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UTILIZING STATCOM FOR POWER QUALITY IMPROVEMENT UNDER INTEGRATION OF WIND FARMS INTO THE UNIFIED GRID

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Utilizing STATCOM for Power Quality Improvement under Integration of Wind Farms into the Unified Grid

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Abstract– **Wind power plants play an important role in the power system especially under integration of high penetration levels of wind energy into grid. Many requirements for the wind power plants have been proposed in Saudi Arabia Grid Code. One of these requirements is power quality including active and reactive powers, flicker, voltage swell, harmonics and voltage sag. These power quality aspects are generated due to the variation in the environmental conditions as all fluctuations in the wind speed are further transferred as fluctuations in the electrical power delivered to the grid especially in fixed speed wind turbines. Also the problem is that these wind turbines mostly use induction generators, tend to drain large amounts of VArs from the grid, potentially causing low voltage and may be voltage stability problems for the utility. This paper presents the practical solutions to mitigate the voltage fluctuations caused by the aerodynamic aspects of a wind farm in a power system by utilizing a Static Compensator (STATCOM). Also Recommendations are given for improving the voltage profile and reactive power of the wind farms connected to the grid during short circuit using different STATCOM techniques for a safe operation.**

Index Terms**-- Grid Integration, Power Quality, Power System, Smart Grid, STATCOM, Voltage Stability, Wind Energy**

I. INTRODUCTION

The lack of energy, unstable prices of energy, increasing prices of fossil fuels and environment protection result in increase of interest in renewable energy sources. Wind energy is the world’s fastest growing renewable source. The average annual growth rate of wind turbine installation is around 30% during last decade [1]. Wind power plants must provide the power quality required to ensure the reliability of the power system where it is connected to and to fulfill the clients connected to the same grid. This paper addresses the impacts of high penetration levels of wind energy on different power quality factors such as voltage, frequency, and supply interruption. The study involves the assessment of various voltage stability issues such as voltage flicker, voltage distortion, and voltage dips. Frequency fluctuations, harmonics, and inter-harmonics [2]. This paper observes power quality assessment for different types of WTG systems including Power variation, voltage fluctuation and flicker related to the connecting wind farms with induction generators into grid. There are currently three main types of generator systems for large wind turbines. The first type is a fixed-speed wind turbine system using a gearbox and a standard SCIG, directly connected to the grid. The second type is a variable speed wind turbine system with a gearbox and a DFIG, where the power electronic converter feeding the rotor winding has a power rating of about 30% of the generator capacity, the stator winding of the DFIG is directly connected to the grid. The third type, PMSG, is also a variable speed wind turbine, where a gearbox with a smaller low speed and a full-scale power electronic converter are used [1].

Since the active power generated by constant-speed wind turbines are fluctuated due to the effects of turbulence, the wind gradient and the tower shadow, the reactive power demand of these squirrel-cage induction generators are also fluctuated . Consequently, the active and reactive power variations can cause fluctuation of the voltage at the point of common coupling (PCC). Therefore, fixed speed wind turbines introduce challenging impacts on the grid performance.

This paper studies the static synchronous compensator implementation in order to address the issue of voltage stability in wind farms connected to the distribution network. STATCOM is used as a dynamic reactive power compensator to stable the voltage at the point of common coupling [3].

A. Power Coefficient and Max. Output Power

This wind speed variation not only can make it difficult to ensure good power quality but also implies in a variation of the power coefficient Cp. The power coefficient is the ratio of the mechanical power obtained by the wind turbine and the mechanical power related to the wind.

$$P_{mech} = C_p P_{wind}$$

The power coefficient is not a constant; it depends on the wind speed, aerodynamic factors and possibly on the blade pitch angle if the wind turbine is pitch-controlled. For most turbines the power coefficient is zero for low wind speeds, which make wind turbine control even more difficult. Wind’s mechanical power may be defined as:

$$P_{wind} = \frac{1}{2}\rho A V_{wind}^3$$

Along with the wind speed variation comes the tower shadow effect, which is a consequence from the spatial distribution of the horizontal axis wind turbine. The tower shadow effect introduces more uncertainty into the power coefficient [4].

Since one blade will eventually be shaded by the wind turbine tower, it will not transfer as much power as it would on other positions. This wind power variation can affect the

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active power output, reactive power consumption and voltage output of an induction machine.

It will also affect the power and voltage output of a synchronous generator. When the wind speed varies, there is also a change in the power coefficient. It is of our interest to keep the power coefficient as high as possible (unless under extremely high wind speeds that can damage the turbine or the electric machine connected to it).

B. Effects of Turbine Speed on Power Quality

1. Fixed-speed Wind Turbines

Fixed-speed wind turbines are equipped with an induction generator that is directly connected to the grid, with a soft-starter and a capacitor bank for reducing reactive power compensation.

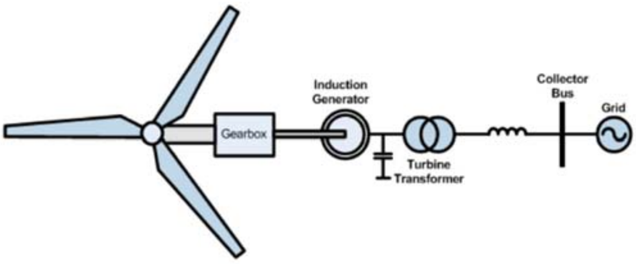

Fig. 1. Fixed Speed Wind Turbine with (SCIG)

They are designed to achieve maximum efficiency at one particular wind speed. The fixed-speed wind turbine has the advantage of being simple, robust, reliable, and well-proven. The cost of the fixed-speed wind turbines electrical parts is relatively low. However, some of the disadvantages of fixed-speed wind turbine systems are the uncontrollable reactive power consumption, significant mechanical stresses, and limited power quality controllability. Due to its fixed-speed operation, all fluctuations in the wind speed are further transferred as fluctuations in the mechanical torque, hence as fluctuations in the electrical power delivered to the grid [5].

Wind farms with induction generators generate real power and consume reactive power. The over-speed of the induction generator resulted from transient currents drawn by the induction generator from the electrical power system can exceed the stability limit resulting collapse of the system and islanding operation. Voltage fluctuations during normal operations can be mitigated and voltage instability during grid faults can be prevented by using dynamic reactive compensation [6].

From the distribution system point of view, reactive power compensation is an important issue. Excessive reactive current increases distribution losses, reduces system power factor and causes large variations in bus voltages. Moreover, power quality, voltage swells, voltage sag issues, as well as harmonics propagation are other aspects that require attention with dispersed wind energy interface and wind farm installations [6].

2. Variable-speed Wind Turbines

Variable-speed wind turbines are designed to achieve maximum aerodynamic efficiency over a wide range of wind speeds. It has more complicated electrical system than that of a fixed-speed wind turbine. It is typically equipped with an induction or synchronous generator and connected to the grid through a power converter. The power converter controls the generator speed. The advantages of variable-speed wind turbines are the increased energy capture, improved power quality, and reduced mechanical stresses on the wind turbine. However, some of the disadvantages are losses in power electronics, use of more components and the increased cost of equipment because of the power electronics. The introduction of variable-speed wind turbine types increases the number of applicable generator types and also introduces several degrees of freedom in the combination of generator type and power converter type [5].

II. UTILIZING (STATCOM) FOR POWER QUALITY IMPROVEMENT

A. STATCOM Technology and Principle

The STATCOM operates according to the voltage source converter principle (VSC), which together with PWM (Pulsed Width Modulation) switching of IGBTs (Insulated Gate Bipolar Transistors) gives it unequalled performance in terms of effective rating and response speed [7].

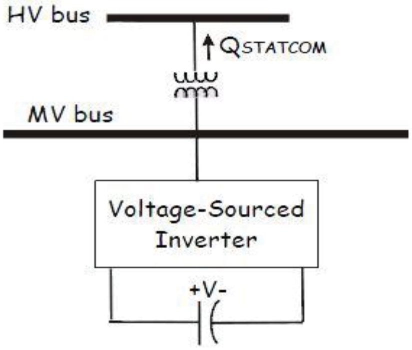

Fig. 2. Schematic Diagram of Basic STATCOM

STATCOM can be seen as a voltage source behind a reactance. Physically it is built with modular, multilevel converter (MMC) blocks each operating on a constant, distributed dc voltage. It provides reactive power generation as well as absorption purely by means of electronic processing of voltage and current waveforms in a voltage source converter (the grid will see it as a synchronous machine without inertia). This means that shunt capacitor banks and shunt reactors are not needed for generation and absorption of reactive power from the VSC, facilitating a compact design and a small footprint. See Figure 4, 5 for an illustration of how the VSC operates in capacitive and inductive modes relative to the grid voltage [8].

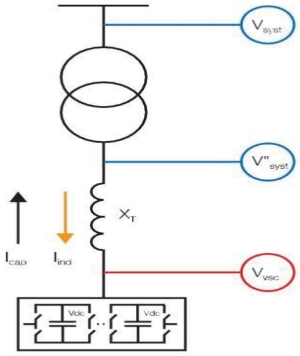

Fig. 3. Schematic Diagram of STATCOM Voltages

When the voltage of the VSC (red) is less than the system voltage (blue) as in the top graph, then the VSC will be absorbing reactive power (i.e. operating inductively) as the current is phase shifted, lagging, compared to the voltage as per fig.4.

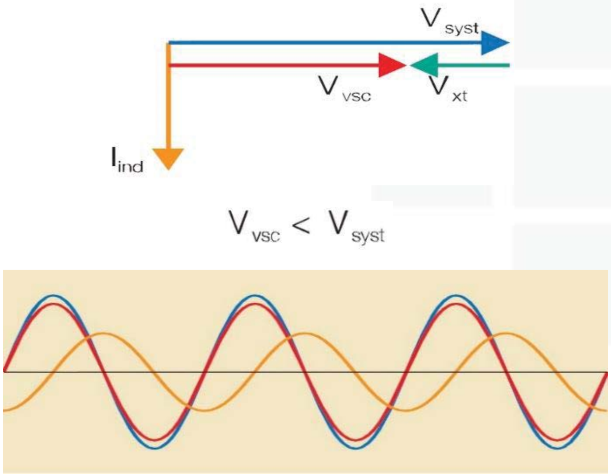

Fig. 4. STATCOM Operation of Inductive Mode

On the other hand, when the VSC voltage is higher than the system voltage as in the bottom graph, the VSC will be supplying reactive power (i.e. operating capacitively) as the current is phase shifted, leading, compared to the voltage as per fig.5.

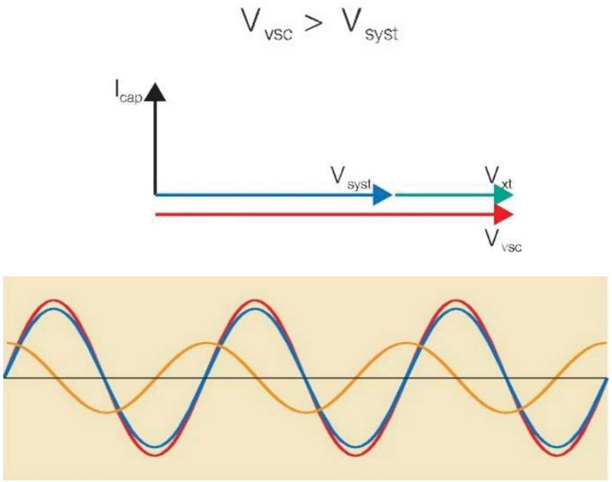

Fig. 5. STATCOM Operation of Capacitive Mode

B. Topologies of (STATCOM) Versus (SVC)

The V/I curve is a useful tool to see how a device will operate in the network, and is particularly useful to evaluate under/over voltage abilities of the various FACTS devices.

As per below figures, for under voltages, the STATCOM has superior reactive power compensation as compared to an SVC for similar sizing at 1 p.u voltage. This can be seen by the fact that the current remains constant at low voltages.

For a classical SVC on the other hand, the current decreases linearly as the voltage decreases meaning that the reactive power will be less as compared to the STATCOM by a factor of V (per-unit voltage). On the other side, a classical SVC will outperform a STATCOM during over voltage disturbances for similar sizing at 1 p.u voltage (see the right-hand side of the V/I diagram).

For each extra amount of voltage at the SVC point of common coupling (PCC), it will return more current and therefore more reactive power by a factor of V (per-unit voltage) as compared to a STATCOM [8] .

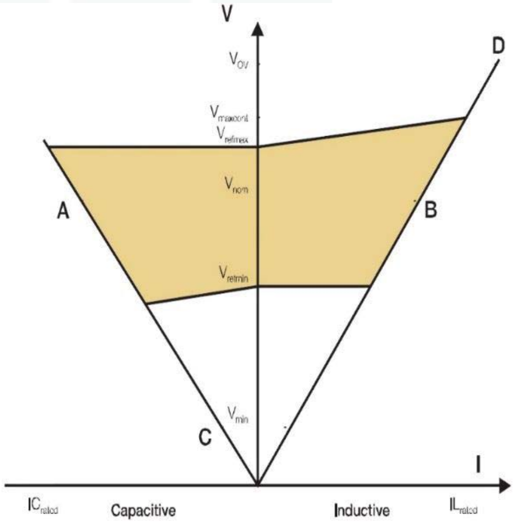

Fig. 6. V/I Diagram for SVC

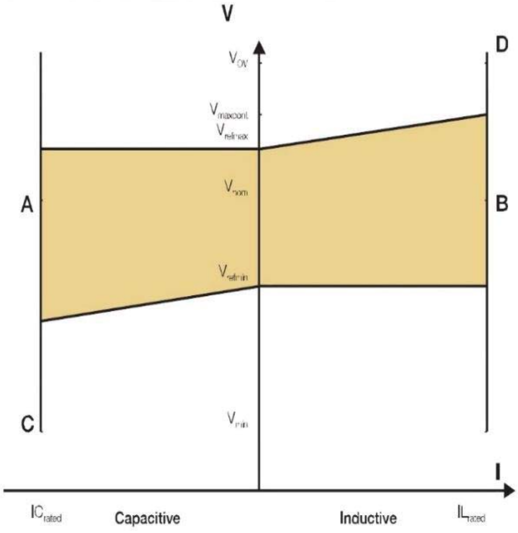

Fig. 7. V/I Diagram for STATCOM

III. POWER QUALITY ASSESSMENT FOR DIFFERENT TYPES OF WTG SYSTEMS

A. Squirrel Cage Induction Generator (SCIG)

This generator is used for constant-speed wind turbines. The generator and the wind turbine rotor are coupled through a gearbox. Wind turbines based on a SCIG are typically equipped with a soft-starter mechanism and an installation for reactive power compensation, as SCIG's consume reactive power. SCIGs have a steep torque speed characteristic and therefore fluctuations in wind power are transmitted directly to the grid. These transients are especially critical during the grid connection of the wind turbine, where the in-rush current can be up to 7 – 8 times the rated current. Therefore, the connection of the SCIG to the grid should be made gradually in order to limit the in-rush current. Because of the high magnetizing current, the full load power factor becomes relatively low. Too low power factor is compensated by connecting capacitors in parallel to the generator. In the case of a fault, SCIG's without any reactive power compensation system can lead to voltage instability on the grid.

The wind turbine rotor may speed up for instance when a fault occurs, owing to the imbalance between the electrical and mechanical torque. Thus, when the fault is cleared, SCIG's draw a large amount of reactive power from the grid, which leads to a further decrease in voltage [5], the power extracted from the wind needs to be limited, because otherwise the generator could be overloaded or the pull out torque could be exceeded, leading to rotor speed instability. In this notion, this is often done by using pitch angle control [9].

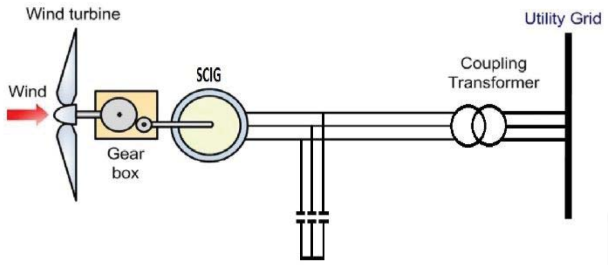

Fig. 9. Squirrel Cage Induction Generator (SCIG) Wind Turbine System

B. Doubly-fed Induction Generator (DFIG)

The stator winding of the DFIG is coupled to the grid; the rotor winding is coupled to a back-to-back voltage source converter. The other side of the converter that feeds the rotor winding is coupled to the grid. The converter decouples the electrical grid frequency and the mechanical rotor frequency [4], thus enabling variable-speed operation over a large, but restricted, range. The rotor speed is allowed to vary between 0.3 and −0.3 slip; thus, the power converter can be sized to about 30% of rated power (partial rating) [9]. The term 'doubly fed' refers to the fact that the voltage on the stator is applied from the grid and the voltage on the rotor is induced by the power converter. [5]. The wind turbine is operated at optimum Cp (wind rotor coefficient of performance) below rated wind speed, and it is operated at Prated above rated wind speeds. Thus, maximum energy yield is accomplished for low to medium wind speeds. Above rated wind speeds, the aerodynamic power is controlled by pitch to limit rotor speed and to minimize mechanical loads. With the use of power converters, the real and reactive power can be independently and instantaneously controlled within design limits. Generally, the real power control capability is used to maximize Cp below rated speed and to limit output power above rated wind speeds.

The reactive control capability is used to control the reactive power, power factor, or voltage [9]. The use of the power converter allows the rotor speed to rotate at a different speed with respect to the synchronous speed; thus, the rotor speed is not synchronized to the air gap flux. With this capability, the generator is capable of not participating in the power system oscillation, which may result in a post transient condition. Flexible grid integration, good power quality, and voltage ride through can be realized in this type of WTG [2]. It has the ability to control reactive power and to decouple active and reactive power control by independently controlling the rotor excitation current. The DFIG has not necessarily to be magnetized from the power grid; it can be magnetized from the rotor circuit, too. It is also capable of generating reactive power that can be delivered to the stator by the grid-side converter. In the case of a weak grid, where the voltage may fluctuate, the DFIG may be ordered to produce or absorb an amount of reactive power to or from the grid, with the purpose of voltage control. The converter used in DFIG is back to back converter. The back-to-back converter is highly relevant to wind turbines today.

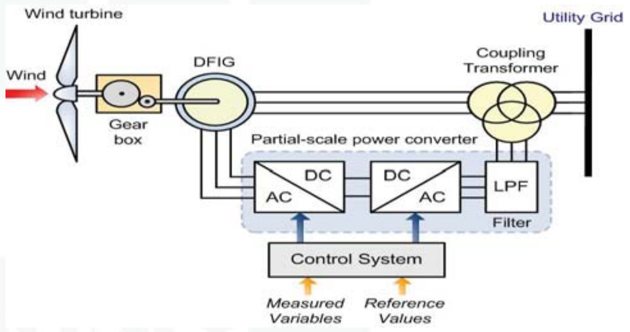

Fig. 9. Doubly-fed Induction Generator (DFIG) Wind Turbine System

C. Permanent Magnet Synchronous Generator (PMSG)

In the permanent magnet machine, the efficiency is higher than in the induction machine, as the excitation is provided without any energy supply [5], the permanent-magnet synchronous generator connected to the grid through a full-scale power converter [1], the wind turbine is operated at optimum Cp below rated wind speed, and it is operated at Prated above rated wind speeds. Thus, maximum energy yield is accomplished for low to medium wind speeds. Above rated wind speeds, the aerodynamic power is controlled by pitch to limit rotor speed and to minimize mechanical loads. Full power conversion allows the separation between the WTG and the grid; thus, the mechanical dynamic can be buffered from entering the grid and the transient dynamic on the grid can be buffered from entering the wind turbine dynamic. Thus, while the grid operates at 60 Hz, the stator winding of the generator may operate at variable frequencies. The temporary imbalance between the aerodynamic power and the generated power during a transient is handled by pitch control, dynamic brakes, and power converter control. Compared with the variable speed concept with a partial scale power converter, the full-scale power converter can perform smooth grid connection over the entire speed range. However, is has a higher cost and a higher power loss in the power electronics, since all the generated power has to pass through the power converter. The synchronous nature of the PMSG may cause problems during start-up, synchronization and voltage regulation. It does not readily provide a constant voltage. Another disadvantage of PMSGs is that the magnetic materials are sensitive to temperature. Therefore, the rotor temperature of a PMSG must be supervised and a cooling system is required.

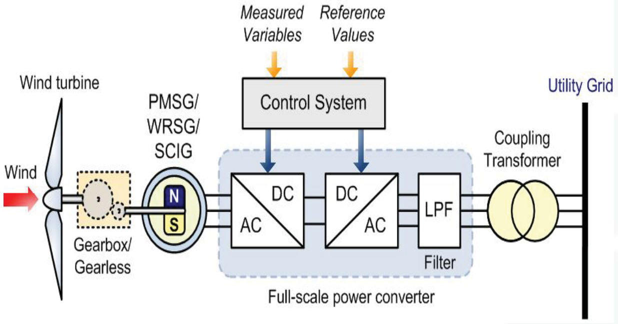

Fig. 10. Permanent Magnet Synchronous Generator (PMSG) Wind Turbine Syste

IV. WIND POWER QUALITY ISSUES

The power quality depends on the interaction between the grid and the wind turbine.

Perfect power quality means that the voltage is continuous and sinusoidal having a Constant amplitude and frequency. Power quality can be expressed in terms of physical Characteristics and properties of electricity. It is most often described in terms of Voltage, frequency and interruptions [3].

The quality of the voltage must fulfill requirements stipulated in national and international standards. In these standards, voltage disturbances are subdivided into voltage variations, flicker, transients and harmonic distortion.

A. Induction Generators Self-Excitation

Due to it's relative low cost, low need for maintenance and simple operation many wind power plants have adopted the induction asynchronous generator as the device responsible for the electromechanical energy conversion. When using an induction generator, the voltage and frequency are determined by the balancing of the system. The induction machine needs reactive power in order to produce active power, thus it is a common technique to compensate that reactive power with a shunt capacitor. Shall a grid fault occur, self-excitation of the induction generator may occur causing voltage and frequency to variate. This situation is extremely undesirable since it can damage several types of equipments including the wind turbine and high voltages produced may be a threat to human life.

B. Voltage Transients

Some capacitor banks use mechanical switches in order to provide the right amount of reactive power to induction generators. These mechanical switches can introduce large voltage transients into the wind energy generation grid very frequently. Frequent occurrences of voltage transients can damage sensitive electronic equipment used in wind energy control systems [10].

C. Voltage Unbalance

When large unbalanced loads are present in the distribution grid negative sequence currents flow into induction machines, causing them to overheat. This implies in a shorter life time For the machine and the need of it to be de-rated [6].

D. Voltage Fluctuation and Flicker

The voltage fluctuations due to wind speed variations are not only a stability issue but can also cause flicker. Flicker takes place when voltage fluctuates in a range of frequency between 10-35Hz, it may produce light disturbances to the human eye through incandescent lamps, which can trigger epileptic attacks of photosensitive persons and also damage sensitive equipment. This document presents energy storage techniques that can be used in order to avoid flicker due to wind speed variations.

V. HARMONIC DISTORTION

Voltage Total Harmonic Distortion may be defined as follows:

$$THD_v = \sqrt{\sum_{h=2}^{N} \frac{V_h^2}{V_1^2}}$$

Where Vh is the voltage rms value for the harmonic of order h. N for the ANSI std 368 should be 83 for a 60Hz system.Current Total Harmonic Distortion may be defined analogously:

$$THD_i = \sqrt{\sum_{h=2}^{N} \frac{I_h^2}{I_1^2}}$$

Harmonic Distortion can cause reduction in equipments lifetime, malfunctioning of sensitive equipment, power losses, heating of transformer cores and many other issues. Sub harmonics, voltage or current components that present a frequency under 60Hz are also a big issue in power quality and can damage generators due to it's low frequency of oscillation. It is common practice to rectify the electric power from a wind power plant and feed it into an inverter, in order to control the injected current phase and total harmonic distortion [6].

VI. SIMULATION AND RESULTS

A wind farm consisting of six 1.5MW wind turbines is connected to a 25kV distribution system exports power to a 120kV grid through a 25km 25kV feeder.

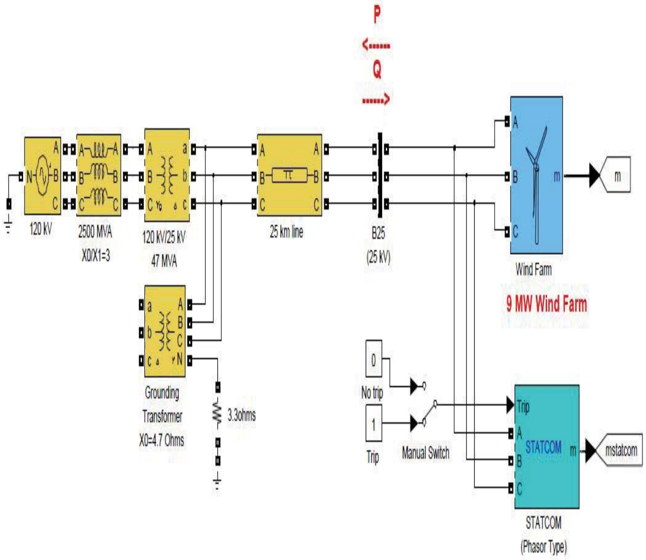

Fig. 11. Case Study System for Wind Farm Connected to the Grid

The 9MW wind farm is simulated by three pairs of 1.5 MW wind turbines. Wind turbines use squirrel cage induction generators (IG).The stator winding is connected directly to the 60 Hz grid and the rotor is driven by a variable pitch wind turbine. The pitch angle is controlled in order to limit the generator output power at its nominal value for winds exceeding the nominal speed (9 m/s).

In order to generate power the IG speed must be slightly above the synchronous speed. Speed varies approximately between 1 pu at no load and 1.005 pu at full load. Each wind turbine has a protection system monitoring voltage, current and machine speed.

The turbine mechanical power as function of turbine speed is displayed for wind speeds ranging from 4 m/s to 10 m/s. The nominal wind speed yielding the nominal mechanical power (1pu=3 MW) is 9 m/s.

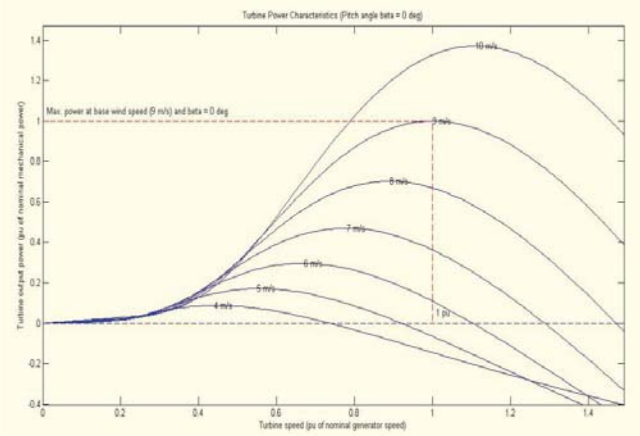

Fig. 12. Wind Turbine Power V.S. turbine Speed

Reactive power absorbed by the IGs is partly compensated by capacitor banks connected at each wind turbine low voltage bus (400 kvar for each pair of 1.5 MW turbines). The rest of reactive power required to maintain the 25kV voltage at bus B25 close to 1 pu is provided by a 3Mvar STATCOM with a 3% droop setting.\

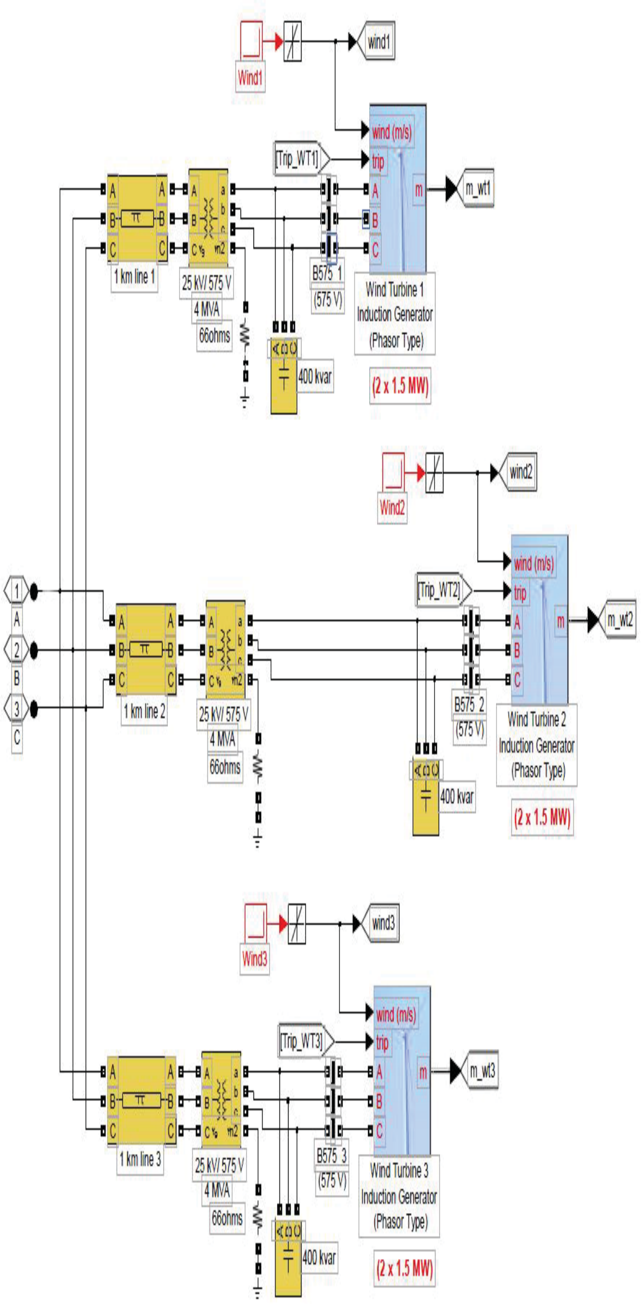

Fig. 13. Case Study System for (6x1.5MW) Wind Farm Connected to the Grid

Initially, wind speed is set at 8 m/s, then starting at t=2s for "Wind turbine 1", wind speed is rammed to 11 m/s in 3 seconds. The same gust of wind is applied to Turbine 2 and Turbine 3, respectively with 2 seconds and 4 seconds delays.

At first, without using STATCOM and by observing the signals on the "Wind Turbines" scope monitoring active and reactive power, generator speed, wind speed and pitch angle for each turbine.

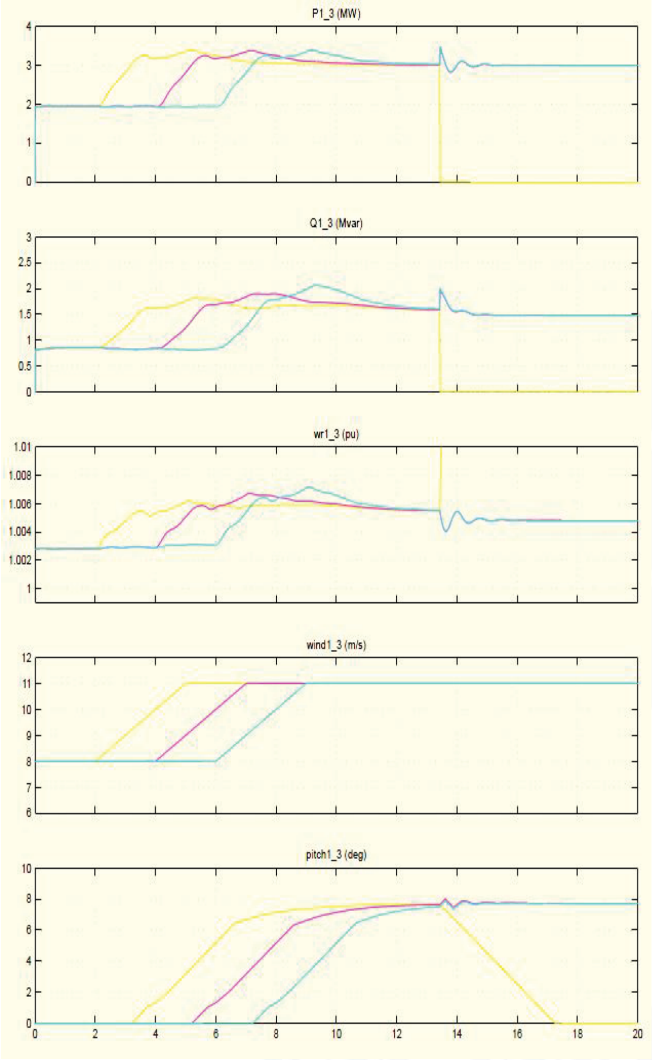

Fig. 14. Active power, reactive power at buses B575 (1, 2, 3), Speed of SCIGs and pitch angles without STATCOM

For each pair of turbine the generated active power starts increasing smoothly (together with the wind speed) to reach its rated value of 3 MW in approximately 8s. Over that time frame the turbine speed will have increased from 1.0028 pu to 1.0047 pu.

Initially, the pitch angle of the turbine blades is zero degree. When the output power exceed 3 MW, the pitch angle is increased from 0 deg to 8 deg in order to bring output power back to its nominal value. Observe that the absorbed reactive power increases as the generated active.

Observe on “B25 Bus" scope that because of the lack of reactive power support, the voltage at bus "B25" now drops to 0.91pu. This low voltage condition results in an overload of the IG of "Wind Turbine 1". "Wind Turbine 1" is tripped at t=13.43 s.

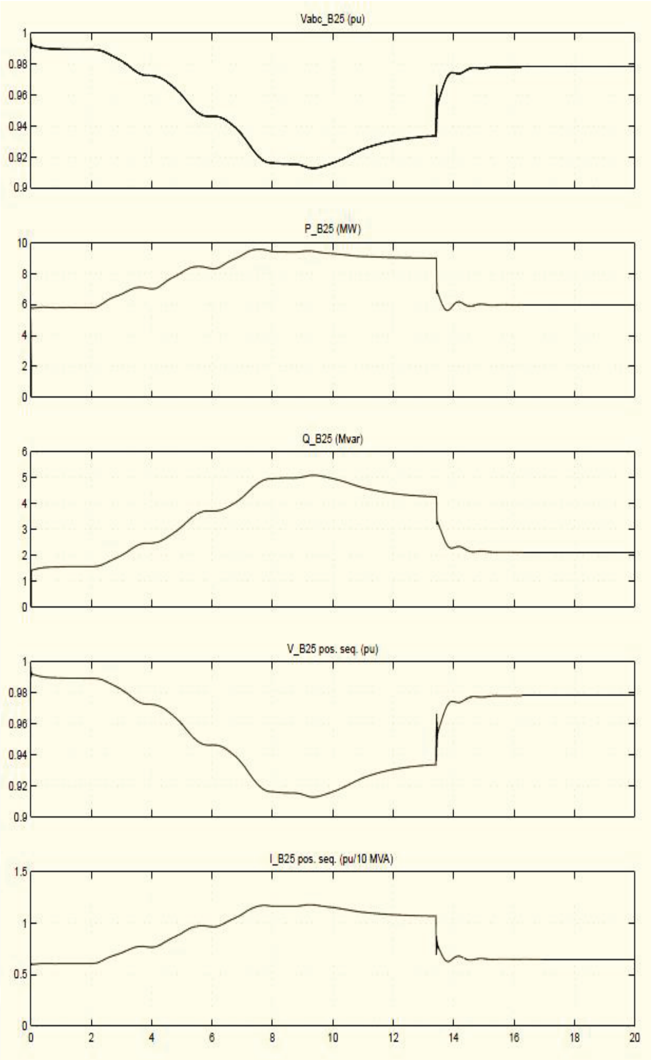

Fig. 15. The voltage, the current, active power and reactive power at bus B25 without using STATCOM

If you look inside the "Wind Turbine Protections" block you will see that the trip has been initiated by the AC Overcurrent protection.

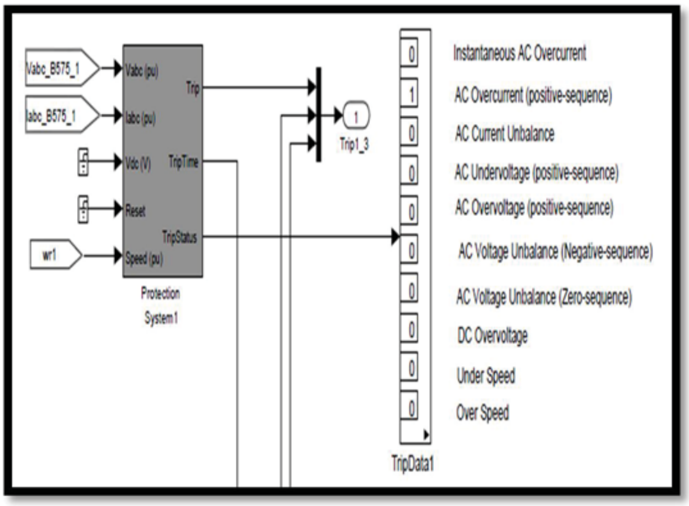

Fig. 16. Tripping status for AC overcurrent (positive sequence

By connecting STATCOM to "B25" bus as per Fig.17:

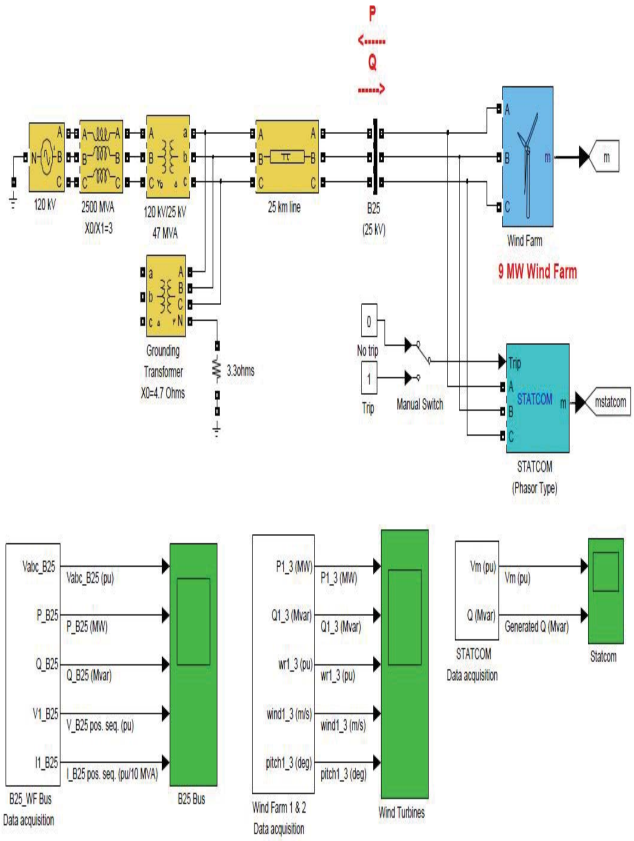

Fig. 17. Utilizing STATCOM for Wind Farm Connected to the Grid

Now, Observing the same scope monitoring by connecting STATCOM , For a 11m/s wind speed, the total exported power measured at the B25 bus is 9 MW and the STATCOM maintains voltage at 0.984 pu by generating 1.62 Mvar (see "B25 Bus" characteristics in Fig.22 and "STATCOM" characteristics in Fig.21).

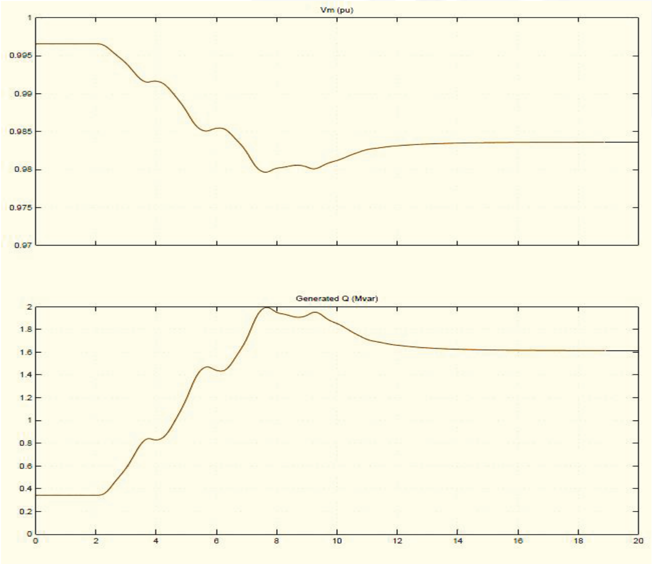

Fig. 18. Voltage (p.u) and generated reactive power at STATCOM scope

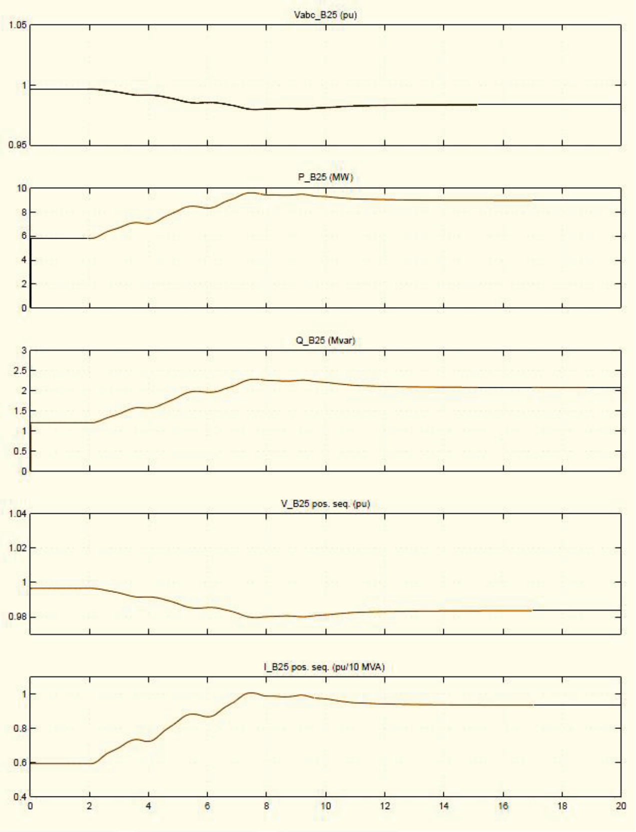

Fig. 19. The voltage, the current, active power and reactive power at bus B25 after using STATCOM

By utilizing STATCOM, all turbines will be stable as shown in fig.20.

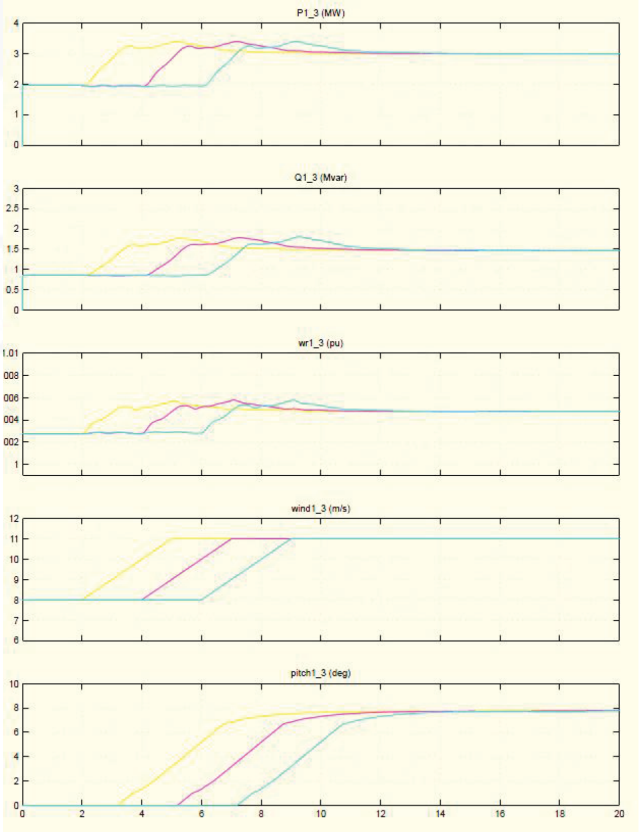

Fig. 20. Active power, reactive power at buses B575 (1, 2, 3), Speed of SCIGs and pitch angles after using STATCOM

VII. CONCLUSION

In this paper we considered a system with static synchronous compensator (STATCOM) and without it and have compared the results. The simulation results show that STATCOM has compensated reactive power in the best manner and has provided voltage stability when the wind farm is acting as a supplier of energy to the consumers and the voltage profile has been improved well. Also, it should be noted that the existence of fixed capacitor banks allows reducing the rating of STATCOM with considerable decrease in device cost. On the other hand the model of FSWT has been presented in order to study the dynamic behavior of this system when connected to a public power system.

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