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Application of STATCOM for Improved Reliability of Power Grid Containing a Wind Turbine

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Abstract-- **Larger wind farms when integrated to the power system pose stability and control issues. This paper investigates the use of a Static Synchronous Compensator (STATCOM) with wind farms for the purpose of stabilizing the grid voltage after a grid-side disturbance viz., a three phase short circuit fault and load changes. The strategy focuses on a fundamental grid operational requirement to maintain proper voltages at the point of common coupling by regulating the voltage at the collector bus of a wind farm. The DC voltage at individual wind turbine (WT) inverters is also stabilized which facilitates the continuous operation of each WT during disturbances.**

Index Terms-- **Wind turbine, Doubly-fed Induction Generator, STATCOM, three phase faults, and reactive power support**.

I. Introduction

The increase in electric power demand and the depleting natural resources has led to the increased need for production of energy from renewable sources such as wind energy. The latest technological advancements in wind energy conversion and the increased support from government 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 is 11,603 MW in 2006 and is expected to increase by 26% in the year 2007 [1]. Wind power penetration has increased multifold in the past few years; hence it has become necessary to address the problems associated with maintaining a stable electric power system which has different sources of energy including hydro, thermal, coal, nuclear, wind, solar and many others. 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 big concern. With increasing share from the wind power sources, it has become important for continuous connection of the wind farm to the system to enable uninterrupted power supply to the load even in the case of some minor disturbances. The capacity of wind farms are being increased by installing more and bigger wind turbines connected online which implies that more impedance is being added to the system, thus making the connected system as a weak grid [2]. Voltage stability and an efficient fault ride through capability are the basic requirements of higher penetration. The wind turbines have to be able to continue uninterrupted operation under transient voltage conditions to be in accordance with the grid codes. Grid codes are certain standards set by regulating agencies and the wind power systems should meet these requirements for their interconnection to the grid. There are different grid code standards established by different regulating bodies and the Nordic grid codes are becoming increasingly popular.

Flexible AC Transmission Systems (FACTS) based power electronic converters like 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 [3]. 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.

One of the major issues concerning a wind farm interconnection to a power grid is its dynamic stability considerations on the power system [4]. Stand alone systems are easy to simulate, analyze and control when compared to large power systems. A wind farm is usually spread over a wide area having many wind generators each producing different power as they are exposed to different wind patterns.

The applicability of a STATCOM to a wind farm has been investigated and the results from these early studies indicate that the STATCOM 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 [5]. The authors in [3, 6] have shown that the transient and short-term stability conditions of a generator have improved when a STATCOM has been introduced into the system as an active voltage/var supporter.

The methods used to develop an equivalence of a collector system in a large wind power plant are described in [7]. The requirements, assumptions and structure of an aggregate model of a wind park with constant speed turbine and variable speed turbines are discussed in [8].

This paper explores the possibility of enabling wind farms to provide voltage support during normal conditions as

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well as under conditions when system voltages are not within desired limits. Also, this paper evaluates the combined use of a STATCOM device with the wind farms for the purpose of stabilizing the grid voltage after a grid disturbance such as a line outage or various system faults.

In this paper, doubly fed induction generators (DFIG) with variable speed operation are considered. A DFIG has a power electronic converter using which both real power and reactive power is controllable. A STATCOM is employed to regulate the voltage at the collector bus thereby maintaining 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 thereby enabling the wind farm to participate in grid side voltage and power control.

The dynamic model of the DFIG available in DIgSILENT PowerFactory Version 13.2 [9] is used for the simulations. The STATCOM with a higher rating capacity has been developed based on the study of an available low capacity STATCOM example. The complete power grid studied in the paper is a combined study case of a wind turbine, a STATCOM and the developed four bus system all interconnected as shown in Section IV.

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 on 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 from the system. Low Voltage Ride Through (LVRT) is a recently introduced requirement that transmission operators demand to wind farms. STATCOM is being evaluated for its performance to effectively provide LVRT for wind turbines in a wind farm.

II. DFIG BASED WIND TURBINE

The DFIG is a wound rotor induction machine with slip rings attached to the rotor. The AC/DC/AC converter is divided into two parts, rotor side and grid side. The rotor is fed by the rotor side power converter and the grid side power converter is used to generate or absorb power in order to keep the DC link voltage constant. Generation of power at variable speeds ranging from below synchronous speed to above synchronous speed can be achieved using DFIG. The model is shown in Fig. 1.

III. STATCOM

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 reactive output power of the compensator is varied to control the voltage at given terminals of the transmission network so as to maintain the desired power flow under possible system disturbances and contingencies. STATCOMs have the ability to address transient events at a faster rate and with better performance at reduced voltages than a Static Voltage Compensator (SVC). The maximum compensation current in a STATCOM is independent of the system voltage. In all, a STATCOM provides dynamic voltage control, power oscillation damping, and improves the transient stability of the system. By controlling the angle Φ, the flow of current either from the converter to the ac system or vice versa, can be controlled

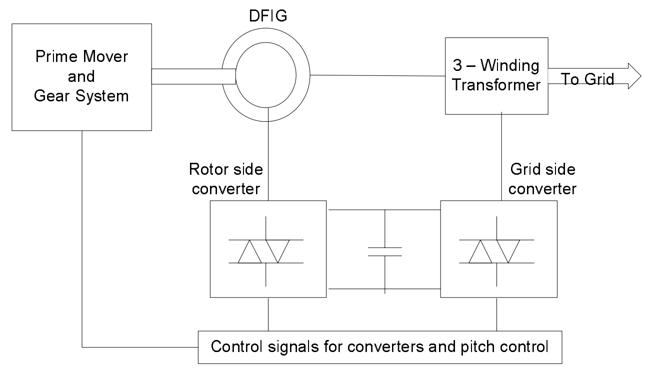

Fig. 1. Block diagram of a variable pitch/speed wind turbine with DFIG

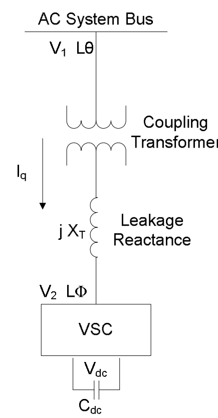

Fig. 2. Basic model of a STATCOM

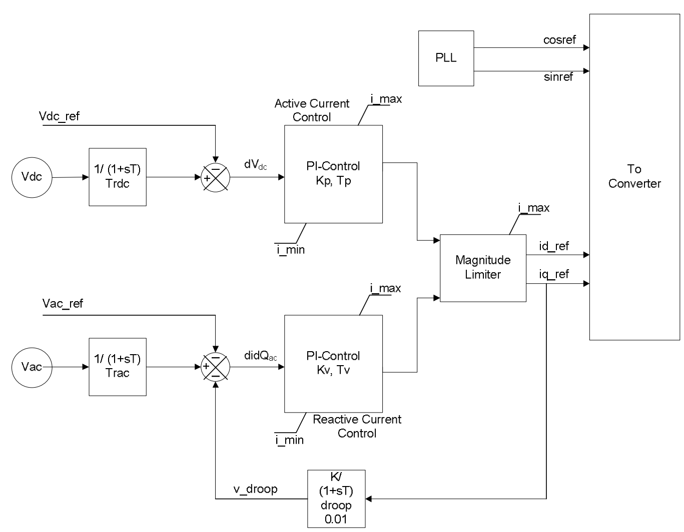

Fig. 3. Control scheme of the STATCOM

The basic model of a STATCOM is shown in Fig. 2 and the controller block diagram is as in Fig. 3. The outputs of the controller are id_ref and iq_ref which are the reference

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currents in the dq coordinates and they are needed to calculate the power injections by the STATCOM as in 1.

$$P_{inj} = V_i \left(i_d \cos\theta_i + i_q \sin\theta_i \right)$$
$$Q_{inj} = V_i \left(i_d \sin\theta_i - i_q \cos\theta_i \right) \qquad (1)$$

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 exact ratings of STATCOM are derived based on many parameters. The rating of the STATCOM required to serve its purpose is mostly governed by the amount of reactive power demanded by the system to recover and ride through typical faults on the power system and to reduce the interaction of other system equipment from going out of synchronism with the grid. Though the final decision of the desired rating of the STATCOM is decided based on economics of the system the capacity thus chosen will be at least enough for the system to stabilize after temporary disturbances in the system. In the case of this test system, the STATCOM rating chosen is ±150 MVA which is found to be the maximum capacity required to maintain the voltage of the load bus to 0.9p.u. The location of STATCOM is mostly chosen as close as possible to the grid or the load.

Also, a STATCOM connected in a transmission system is mostly used to support the grid voltage at severe disturbances and to control the reactive power. A STATCOM used in distribution networks for controlling the fluctuating active power and power factor, and power quality improvement and also for flicker mitigation.

IV. TEST SYSTEM

The simulation study has been conducted on the system shown in Fig. 4, which represents a typical power system load being supplied by the local synchronous generators and also by the installed wind turbine (DFIG). Fig. 4 is a sketch of the power system that has been studied to evaluate the system performance under different transient conditions like a three phase fault and a sudden load change.

The wind turbine has more constraints and is complex to control and make it react to the emerging power system problems. Hence, additional system equipment is required to help maintain the power grid to be stable during and after the occurrence of a fault. The proposed test system has two generators; one source is the wind turbine which is a Doubly-fed Induction Generator (DFIG) and the other is a synchronous generator. The total system has a typical load connected to the system at bus 3. The active voltage supporter, STATCOM is connected to the load bus. Grid represents an external system which is connected to the system of interest through a weak link. The main reason is that the intent to force the generator and STATCOM to respond to faults in the area of interest. The short circuit power of the connected electric power grid is 10 MVA. This is a very weak grid and hence requires a compensating device of a higher rating. One of the objectives of this paper is to evaluate the specific needs of the system to restore to its initial state after the fault has been cleared. The STATCOM capacity required to restore after a three phase short circuit fault for this test system is about ±150 MVA. This is very high and is the maximum required capacity to restore and prevent the wind turbine from tripping during or after the fault has been initiated. The source of reactive power is always connected as close to point where it is required and this is basically the main motivation for connecting the STATCOM and the load to the same bus. This is specifically done to facilitate the effective operation of the STATCOM and to avoid excessive interaction of the connected power system.

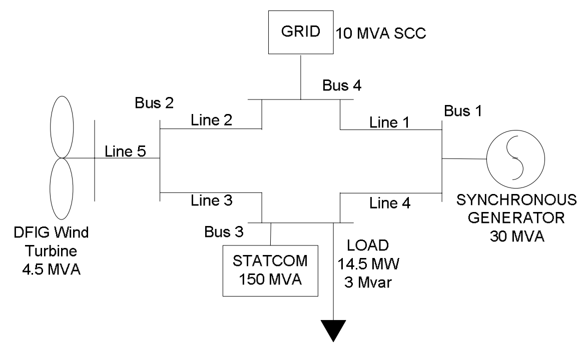

Fig. 4. Single line diagram of the test system

The ratings of all the main circuit data to model the system in DIgSILENT PowerFactory version 13.2 are presented in Appendix I.

V. SIMULATION RESULTS

The different cases studied on this test system are small duration three phase high impedance faults, a line outage, and sudden change in load. The results are presented in the corresponding sections and discussions are mentioned therein.

A. Three phase ground fault:

Three phase high impedance (X_f=5Ω) short circuit fault is studied at the load bus. This is an impedance ground fault which is initiated at t=0.5 sec and is cleared at t=0.7 sec and the value of the ground impedance is X_f = j5 Ohms. It is observed that the voltage of the wind turbine and the load bus does not recover even after the fault is cleared and hence this system does not conform to the grid code requirement. With the use of a STATCOM the voltage drop during the fault has been improved and more over the wind turbine voltage stability has been restored even after the fault has been cleared. 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.

Figs. 5 and 6 show the simulation results for the voltages of the fault bus and the wind turbine, for the system cases without and with the STATCOM respectively. It can be observed that the voltage drop at the fault bus during the period of fault is to 0.4p.u and the system oscillates at a voltage of about 0.8p.u after the fault has been removed. The wind turbine voltage also reacts in the same way as the load bus and there is a great possibility that this might trip and hence go offline. With addition of a STATCOM at the load

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bus, the voltage is increased to about 0.9p.u during the fault and is restored to 1.0p.u when the fault is cleared at 0.7sec. The voltage is quickly restored as there are minimum oscillations after the clearance of the fault in the system with a STATCOM.

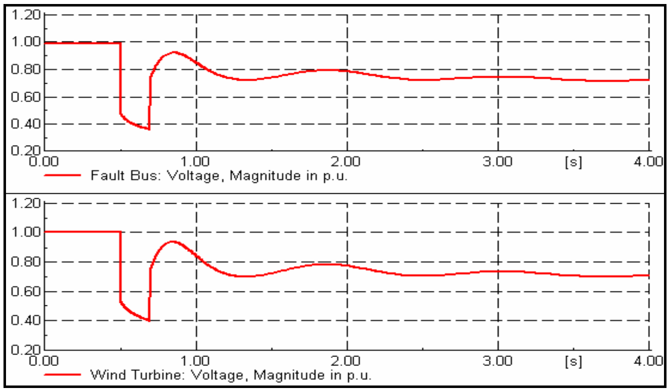

Fig. 5. Voltage at the fault bus and the wind turbine for the system without a STATCOM

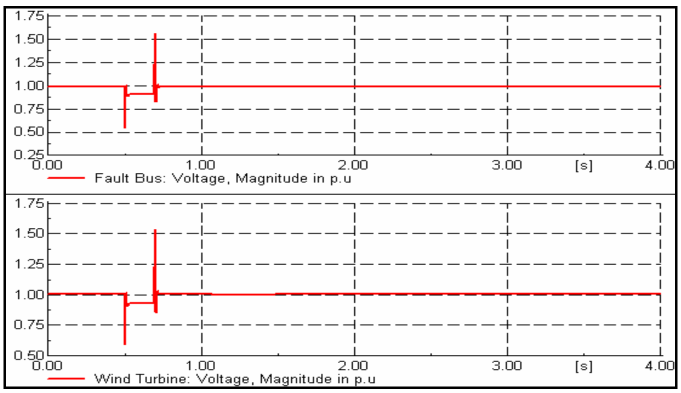

Fig. 6. Voltage at the fault bus and the wind turbine for the system with a STATCOM

Figs. 7 and 8 show the simulation results for voltage of the dc capacitor of the DFIG. The voltage of the capacitor increases as the terminal voltage of the collector bus drops. This is to provide more reactive power to the system and helps to maintain the stability of the system. It can be observed that the capacitor voltage starts to rise at the point when the fault is initiated, and tries to drop and return to the initial value when the fault is cleared. In a system without a STATCOM, the capacitor voltage oscillates and increases positively and hence the voltage at the collector bus sees some second order oscillations. In the other case, the STATCOM assists for the recovery of the dc capacitor voltage and it stabilizes in a short period of time due to effective damping from the system.

Figs. 9 and 10 show the simulation results of the active and reactive powers of the synchronous machine, external grid and the wind turbine. It can be observed that all the parts of the system contribute to maintain the stability of the system. The reactive power contributed by the synchronous generator is the highest and the external grid supplies minimum as it is a very weak grid (short circuit capability is 10 MVA). Once the fault is cleared, the reactive power requirement drops suddenly and the generator and the wind turbine experience a swing, and will not be able to return to its original state due to inertia of the generators. In the case where a STATCOM is employed to provide/absorb additional reactive power to/from the system, the system reaches a stable state owing to the fast operating non-linear controllers of the STATCOM.

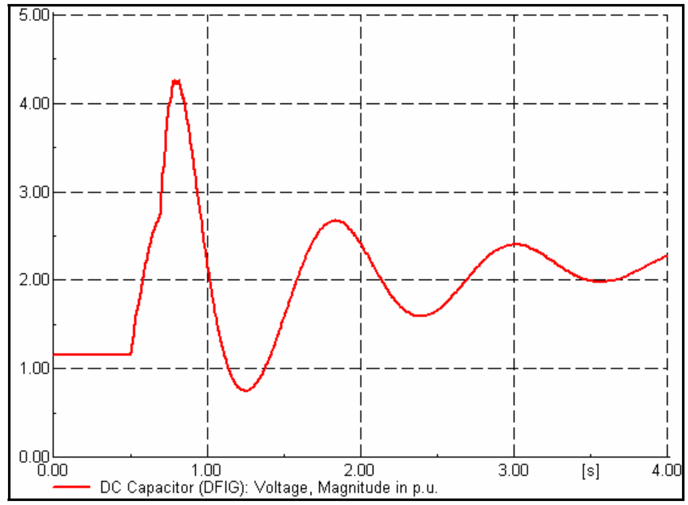

Fig. 7. Voltage at the DC Capacitor of the WT for the system without a STATCOM

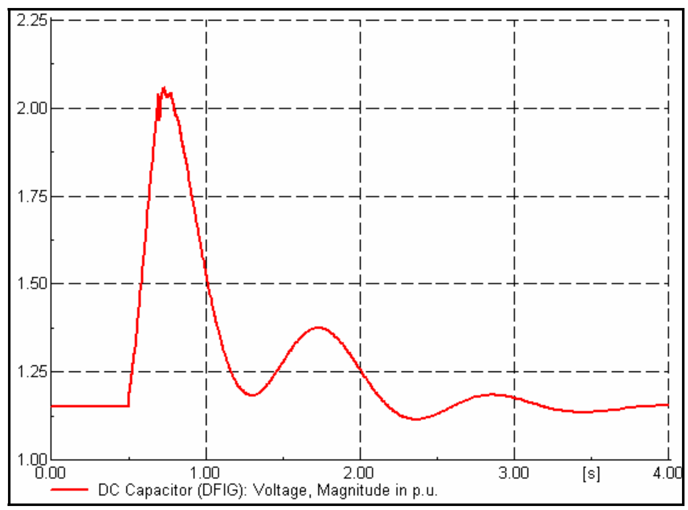

Fig. 8. Voltage at the DC Capacitor of the WT for the system with a STATCOM

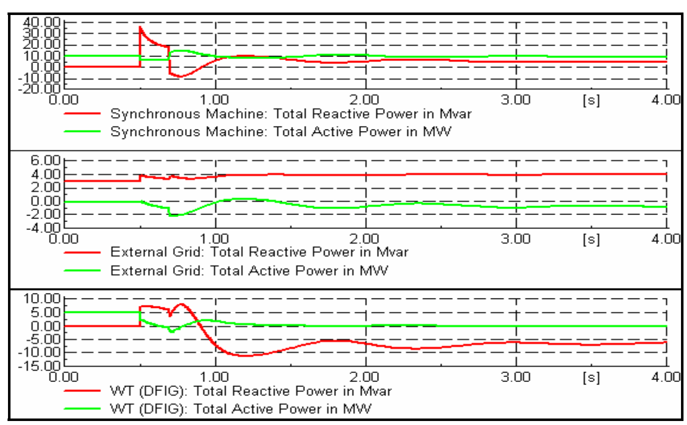

Fig. 9. Active and reactive powers of the synchronous m/c, external grid and wind turbine for the system without STATCOM

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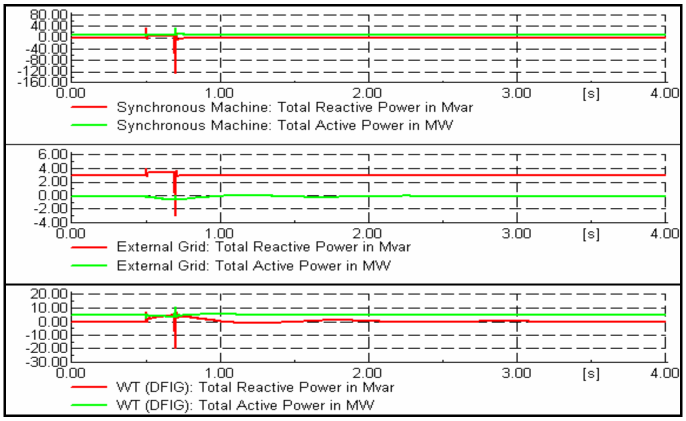

Fig. 10. Active and reactive powers of the synchronous m/c, external grid and wind turbine for the system with the STATCOM

Fig. 11 shows the additional reactive power supplied by the STATCOM. The rating of the STATCOM is chosen high enough to supply all the additional reactive power that would be needed by the system to be able to ride through the fault. This helps from the wind turbines to be tripped in case of a fault. The dc capacitor voltage of the STATCOM is maintained constant as seen in Fig. 11. Fig. 12 and Fig. 13 show the simulation results of electrical frequency of the fault bus. It can be seen that the frequency rises after the fault has been cleared and does not recover. In the system case where a STATCOM is used, the frequency is maintained at 1.0pu. The applicability of STATCOM to provide frequency control and reactive power support thus providing voltage control can be concluded from these simulations.

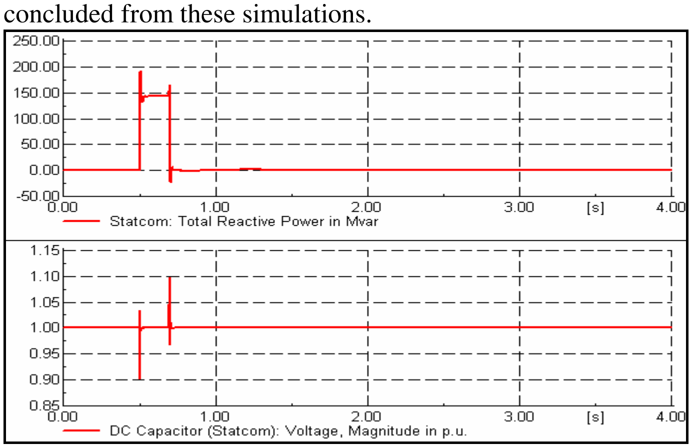

Fig. 11. Reactive power of the STATCOM and its dc capacitor voltage

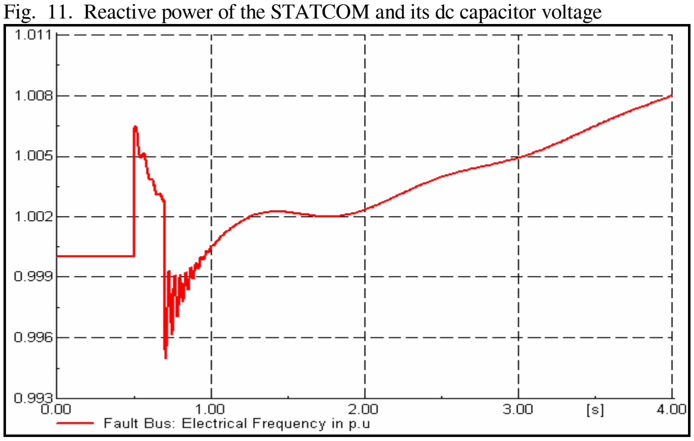

Fig. 12. Electrical frequency of the fault bus for the system without a STATCOM

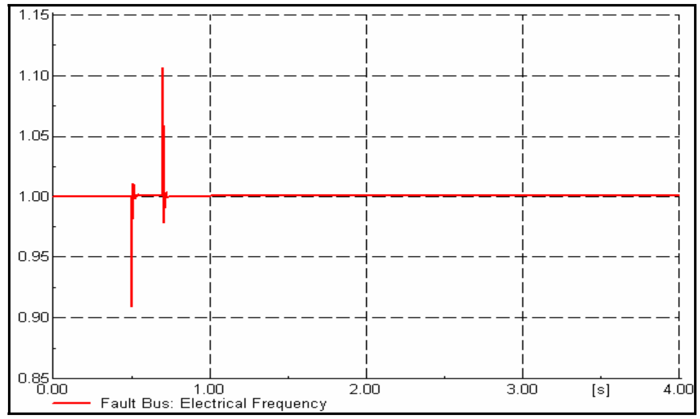

Fig. 13. Electrical frequency of the fault bus in the system with a STATCOM

B. Load change:

In this case, a sudden step load change is studied. At t=0.5sec, the active power load of the system is increased by 5% and the reactive power load by 50%. This particular case is studied because the STATCOM acts like a reactive power reserve and hence can be utilized to produce the incremental reactive power demand. The active power needed can be supplied by the synchronous generator reserve. Though the wind turbine and the synchronous generator share increased load, the wind turbine shares a small fraction of it as it is operating at its maximum rated capacity. This case has more emphasis on the ability of the total system to react effectively to sudden load changes. This case is justified because the system has enough reserves of both active and reactive power sources.

Figs. 14 and 15 show the simulation results for the voltages of the load bus and the wind turbine, for the system cases without and with the STATCOM respectively. It can be observed from Fig. 14, that the voltage drop on the load bus due to the sudden increase in load is gradually from 0.99p.u to 0.87p.u in about 3.5 sec. Also, the wind turbine voltage drops in a similar fashion to 0.87p.u. This calls for additional compensation for the system. From Fig. 15, it can be concluded that STATCOM is capable of providing the additional reactive power support and voltage support as well. The drop in voltage with the increase in load is only about 0.003p.u on the load bus and 0.01p.u on the wind turbine.

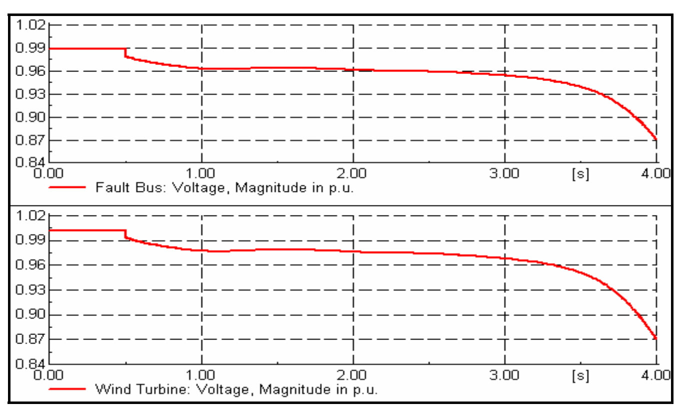

Fig. 14. Voltage at the fault bus and the wind turbine for the system without a STATCOM

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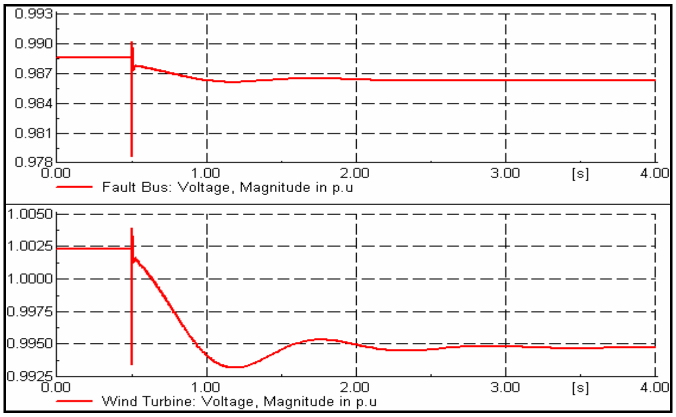

Fig. 15. Voltage at the fault bus and the wind turbine for the system with a STATCOM

Figs. 16 and 17 show the simulation results of the active and reactive powers of the synchronous machine, external grid and the wind turbine. As the load increases, the synchronous generator supplies most of the 5% increased active power requirement and also most of the incremental reactive power demanded. The external grid supplies a small fraction of the increased load. The load change case has more fluctuations in the system and cannot restore its initial conditions and hence a STATCOM is used to provide efficient voltage support and as a reserve for instantaneous reactive power. As seen in Fig. 18, STATCOM supplies most part of the additional reactive power and the voltage of its dc bus is maintained constant.

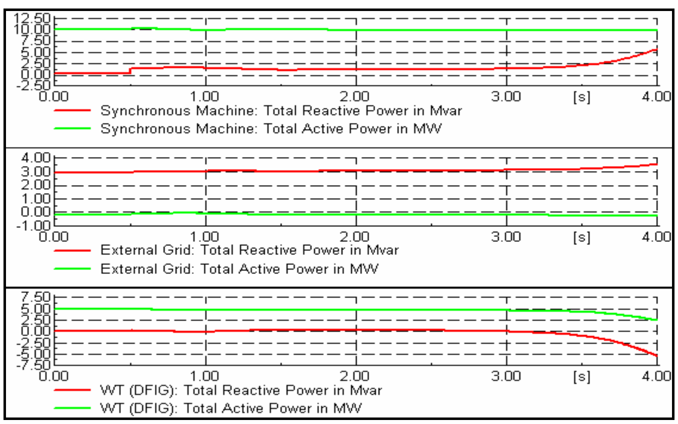

Fig. 16. Active and reactive powers of the synchronous m/c, external grid and wind turbine for the system without the STATCOM

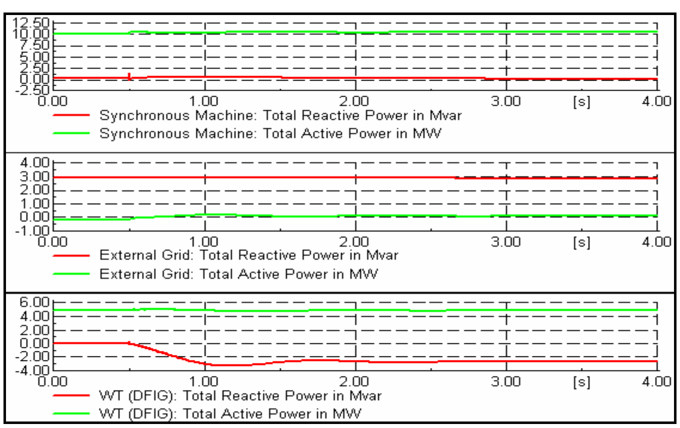

Fig. 17. Active and reactive powers of the synchronous m/c, external grid and wind turbine for the system with the STATCOM

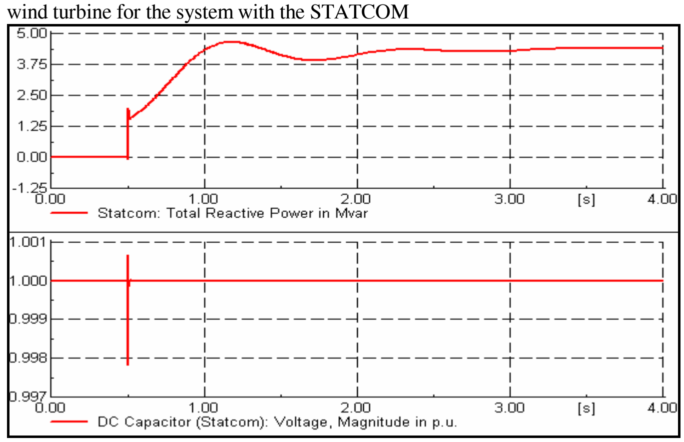

Fig. 18. Reactive power of the STATCOM and its dc capacitor voltage

The electrical frequency of the load bus decreases initially as the load increases and then gradually starts to rise as seen in the Fig. 19 below. In the case where a STATCOM is employed, the electrical frequency of the load bus remains constant as shown in Fig. 20.

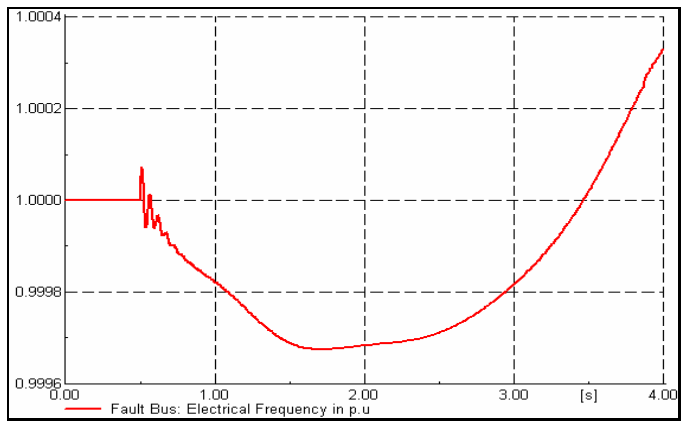

Fig. 19. Electrical frequency at the fault bus for the system without a STATCOM

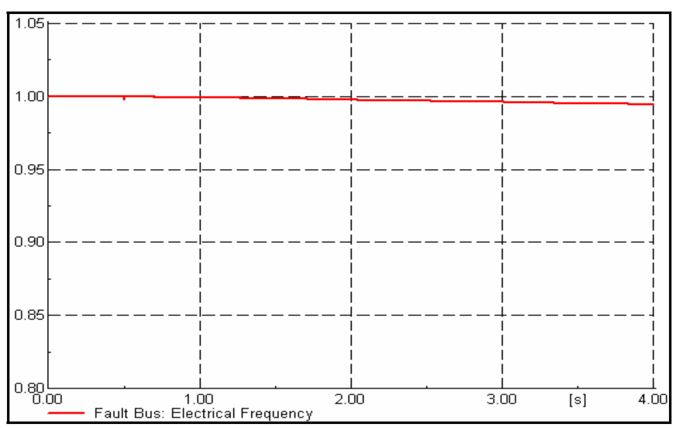

Fig. 20. Electrical frequency at the fault bus for the system with a STATCOM

VI. CONCLUSIONS

The DFIG is an induction machine which requires reactive power compensation during grid side disturbances. STATCOM is a feasible option to provide the necessary reactive power compensation when connected to a weak grid.

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Also, a higher rating STATCOM can be used for efficient voltage control and improved reliability of a wind farm connected to a grid but economics limit the rating of the device.

APPENDIX

Description of input data to model the system in DIgSILENT PowerFactory version 13.2

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: 150 MVA
Reactive power set-point: 0 Mvar
Phase voltage: 30 kV
Transformer 30 kV/0.4 kV (very low impedance)

SYNCHRONOUS GENERATOR
Rating: 30 MVA
Voltage: 30 kV

LOAD
Active power: 14.5 MW
Reactive power: 3 Mvar

EXTERNAL GRID:
Short circuit capacity: 10 MVA

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