tabulates this ratio for the different buses of the system.

Table 5.1 Ratio $\left|\frac{\Delta V}{V_{nom}}\right|$ at different buses

Bus	***Ratio***
Synchronous generator bus	*0.5210*
Collector bus	*0.5998*
Load bus	***0.6611***

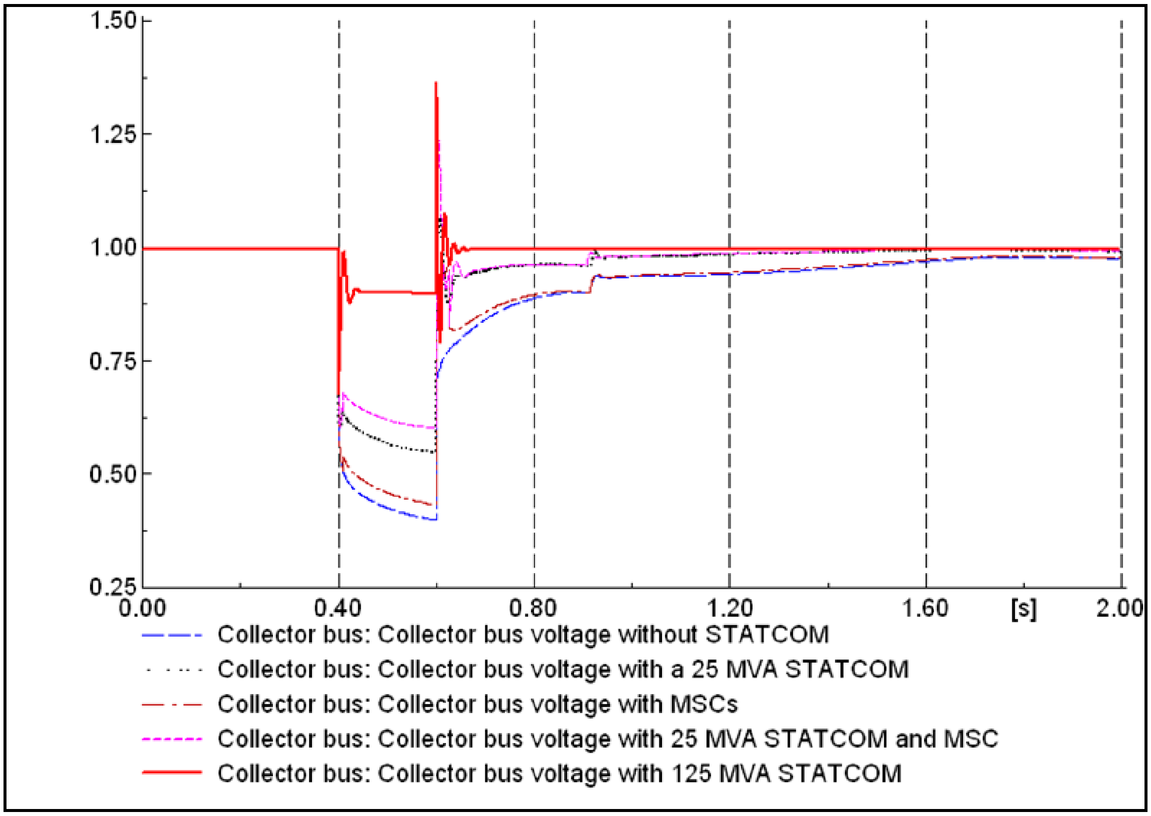

Figure 5.6. Voltage at the collector bus

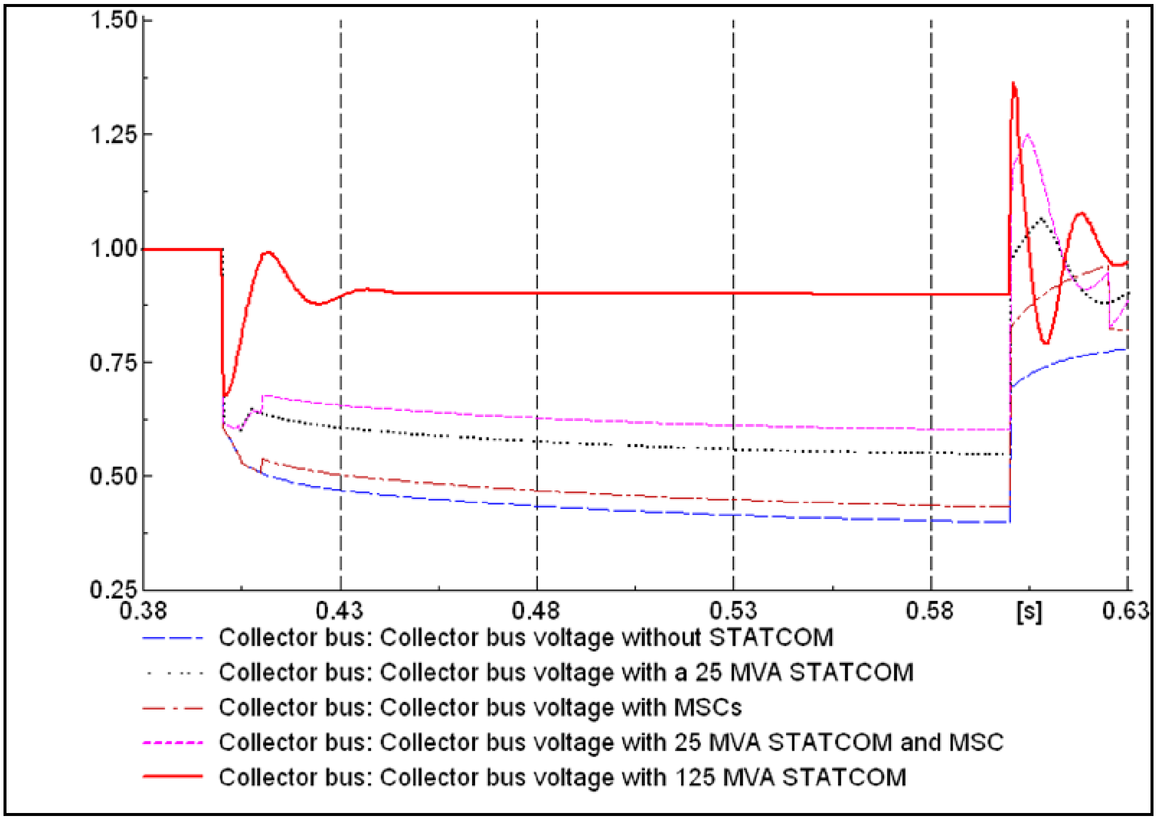

Figure 5.7. Voltage at the collector bus (Zoomed version)

5.2.1.1 Without STATCOM. Figure 5.8 shows the reactive power in the system with no compensating device. When the fault occurs at t=0.4 sec, the synchronous generator immediately responds by supplying the maximum possible reactive power to support system voltages. The reactive power supplied by the synchronous generator slowly decreases during the fault period as the voltage decreases at the load bus. The support provided by the external grid is constant during the fault period which depends on the total required reactive power. At t=0.4044 sec, crowbar protection is triggered in the system, thus, short circuiting the rotor windings of the DFIG, making it a conventional induction generator. These wind turbines now operating as squirrel cage induction generators start to absorb reactive power from the system. The crowbar protection is removed at t=0.9144 sec and the RSC is re-activated. After the DFIG operation starts again, the reactive powers are restored to those steady state values before the occurrence of the fault.

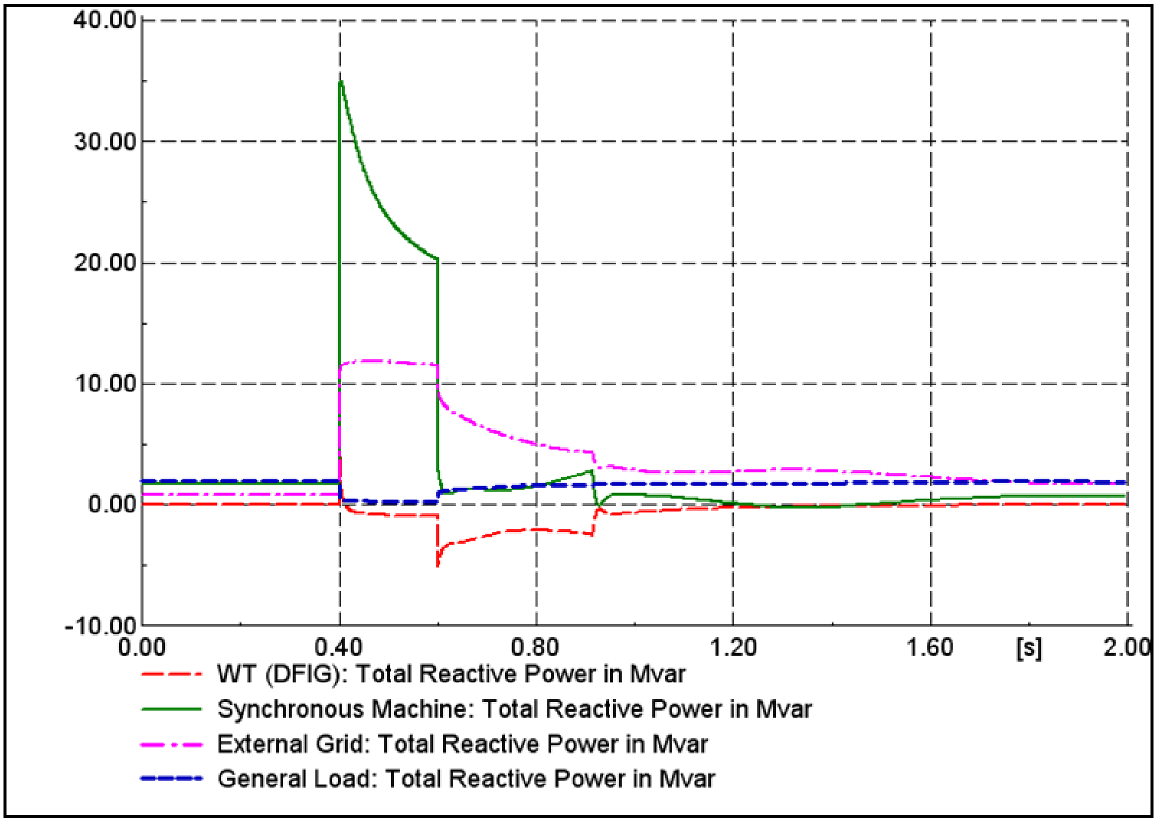

Figure 5.8. Reactive power in the system with no compensating device

5.2.1.2 With a mechanically switched capacitor. Figure 5.9 show the reactive powers of the system with MSC (25 MVA) connected at the load bus. Whenever the load bus voltage drops below its nominal value, the MSC is switched ON and reactive power is supplied by the MSC as shown in Figure 5.10. At t=0.4 sec, a three phase short circuit impedance fault (X_f = 5 ohms) occurs at the load bus. The synchronous machine starts to supply reactive power in order to help the system sustain the voltage variations. The reactive power supplied by the synchronous generator is very high due to excessive available reserve capacity. The external grid also supplies a constant amount of Q to improve the voltage stability of the system. The WT operates in a manner similar to its operation during the system without any compensating devices. At t=0.41 sec, the MSC is connected and it supplies the reactive power as in equation (3). Q_{MSC} is proportional to the square of the voltage at the fault bus. The reactive power supplied by the MSC decreases with the voltage at the fault bus decreasing during the fault.

$$Q_{MSC} = \frac{V^2}{X_{cap}} \tag{3}$$

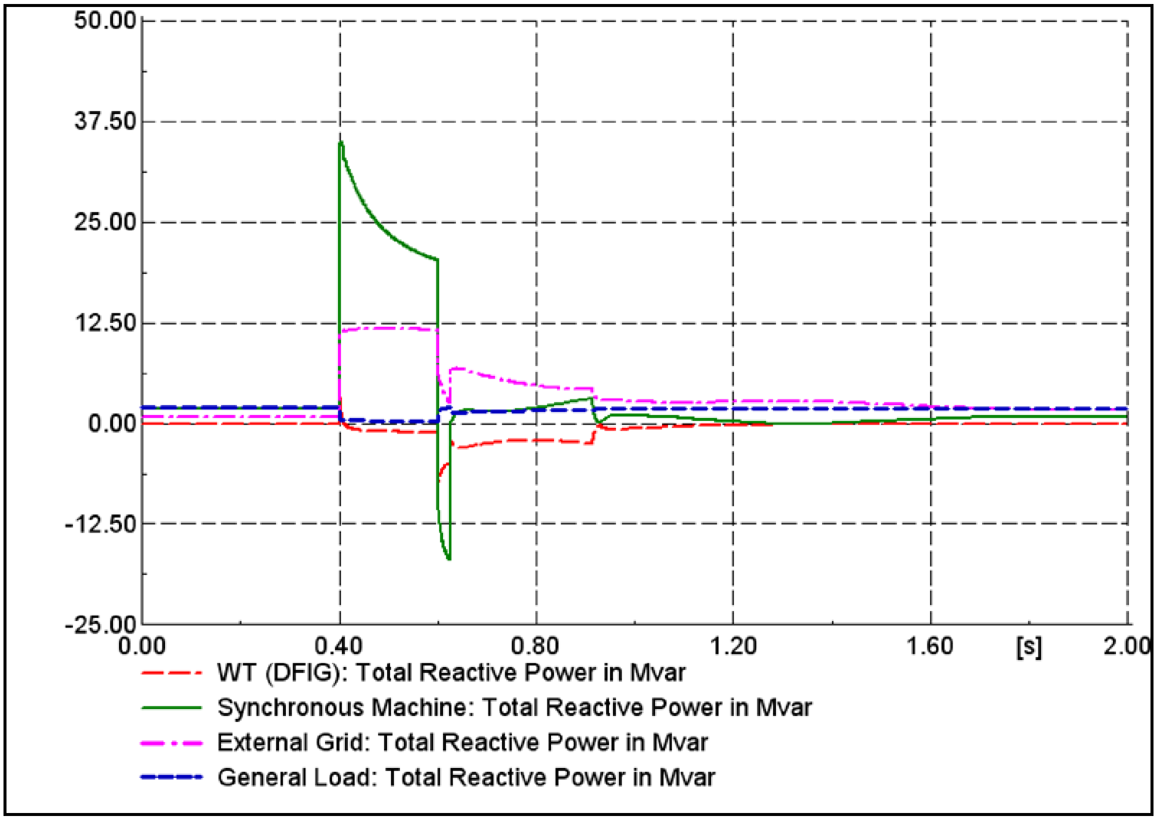

Figure 5.9. Reactive power in the system with mechanically switched capacitors

At t=0.6 sec, the three phase short circuit fault is cleared and the system starts to recover from the fault. The load bus voltage is improved when compared to same without any compensating device. The voltage rises and Q_{MSC} overshoots to a value close to its rated capacity. At t=0.61 sec, the MSC is disconnected from the system at which time Q_{MSC} is zero. At t=0.914 sec, crowbar protection is disconnected from the wind turbine system.

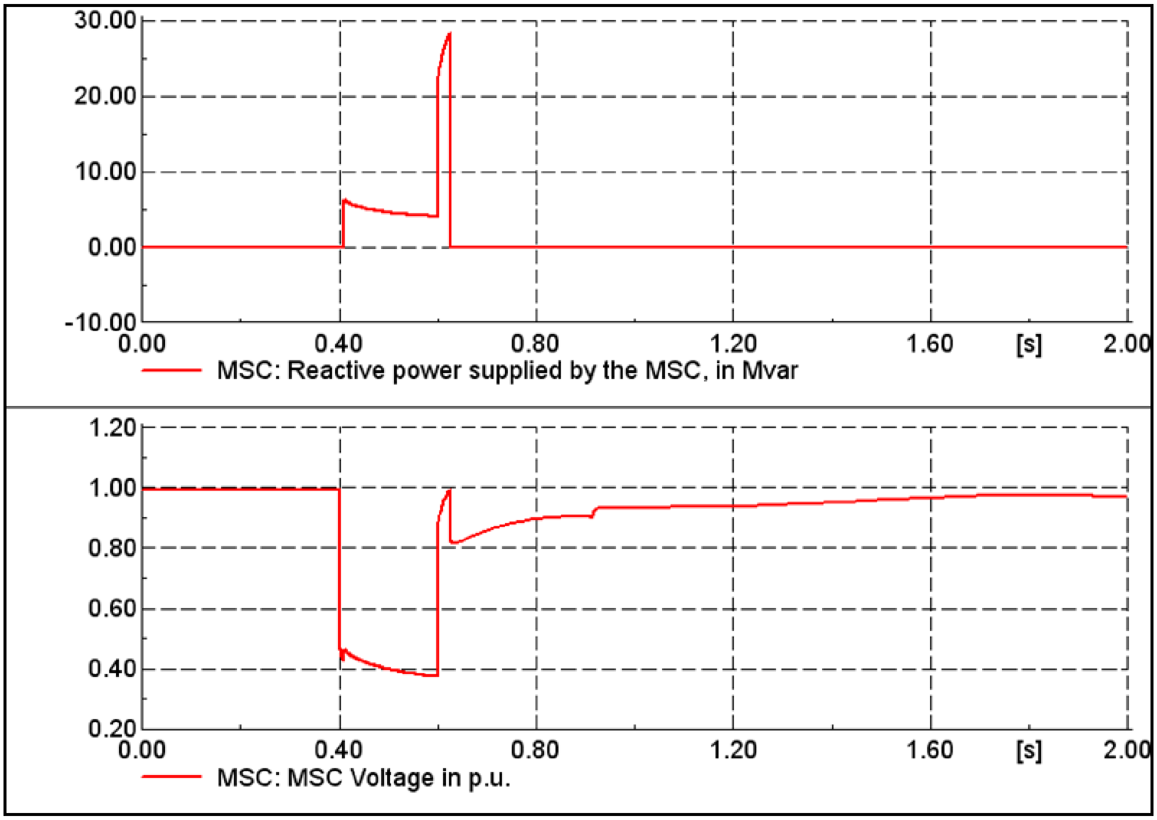

Figure 5.10. Reactive power supplied by the MSC and the MSC terminal voltage

5.2.1.3 With 25 MVA STATCOM. Figures 5.11 show the reactive power and the active power of the STATCOM. Figure 5.12 shows the ac and dc terminal voltages of the STATCOM. At t=0.4 sec, a three phase high impedance short circuit fault occurs at the load bus. The voltage at the fault bus drops depending on the fault location and the fault impedance. This initiates the operation of the STATCOM. The drop in the terminal voltage determines the amount of reactive power needed. The STATCOM can operate at full capacity even at low voltages. The STATCOM in this case supplies its rated reactive power to support the load bus voltage. From t=0.6 sec when the fault has been cleared to the point where the system completely recovers, the STATCOM helps the RSC to return to full operation.

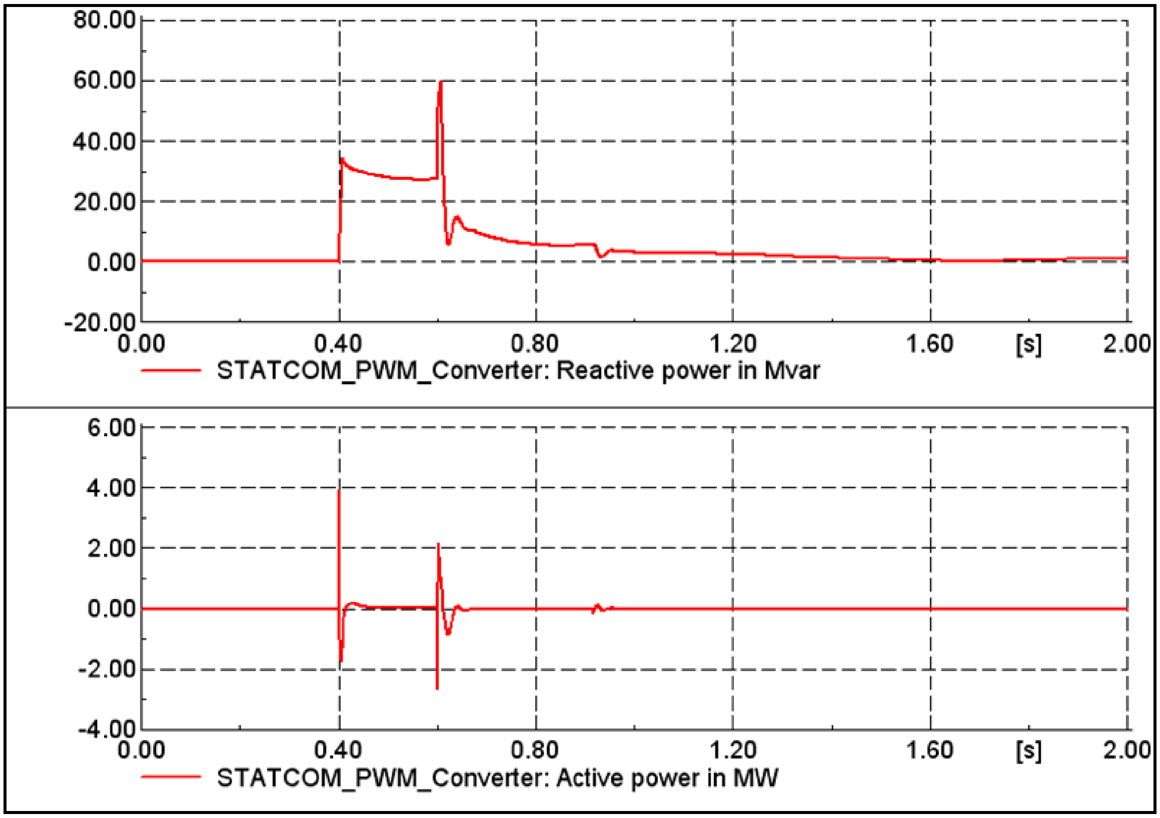

Figure 5.11. Reactive power and active power of the STATCOM

At t=0.6 sec, when the fault is cleared, the voltage rises and the reactive power provided by the STATCOM overshoots. This transient can be ignored as it is well within the limit and the current carrying limits of the STATCOM. As the dc voltage of the STATCOM observes a transient, a small amount of real power exchange occurs at t=0.4 sec and also at t=0.6 sec. The value of the dc busbar voltage of the STATCOM can be maintained stiff by properly choosing the values of K_p and T_p of the controller.

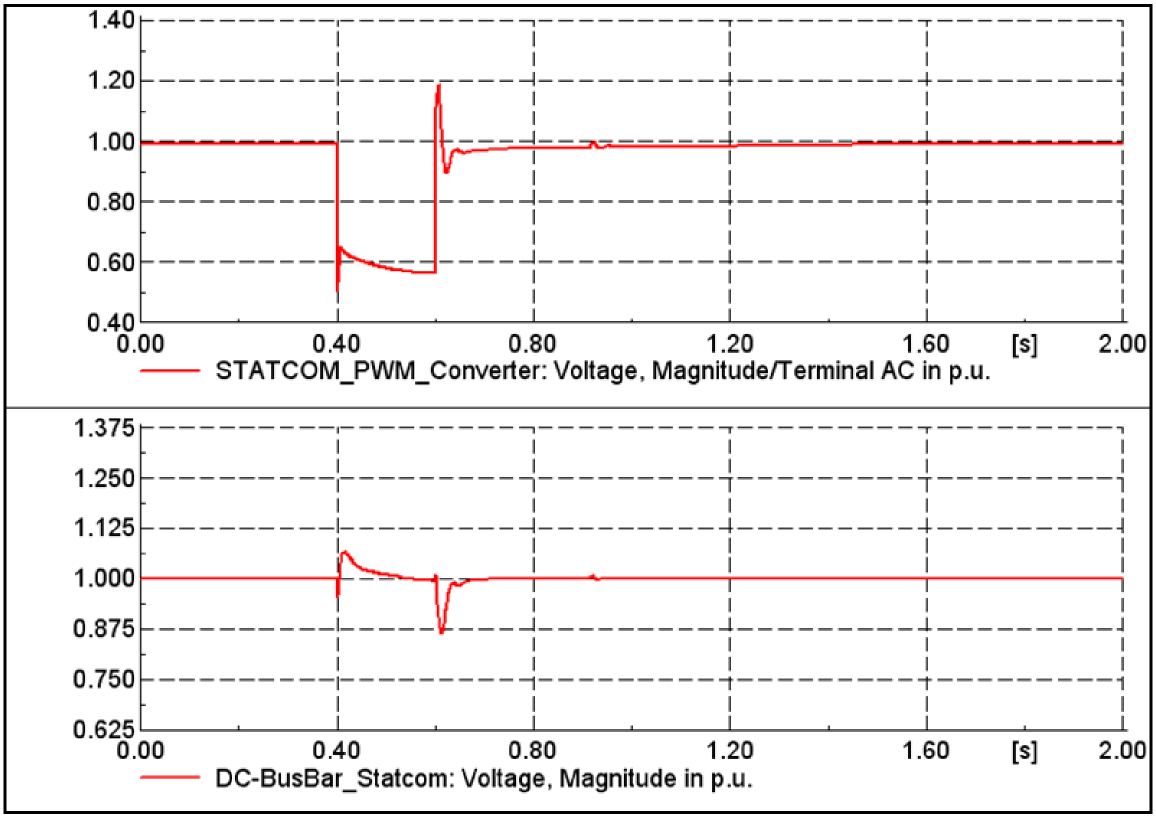

Figure 5.12. AC and DC busbar voltages of the STATCOM

Figure 5.13 show the reactive powers in the system with a 25 MVA STATCOM. Whenever the rotor current exceeds its rated value (at t=0.404 sec), the converter protection shorts the RSC with an impedance, at which time the DFIG becomes a conventional induction generator. The DFIG then absorbs reactive power from the power network, which is necessary for the generator excitation. The control of the RSC is now inactive and dynamic reactive compensation must be incorporated near the wind farm connection point to meet the reactive power demands. The additional dynamic reactive power compensation helps reduce the voltage drop at grid faults and performs dynamic reactive power control.

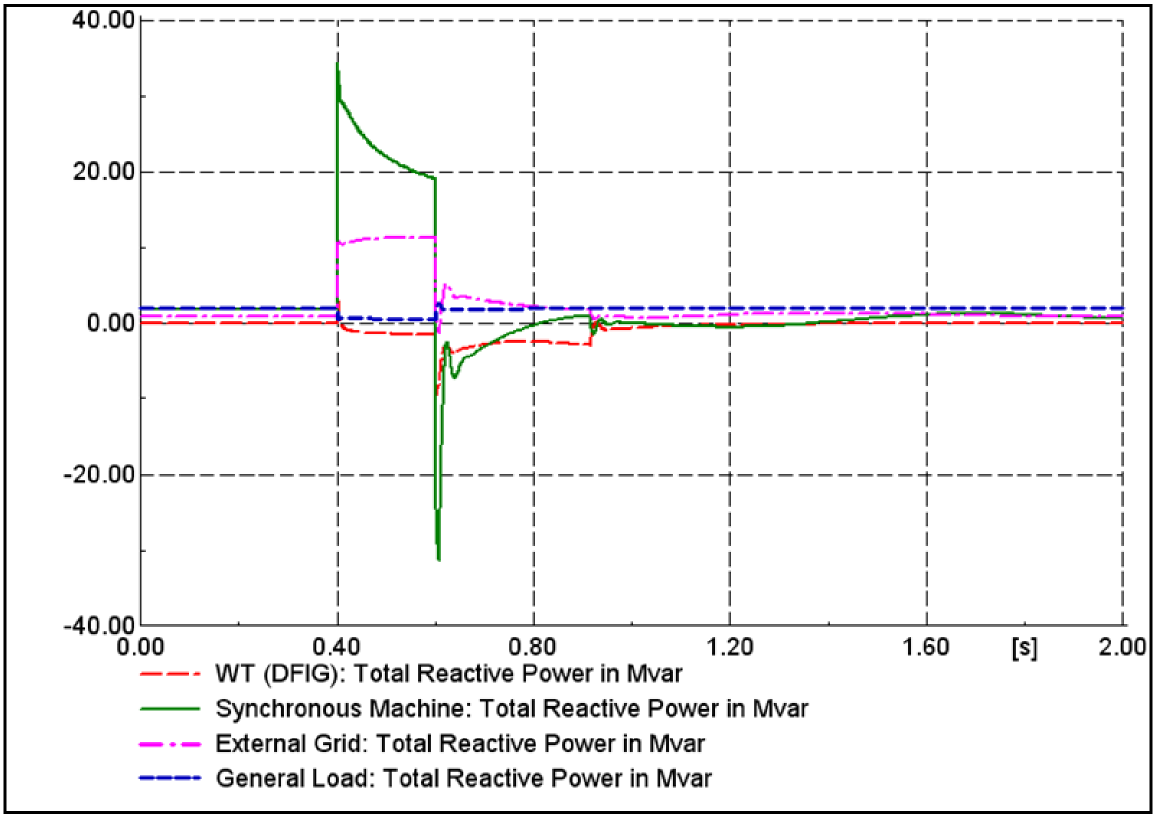

Figure 5.13. Reactive powers in the system with a 25 MVA STATCOM

5.2.1.4 With 25 MVA STATCOM and MSC. Figure 5.14 show the reactive and active powers of the STATCOM. The transient overshoot in the reactive power can be ignored as it within the ratings of the system. At t= 0.61 sec, the MSC is connected, which starts to supply reactive power and the amount shared by the STATCOM is slightly decreased during the fault duration. The voltage increases and the controlled reactive power supplied is to help the RSC to restore operation quickly. The slight transient overshoot in voltage at t=0.41 sec and t= 0.61 sec is due to the interaction of the MSC.

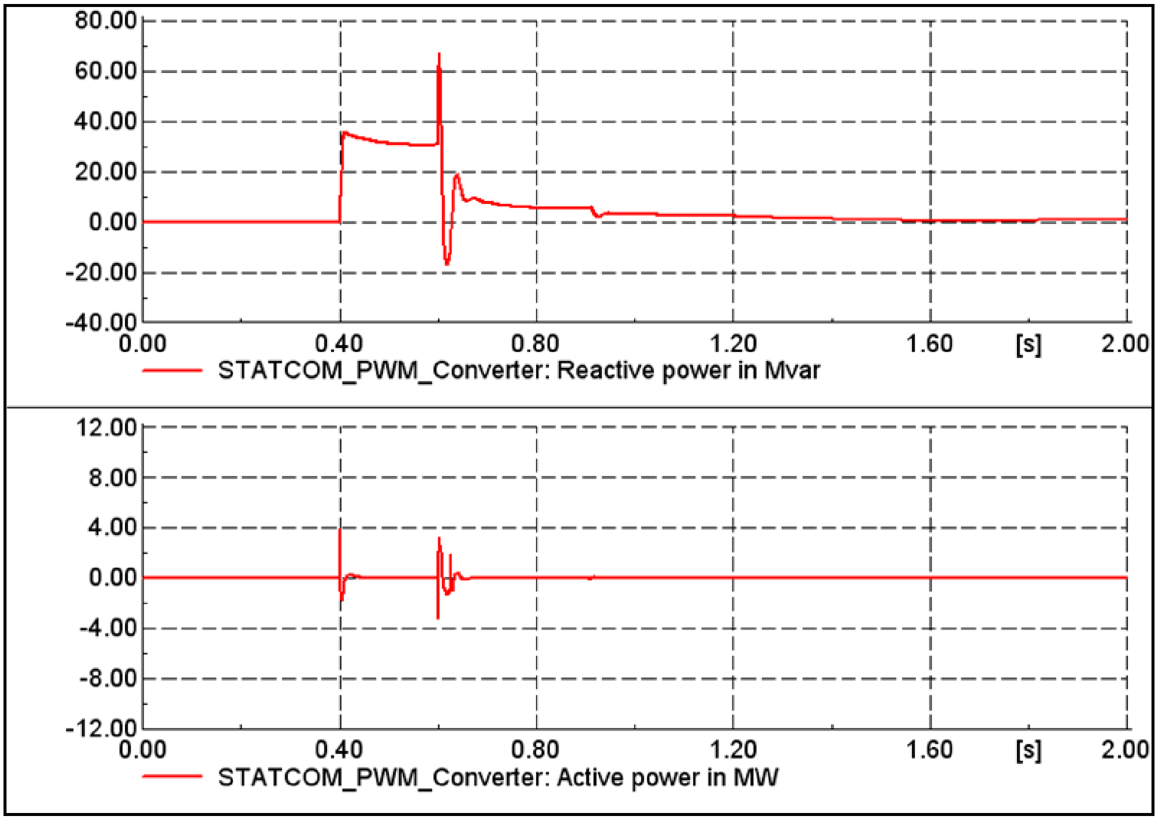

Figure 5.14. Reactive and active powers of the STATCOM

Figure 5.15 show the reactive power and the terminal voltage of the MSC. The peak overshoot between t=0.6 sec and t =0.61 sec in the reactive power is due to the sudden increase in voltage at the fault bus due to fault clearing. The terminal voltage of the MSC will follow the load bus voltage. Figure 5.16 show the ac and dc terminal voltages of the STATCOM.

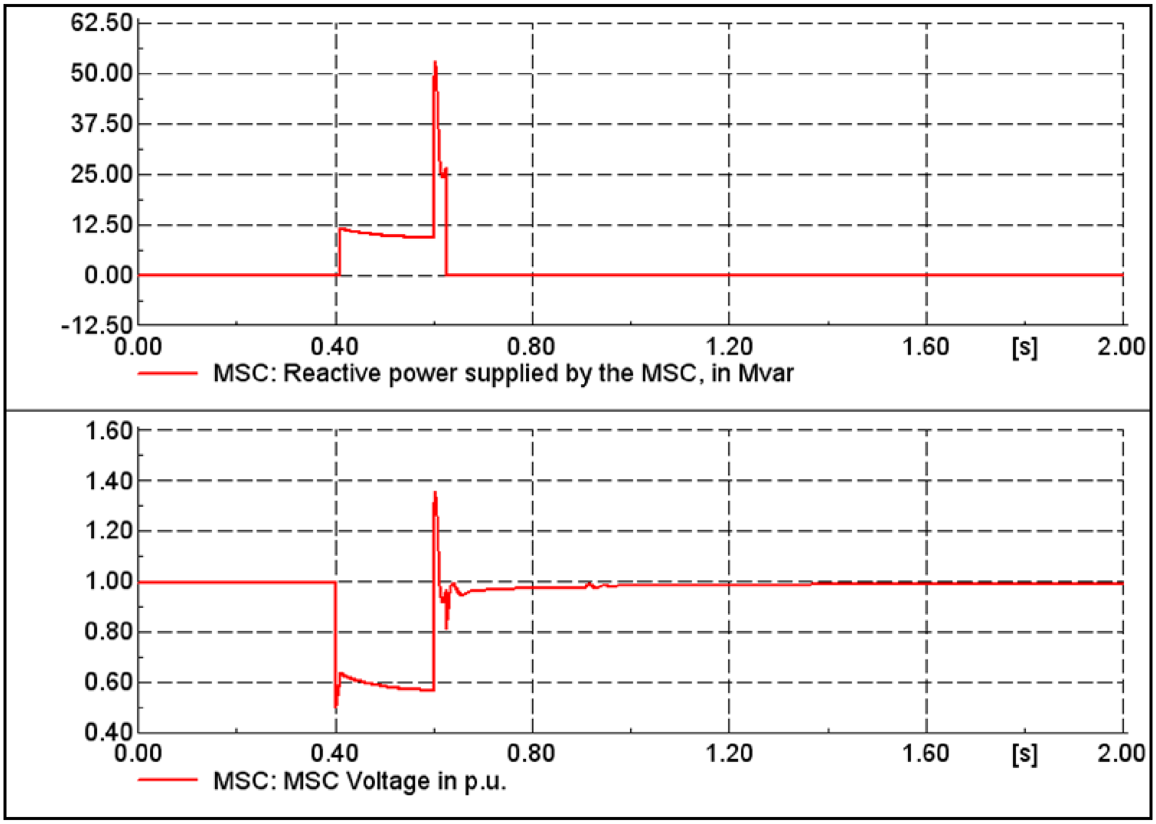

Figure 5.15. Reactive power and terminal voltage of the MSC

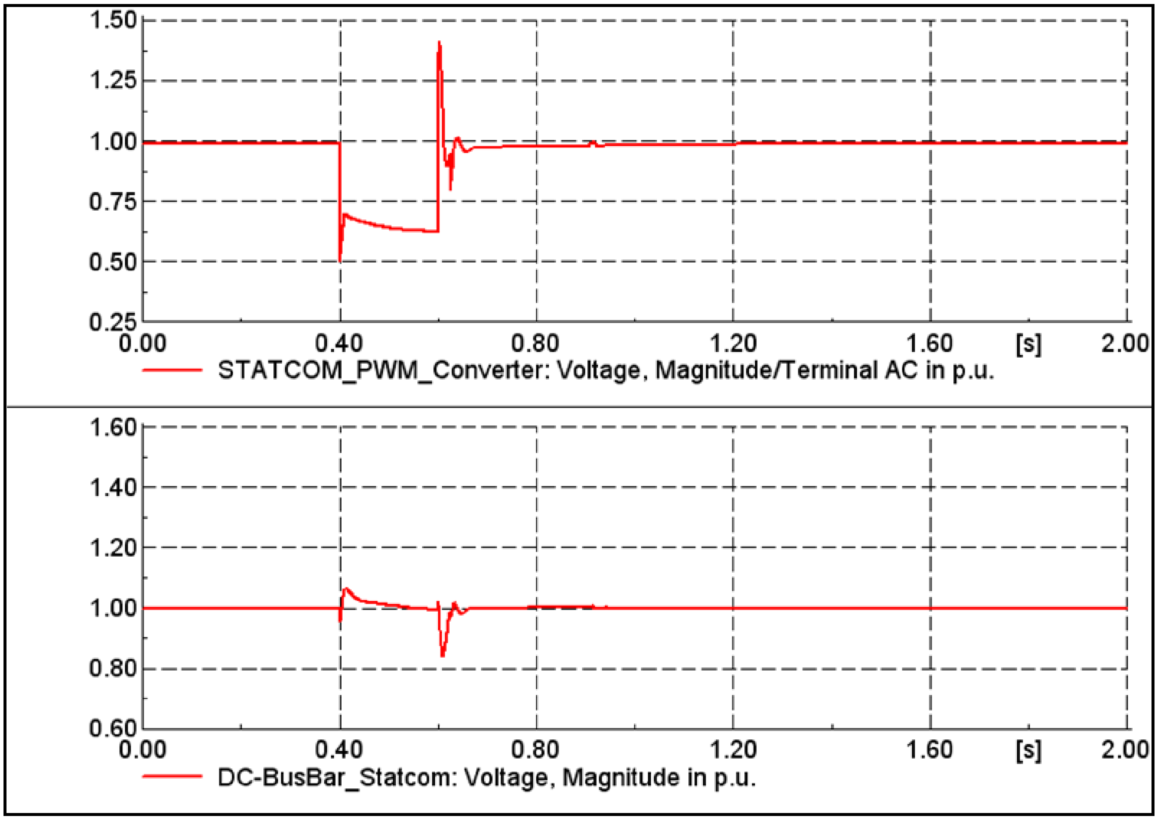

Figure 5.16. AC and DC busbar voltages of the STATCOM

Figure 5.17 show the reactive powers in the system with a STATCOM and MSC. After the crowbar protection is removed the system reactive power reaches its steady state value within a few milliseconds.

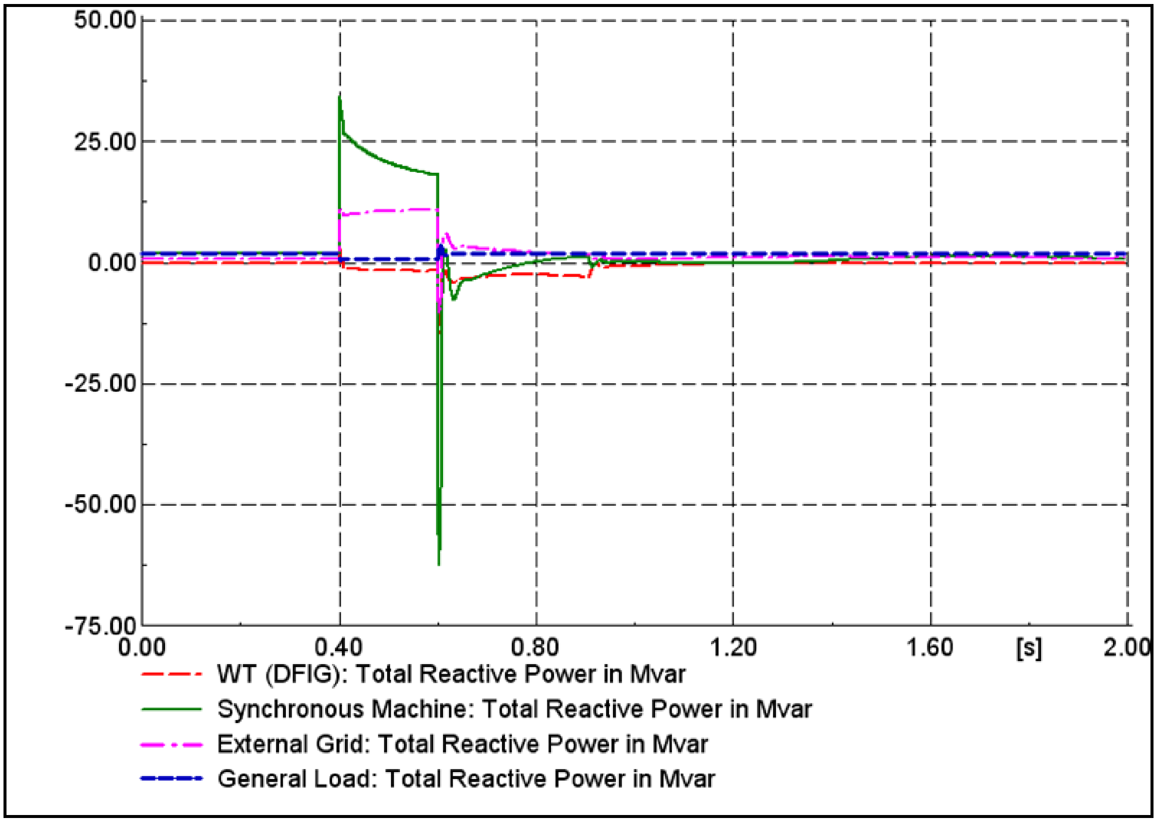

Figure 5.17. Reactive powers of the system with a STATCOM and MSC

5.2.1.5 With 125 MVA STATCOM: The reactive power of the 125 MVA STATCOM is shown in Figure 5.18. The total amount of reactive power required by a system during a fault is decided by the fault impedance and the fault's location. In this specific case, the total amount of reactive power required to boost the voltage to 0.9 pu is about 145 MVA. The 125 MVA STATCOM operates at its full capacity and the synchronous machine supplies the remaining reactive power needed. The ac and dc terminal voltages of the STATCOM are shown in Figure 5.19. The synchronous machine absorbs the reactive power transients as shown in Figure 5.20.

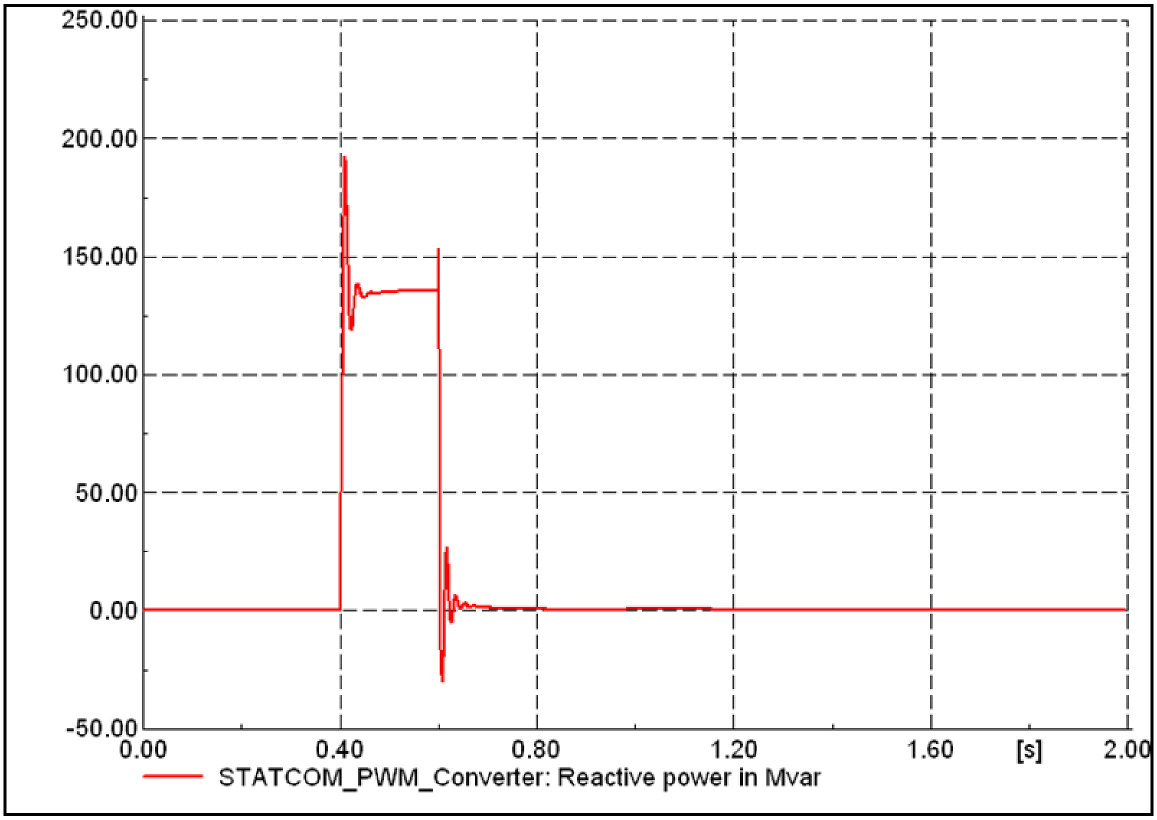

Figure 5.18. Reactive power of the 125 MVA STATCOM

In this case, the STATCOM responds by supplying regulated reactive power. The rotor currents are not exceeded and thus, crowbar protection is not activated. The system is restored to its pre-fault level immediately after the fault has been cleared. The DFIG operation does not change and the STATCOM helps in quick restoration of system voltages. The operation with a high rating device poses issues like temporary overshoot which necessitates the need for protection against temporary overvoltages and currents.

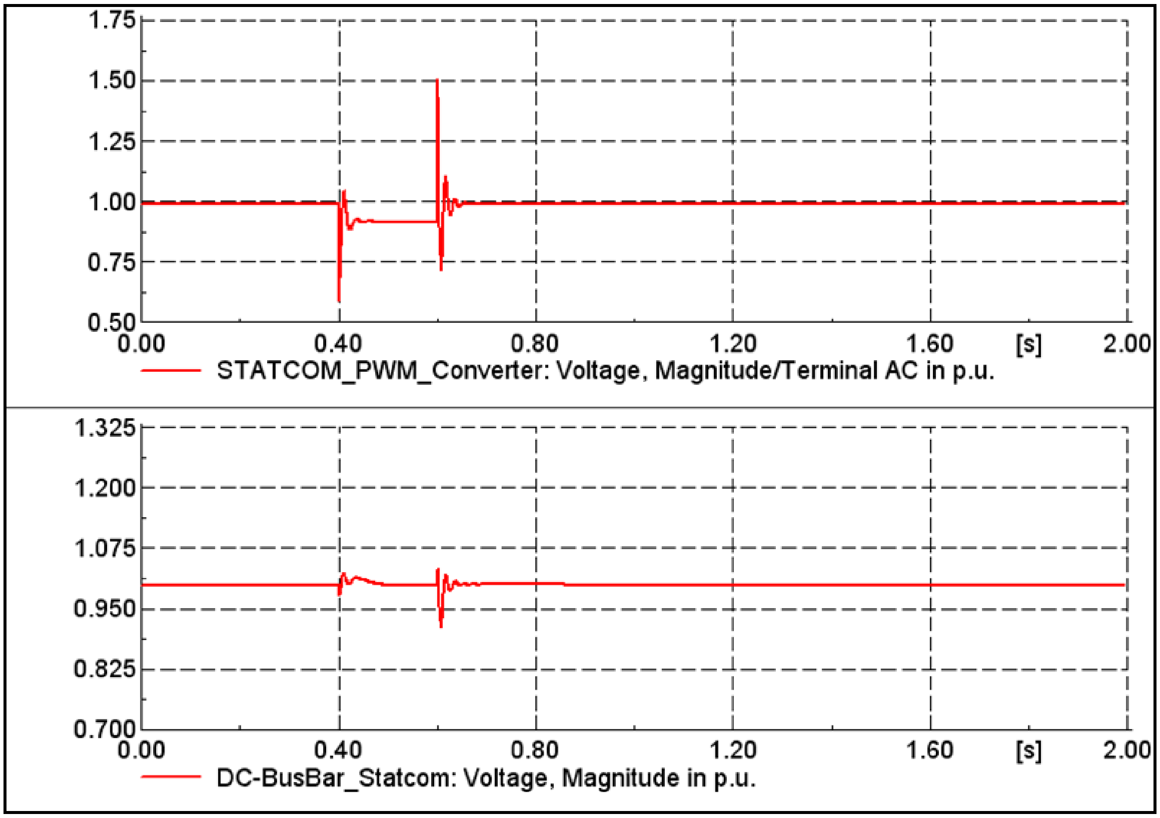

Figure 5.19. AC and DC busbar voltages of the 125 MVA STATCOM

It is observed that the voltage of the wind turbine and the load bus do not recover even after the fault is cleared. With the use of a STATCOM, the voltage profile during the fault has been improved and moreover the wind turbine's terminal voltage has been improved. The use of a higher rating STATCOM improves the voltage drop during the fault and has better voltage recovery after the fault. This enables the continuous connection of the wind farm to the grid and in accordance with the grid codes.

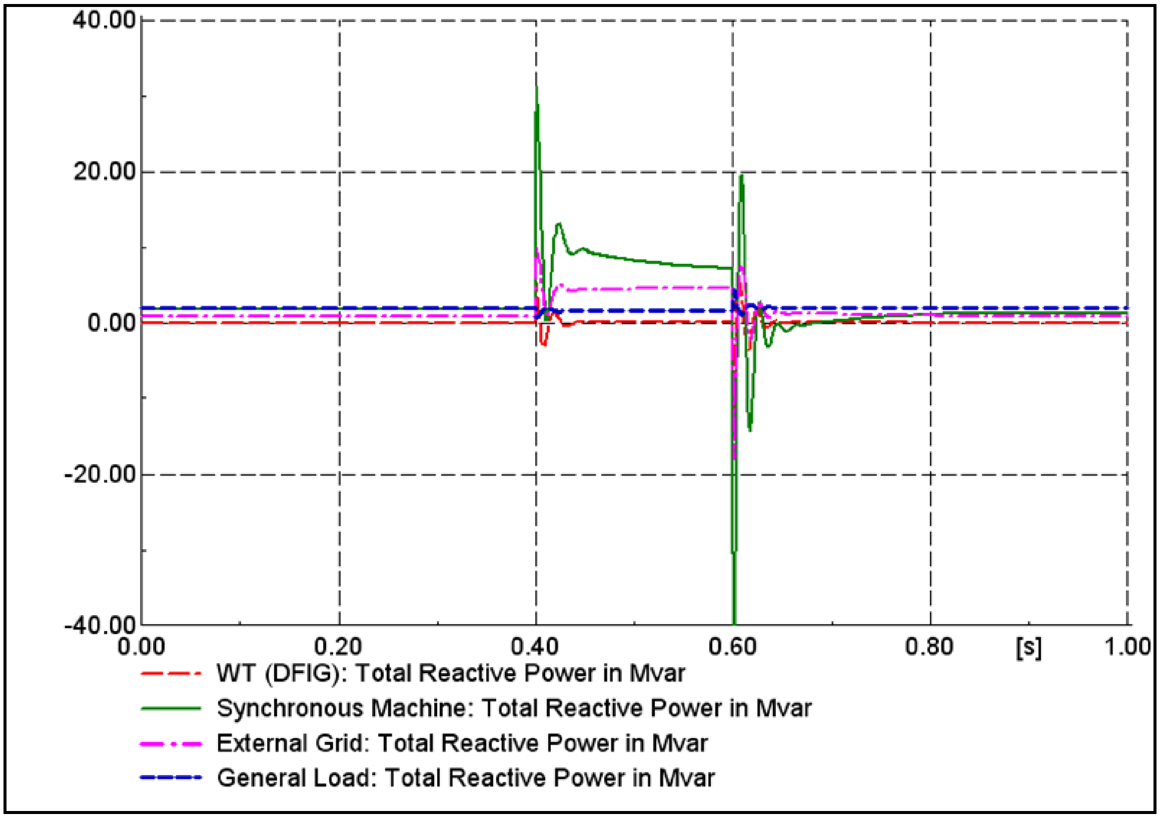

Figure 5.20. Reactive powers of the system with a STATCOM and MSC

In terms of voltage profile during the fault, the performance of the system is best with the 125 MVA STATCOM and worst in the case when the system has no additional compensation. This identifies the need for some form of a compensating device in the power system with wind generation. The voltage overshoot at recovery is very high in the case of a 125 MVA STATCOM which requires that some over voltage clamp or protection be connected. The voltages in the system take a long time to stabilize after fault clearing in the case of no STATCOM which clearly indicates that a STATCOM in the system improves the response time as well as system stability.

5.2.2. Load changes. The applicability of STATCOM to provide support during sudden load changes is studied next. The four cases studied are: a sudden short duration 50% change (+50% and -50%) in the reactive power load, and a sudden 10% change in real power and 50% change in reactive power are studied.

5.2.2.1 50% negative step change in reactive load. In this case, a sudden temporary step reactive load change is studied. At t=0.4 sec, the reactive load is decreased by 50% which is reversed at t=0.6 sec. This particular case is studied because the STATCOM acts like a reactive power reserve and can be used to absorb/produce the incremental reactive power demand. This system has the ability to react effectively to sudden load changes when the STATCOM is connected to the system. Figure 5.21 shows the load bus voltage of the system with and without the STATCOM.

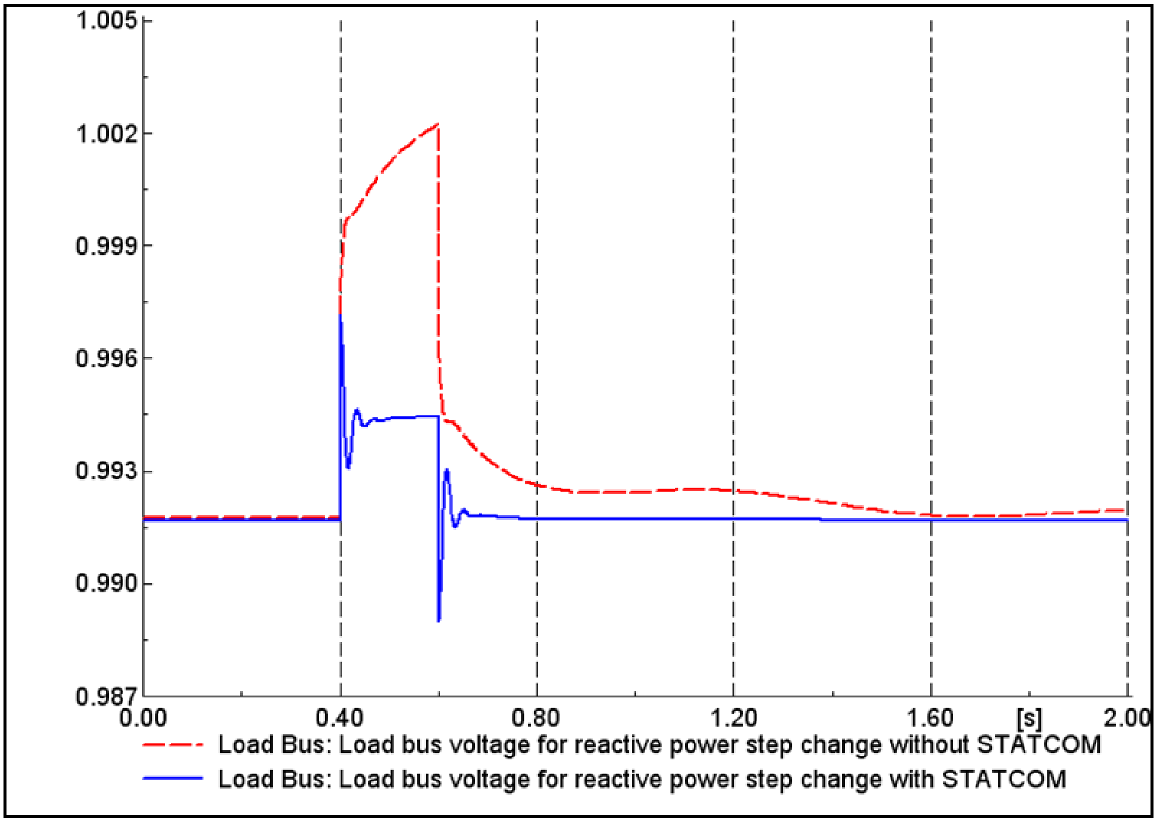

Figure 5.21. Load bus voltages

When there is a sudden reactive power load rejection, the voltage at the bus rises and the ac bus voltage of the STATCOM also rises as seen in Figure 5.22. The excess reactive power is absorbed by the STATCOM as seen in Figure 5.23. With the use of a STATCOM, a better voltage profile is obtained in the system as it limits the over voltage and also assists in the immediate voltage recovery after the load change has been reversed.

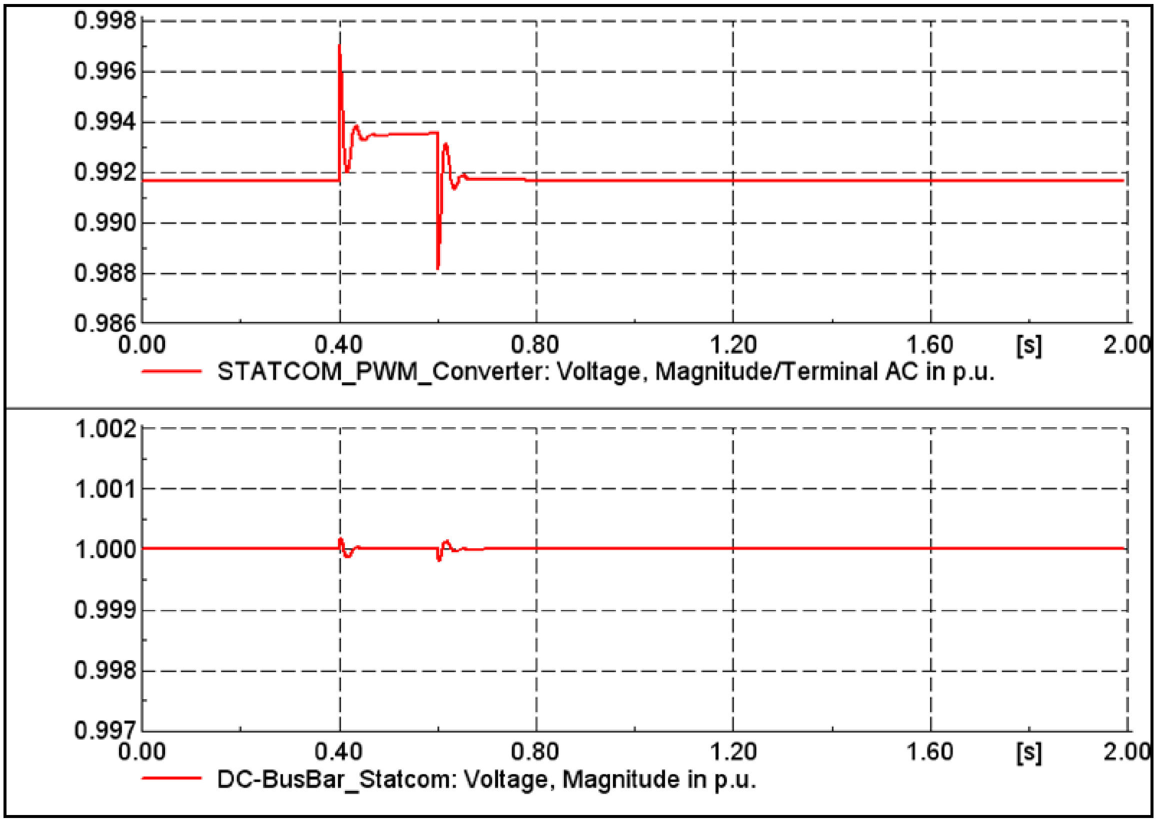

Figure 5.22. AC and DC busbar voltages of the 25 MVA STATCOM

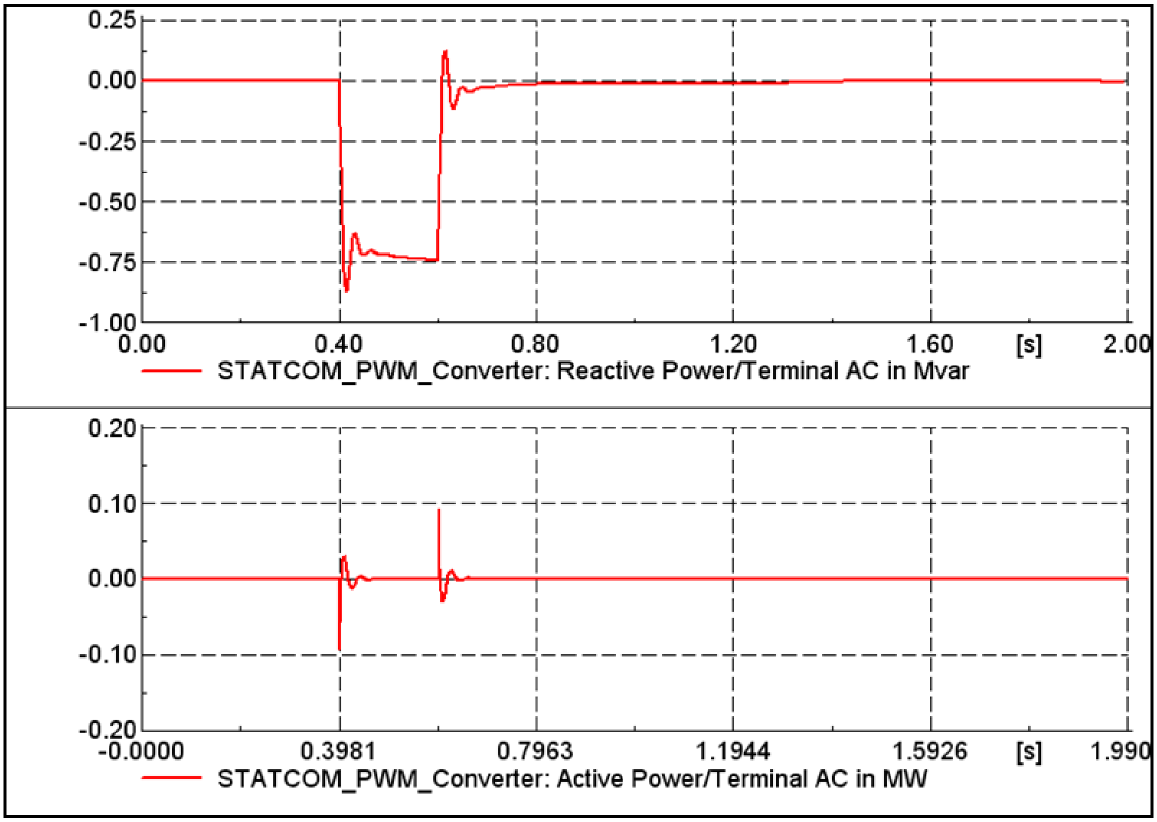

Figure 5.23. Reactive and active powers of the STATCOM

5.2.2.2 50% positive step change in reactive load. In this case, a sudden temporary step reactive load change is studied. At t=0.4 sec, the reactive load is increased by 50% which is reversed at t=0.6 sec. Figure 5.24 shows the load bus voltage of the system with and without the STATCOM.

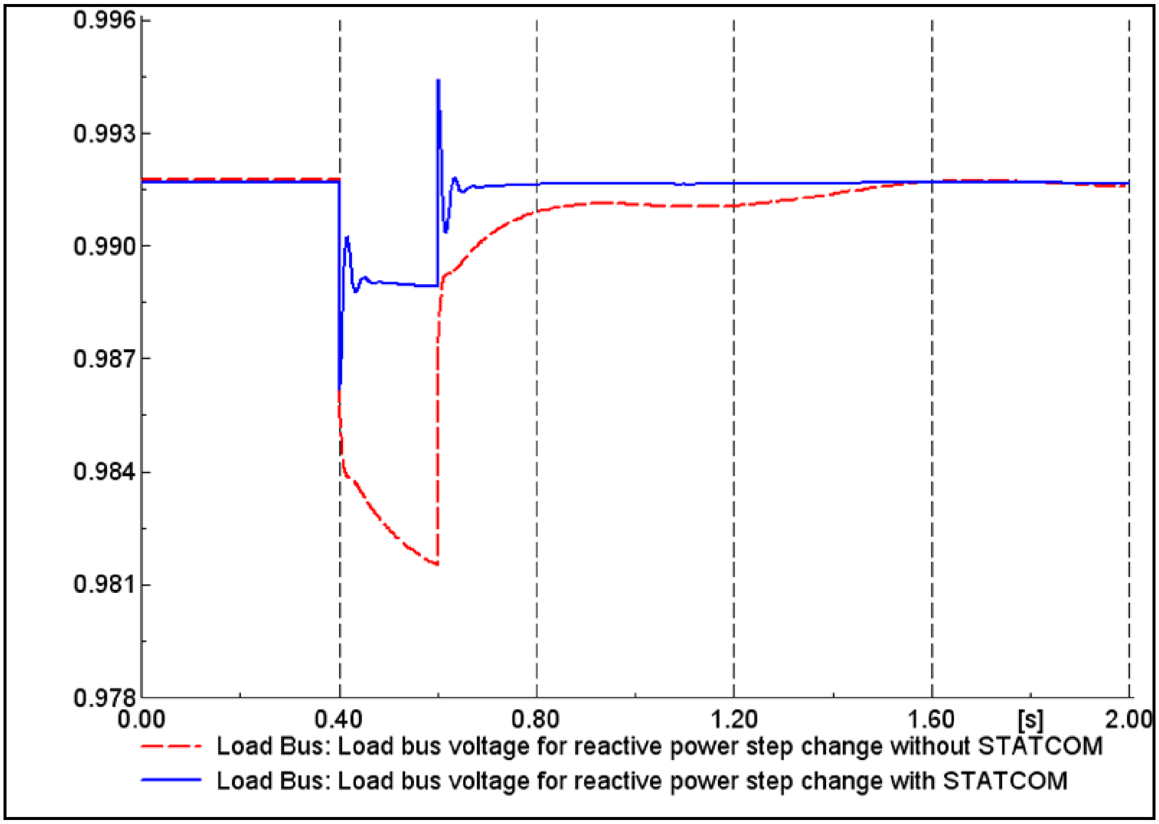

Figure 5.24. Load bus voltages

When there is a sudden increase in the reactive power load demand, the voltage at the bus drops and the ac bus voltage of the STATCOM drops as seen in Figure 5.25. The required reactive power is supplied by the STATCOM as shown in Figure 5.26. The STATCOM improves the voltage characteristics of the system during and after the load change.

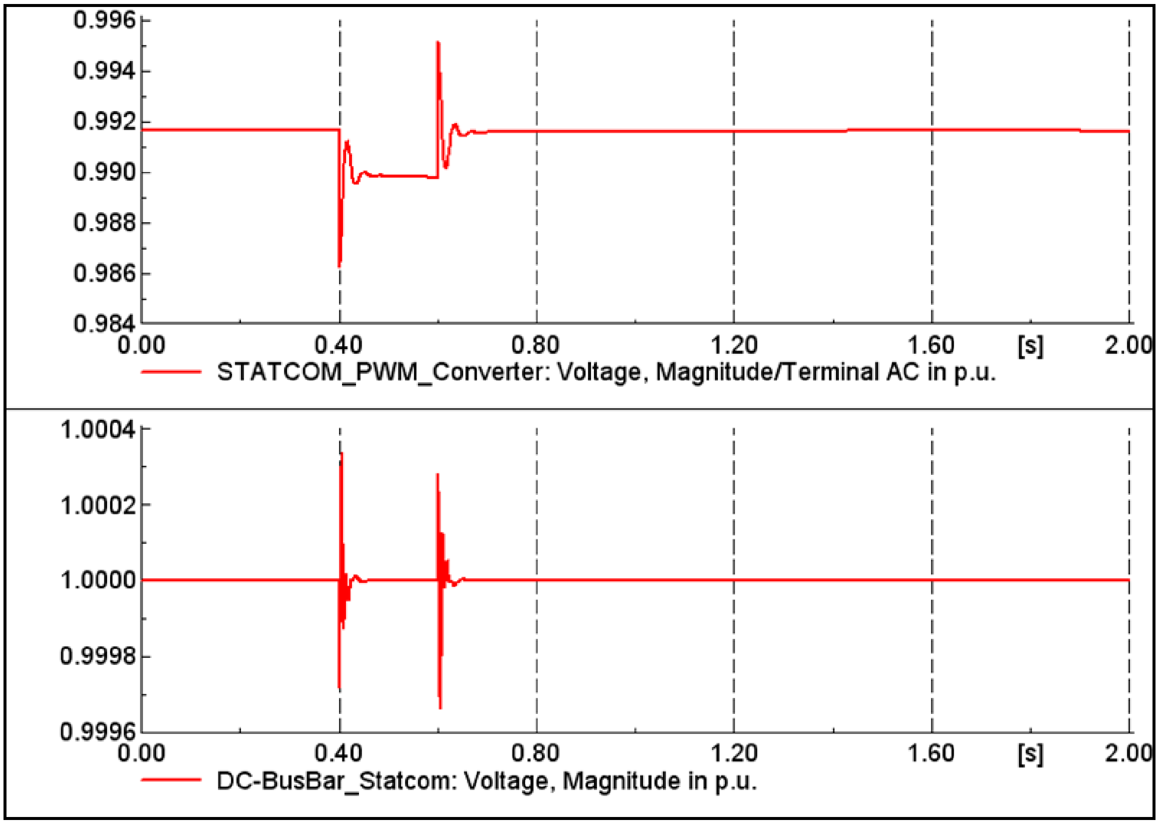

Figure 5.25. AC and DC busbar voltages of the 25 MVA STATCOM

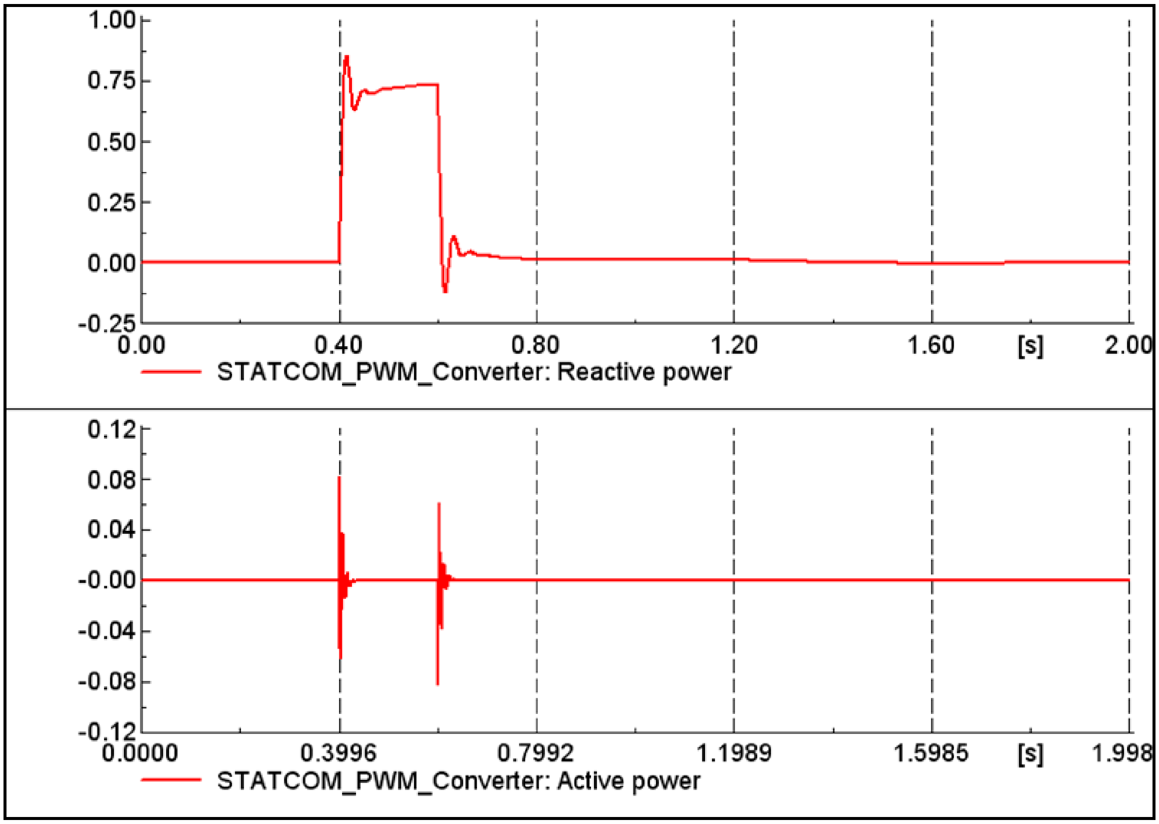

Figure 5.26. Reactive and active powers of the STATCOM

5.2.2.3 10% real and 50% reactive negative step change in load. In this case, a sudden temporary step load change is studied. At t=0.4 sec, the resistive load is decreased by 10% and the reactive load is decreased by 50%, and is reversed at t=0.6 sec. This case also identifies the STATCOM's capability of damping real power oscillations by controlled reactive power flow.

Figure 5.27 shows the load bus voltage of the system with and without the STATCOM. The voltage oscillations after the initial load conditions are restored are due to the real power changes in the system. The prolonged oscillations are due to the fact that real power control of the synchronous generator is not modeled in the test system. The STATCOM helps to quickly damp these oscillations by supplying controlled variable reactive power to the system.

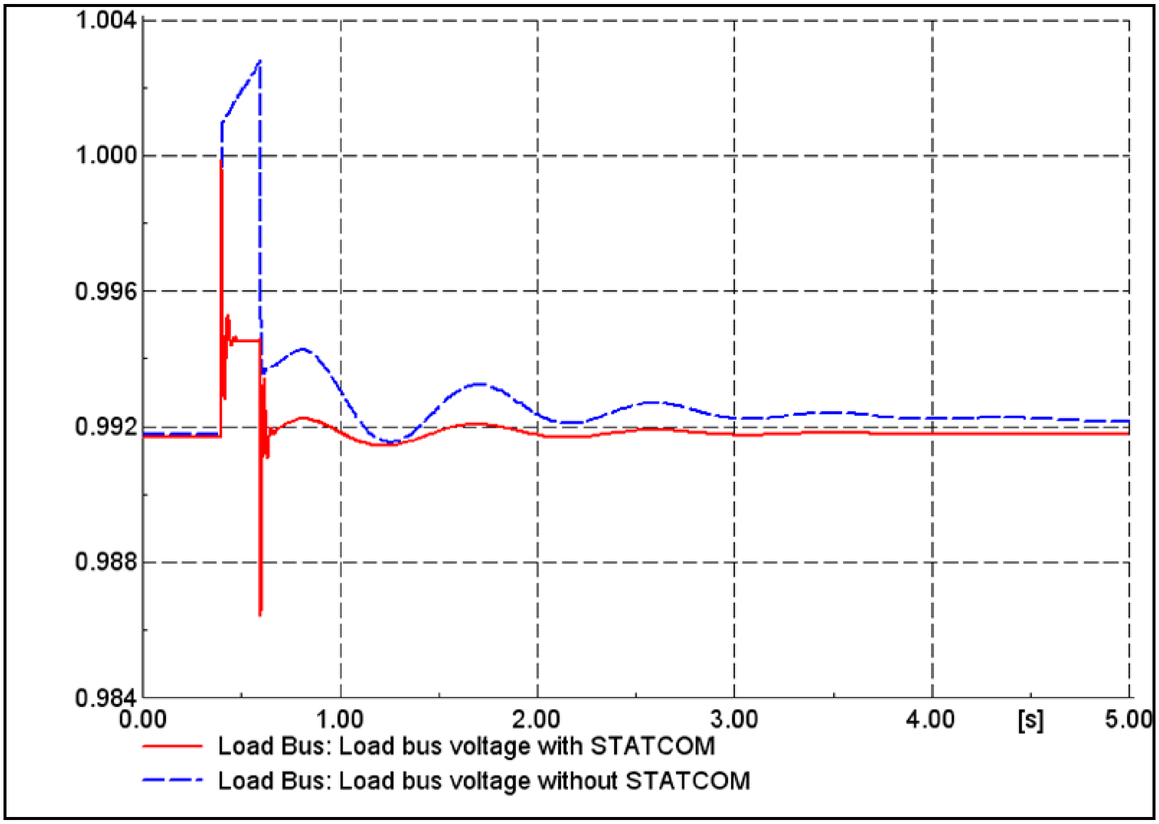

Figure 5.27. Load bus voltages

When there is a sudden decrease in the power demand, the voltage at the bus increases and also the ac terminal voltage of the STATCOM increases as seen in Figure 5.28. The additional reactive power is absorbed by the STATCOM as shown in Figure 5.29. The STATCOM improves the voltage characteristics of the system during and after the load change.

The active power needed can be supplied by the synchronous generator reserve. Though the wind turbine and the synchronous generator share the increased load, the wind turbine shares a small fraction of it as it is operating at its maximum rated capacity. This case is justified because the system has enough reserves of both active and reactive power sources.

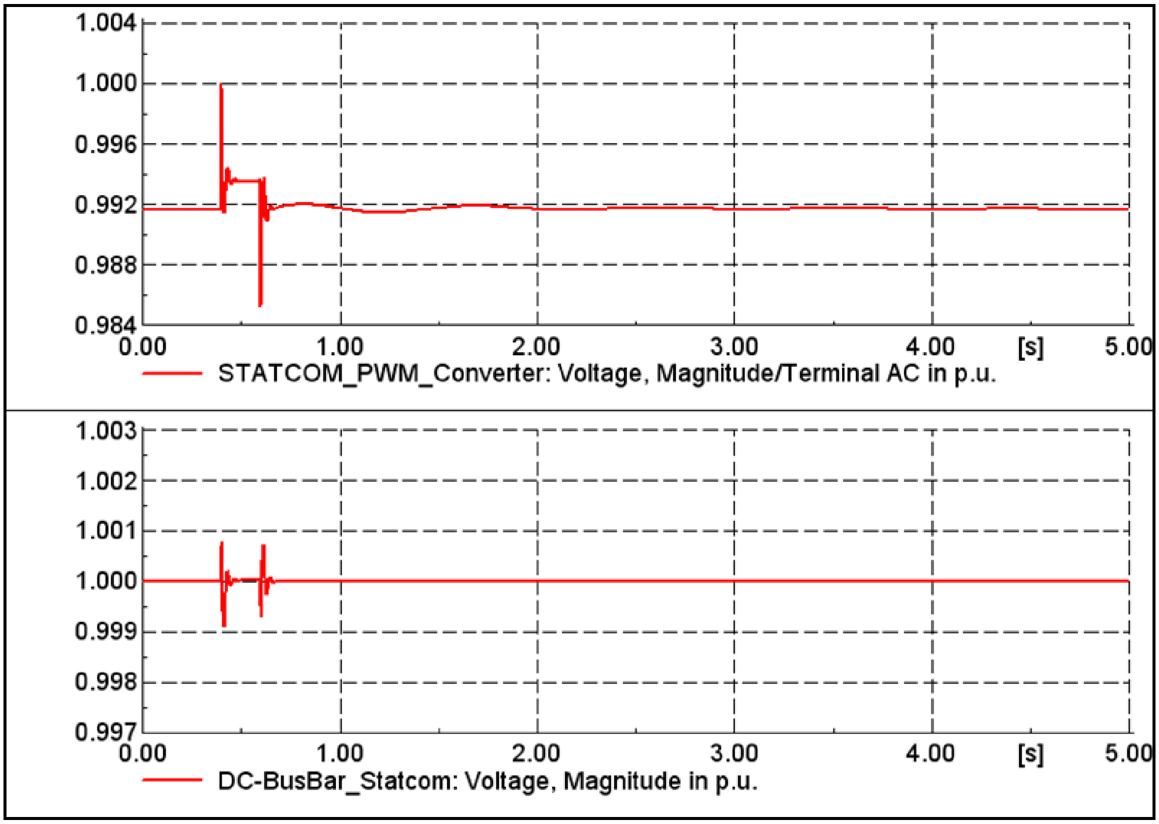

Figure 5.28. AC and DC terminal voltages of the STATCOM

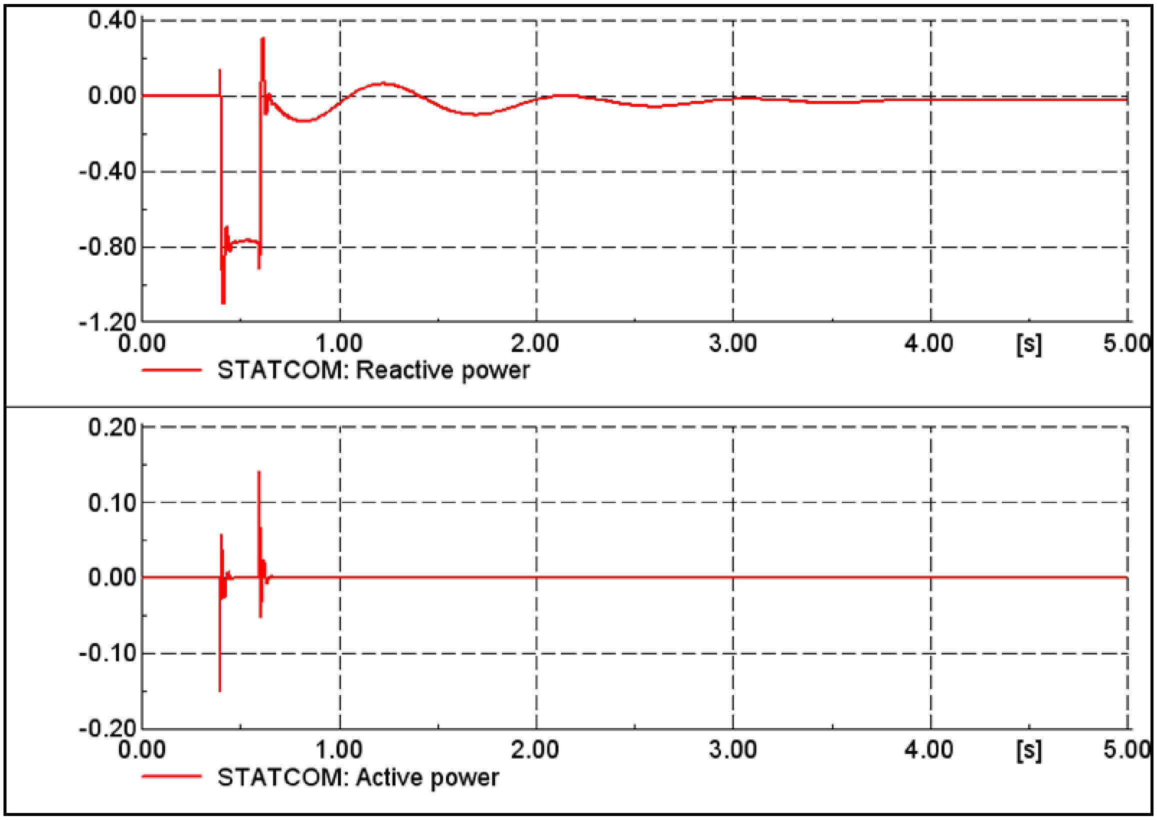

Figure 5.29. Reactive and active powers of the STATCOM

5.2.2.4 10% real and 50% reactive positive step change in load. In this case, a sudden temporary load step change is studied. At t=0.4 sec, the resistive and the reactive loads are increased by 10 and 50% respectively which is reversed at t=0.6 sec. This case also identifies the STATCOM's capability to damp the real power oscillations by controlling reactive power flow. Figure 5.30 shows the load bus voltage of the system with and without the STATCOM. The voltage oscillations after restoring the initial load conditions are due to the change in real power in the system. The STATCOM helps to quickly damp these oscillations by supplying controlled variable reactive power to the system.

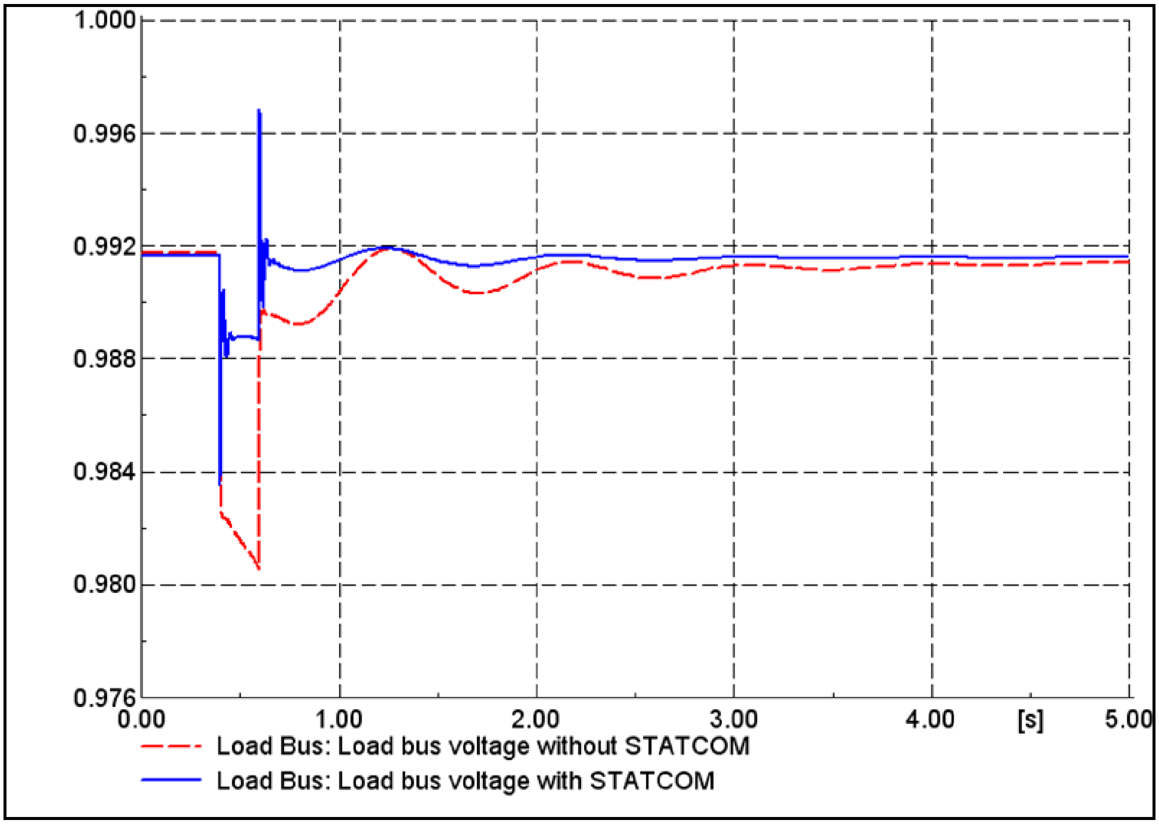

Figure 5.30. Load bus voltages

When there is a sudden increase in the power demand, the voltage at the bus drops and also the ac bus voltage of the STATCOM drops as seen in Figure 5.31. The required reactive power is supplied by the STATCOM as shown in Figure 5.32. The STATCOM improves the voltage characteristics of the system during and after the load change. The wind turbine and the synchronous generator share the increased load but the wind turbine shares a small fraction of it as it is operating close to its maximum rated capacity.

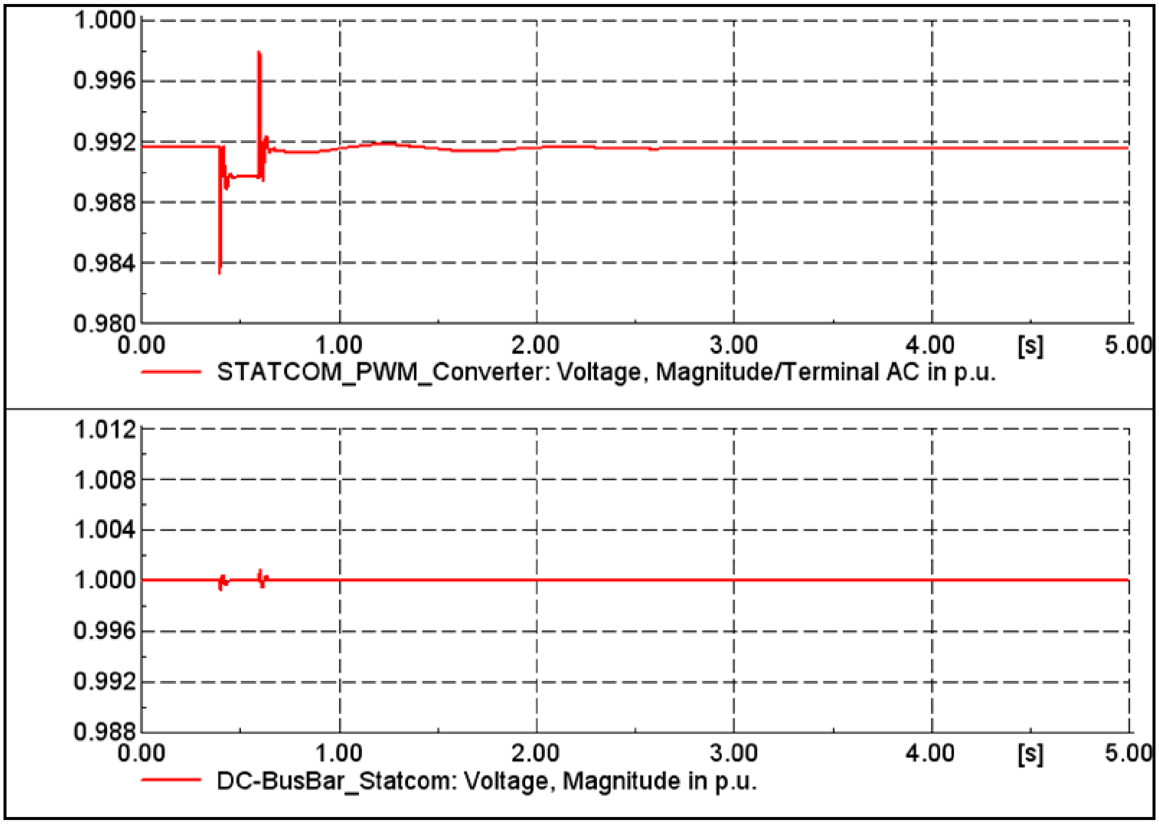

Figure 5.31. AC and dc terminal voltages of the STATCOM

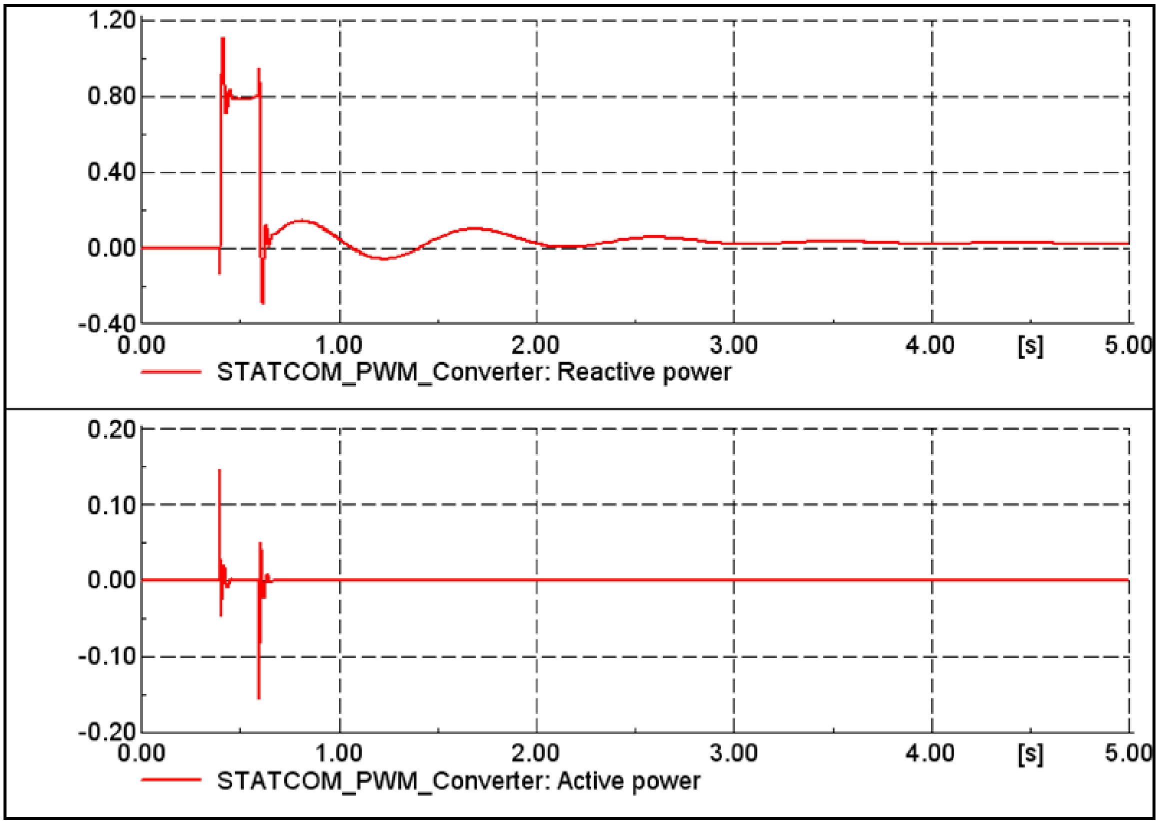

Figure 5.32. Reactive and active powers of the STATCOM

5.2.3. Short term tripping of a Wind Turbine. The third case studied is a temporary trip of a wind turbine. A wind turbine is tripped at t=0.4 sec and is brought back to service at t=0.6 sec. Figure 5.33 shows the load voltage for the system without STATCOM. The load voltage response to this disturbance is oscillatory with about five times longer settling time than in the case with a STATCOM.

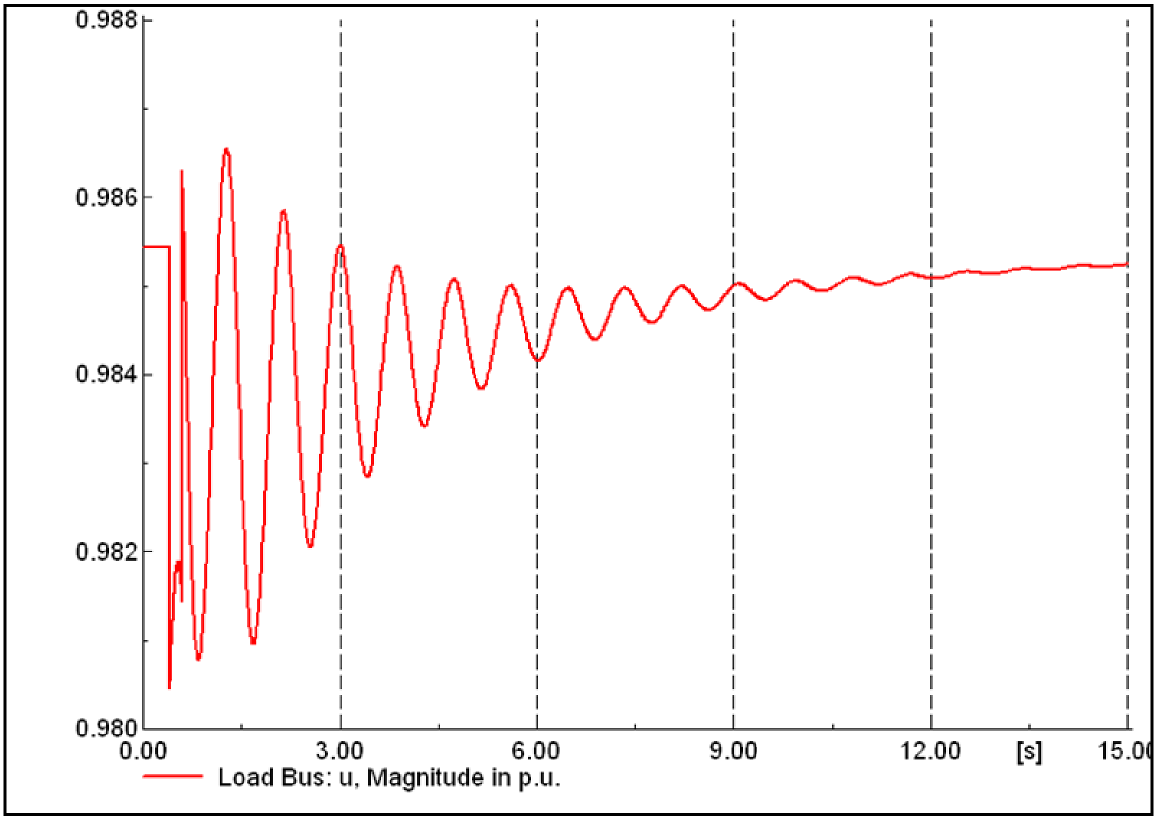

Figure 5.33. Load bus voltage without STATCOM

Figure 5.34 show the voltage of the load bus in a system with the STATCOM. The total reactive and active power supplied by the STATCOM is shown in Figure 5.35.

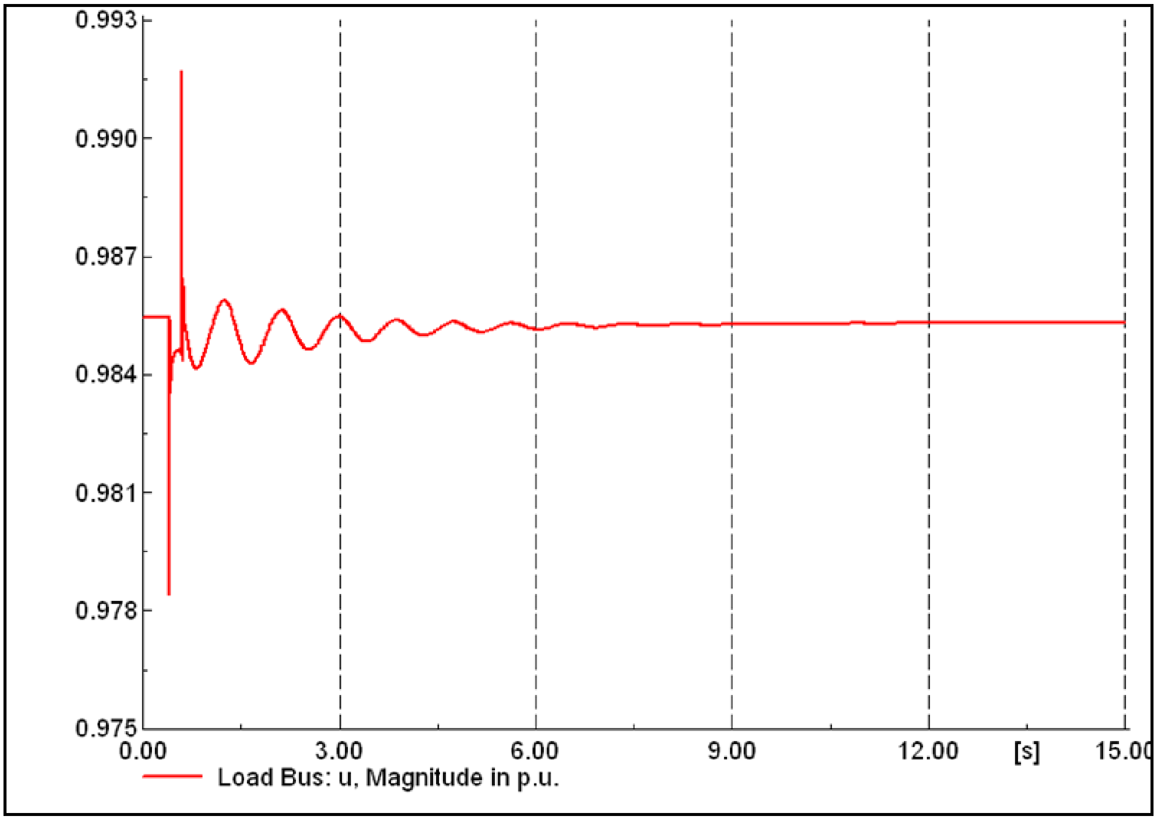

Figure 5.34. Load bus voltage with STATCOM

The STATCOM supplies variable reactive power and supports voltage at the load bus thus reducing the oscillations in the load voltage. Also, the load has some wide power oscillations in the system without the STATCOM that can be reduced with the help of a STATCOM.

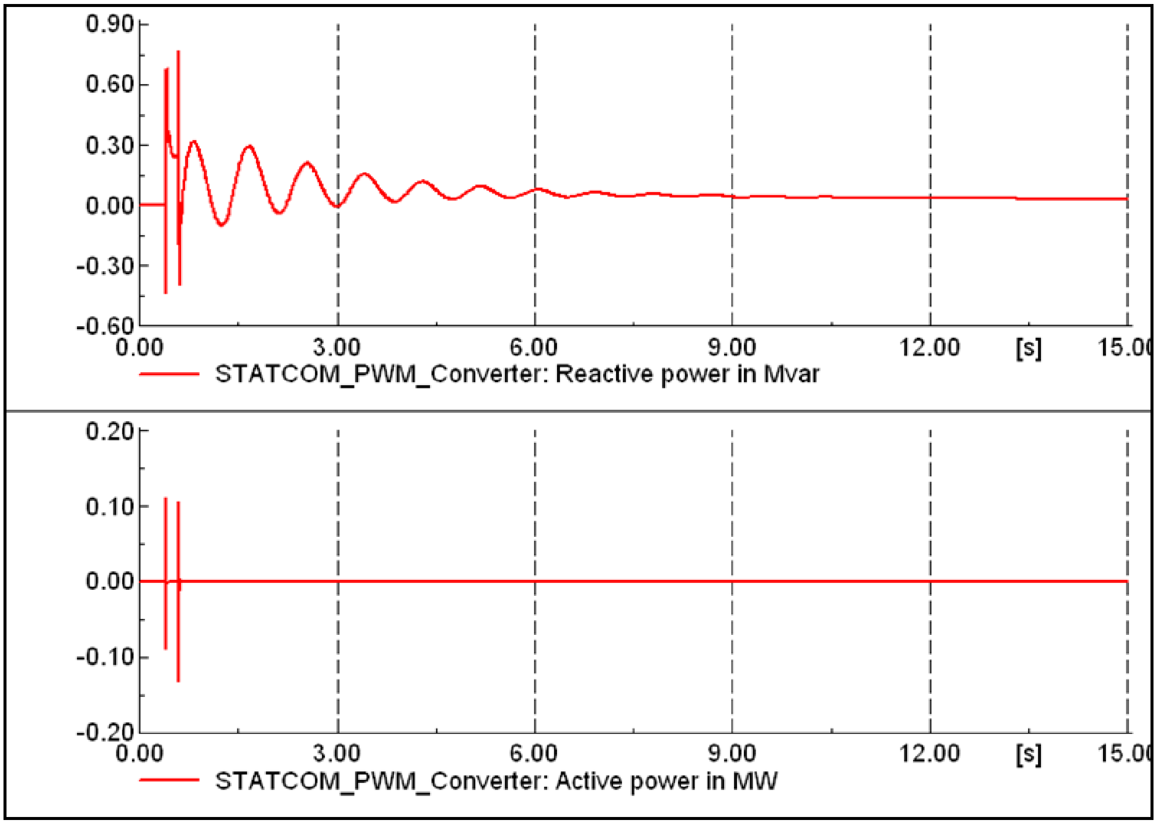

Figure 5.35. Reactive power and active power of the STATCOM

6. CONCLUSION AND FUTURE WORK

6.1. CONCLUSION

A pressing demand for more electric power coupled with the depleting natural resources have led to an increased need for energy production from renewable sources such as wind and solar energy. The electrical output power generated from these sources of energy is variable in nature and hence, efficient power control is required for these energy sources. Wind power has seen increased penetration in the recent past and certain stringent grid interconnection requirements have been developed. Wind turbines have to be able to ride through a fault without disconnecting from the grid. When a wind farm is connected to a weak power grid, it is necessary to provide efficient power control during normal operating conditions and enhanced support during and after faults. Voltage instability problems occur in a power system that is not able to meet the reactive power demand during faults and heavy loading conditions. Dynamic compensation of reactive power is an effective measure of preserving power quality and voltage stability.

When many wind turbines are added to the system, the grid becomes weaker as these types of generators require additional control equipment since they do not have any self recovery capability like the conventional synchronous generators. This requires a thorough study of the normal and dynamic performance of the wind turbines during and after a disturbance. This thesis explores the possibility of connecting a STATCOM to the wind power system in order to provide efficient control. In this thesis, the wind turbine modeled is a DFIG that is an induction machine which requires reactive power compensation during grid side disturbances. An appropriately sized STATCOM can provide the necessary reactive power compensation when connected to a weak grid. Also, a higher rating STATCOM can be used for efficient voltage control and improved reliability in grid connected wind farm but economics limit its rating.

Simulation studies have shown that the additional voltage/var support provided by an external device such as a STATCOM can significantly improve the wind turbine’s fault recovery by more quickly restoring voltage characteristics. The extent to which a STATCOM can provide support depends on its rating. The higher the rating, the more support provided. The interconnection of wind farms to weak grids also influences the safety of wind turbine generators. Some of the challenges faced by wind turbines connected to weak grids are an increased number and frequency of faults, grid abnormalities, and voltage and frequency fluctuations that can trip relays and cause generator heating.

The dynamic performance of wind farms in a power grid is improved by the application of a STATCOM. The STATCOM helps to provide better voltage characteristics during severe faults like three phase impedance short circuit faults as well. The response of a wind farm to sudden load changes is improved by the use of a STATCOM in the system. Table 6.1 show the comparison of the dynamic performance features for the three phase impedance faults studied.

Table 6.1 Comparison of the dynamic performance features for three phase fault studies

Impact of system performance / **Cases**	**Overshoot**	**Settling time**	**Voltage during the fault**	**System performance**
Without STATCOM	No (0)	High (~2sec)	Very Low (0.3 pu)	Unacceptable
With MSC	No (0)	High (~2sec)	Low (0.45 pu)	Poor
With 25 MVA STATCOM	Low (20 %)	Low (~0.7sec)	Medium (0.55 pu)	Average
With 25 MVA STATCOM + MSC	Low (40 %)	Low (~0.7sec)	Medium high (0.6 pu)	Good
With 125 MVA STATCOM	High (50 %)	Very low (<0.1 sec)	Excellent (0.9 pu)	Excellent

6.2. FUTURE WORK

In this thesis, simulation studies show that the dynamic performance of wind farms is improved with the use of a STATCOM. Future work can involve analyzing the harmonics in the system and evaluate methods to reduce the system harmonics. A multi-level STATCOM can be modeled to reduce lower order harmonics. Three phase high impedance short circuit faults have been studied in this thesis that can be extended to observe the response of the system to other types of faults. The wind turbines here are modeled as individual turbines, which could be extended to represent a wind farm by modeling them as a single equivalent wind turbine. The study has been based on the performance for DFIG that could be further extended to various types of wind turbines. This study can be extended to a larger system to evaluate the support provided by the use of a STATCOM.

APPENDIX

TEST SYSTEM DATA

System voltage: 30 kV
System frequency: 60 Hz

Doubly-fed Induction Generator
Rating: 5 MVA
Real power: 4.5 MW
Reactive power: 0.2 Mvar
Rotor side dc voltage: 132.25 V (1.15p.u)
Slip: 8%
Slip ring voltage: 1939 V
Machine commanded rated speed: 13.8 m/s

STATCOM
Rating: 25 MVA / 125 MVA
Reactive power set-point: 0 Mvar
Transformer 30 kV/0.4 kV (very low impedance)

Kp: Active power control gain [pu]
Tp: Active power control time constant [s]
Kv: Voltage control gain [pu]
Tv: Voltage power control [s]

Synchronous Generator
Rating: 30 MVA

Load
Active power: 18 MW
Reactive power: 2 Mvar

External Grid
Short circuit capacity: 50 MVA

Transmission Lines
Resistance: 0.06 ohm/km
Reactance: 0.6 ohm/km
Three phase, Overhead line

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