Dynamic Stability Improvement of an Integrated Grid-Connected Wind Farm Using a STATCOM

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Abstract: The main objective of the paper is to enhance the voltage stability of integrated grid connected wind farm using squirrel cage induction generator with STATCOM. Grid connected Fixed Speed Wind Turbines (FSWT) may cause voltage stability problems which results in islanding of the generator from the grid. Voltage stability is a major issue to achieve the uninterrupted operation of wind farms equipped with FSWTs. The dynamic STATCOM is validated by simulation with simulation techniques. The voltage fluctuations of the AC bus subject to the active-power variations of the studied system can also be effectively controlled by the proposed control scheme. To analyze the performance of the STATCOM connected in shunt with the transmission line, an induction generator based wind farm has been considered. The complete digital simulation of the STATCOM incorporated into the power system is performed and the results are presented to validate the feasibility of the proposed topology.

Key words: Wind Farm % Induction Generator % Point of Common Coupling (PCC) % Voltage Source Converter (VSC) % Flexible AC

INTRODUCTION

Wind power very often is a source of voltage fluctuating and flicker. The dominating type of wind generators are induction generators, since they are robust and cost effective. But they do not contribute to voltage regulation because they are substantial absorbers of reactive power. Voltage control problems are remedied by installation of fixed and Mechanically Switched Capacitors (MSC). Regular voltage flicker and voltage fluctuations caused by varying output wind generators cannot be solved using conventional methods.

To solve this problem dynamic reactive power compensation must be provided which improves the voltage stability and makes the wind farm to meet the grid code requirements. To achieve this, FACTS controller STATCOM plays a vital role in the voltage stability in power system network. STATCOM provides superior voltage support capability with its nature of voltage source. The dynamic simulations are used to verify the performance of the proposed STATCOM control strategy using MATLAB/SIMULINK software tool.

Grid Code Requirements: In earlier years of the wind power industry most individual wind turbines or first small wind farms were connected to distribution networks. Because the levels of integration were very small at that time, TSO's regarded connected wind turbines as negative loads. But as larger wind turbines were merging into wind farms with sizes starting to reach comparable levels with conventional power plants, TSO's concern grew due to power quality and network stability problems.

As a result, based on a number of parameters, such as grid stiffness, transmission voltage levels, wind turbine topology, TSO's issued a number of requirements for wind turbines to fulfill in order to get grid connection agreement. These requirements were called grid codes and they became more demanding as wind penetration levels grew and regional specific as well. The grid codes regarding Wind Power are country specific. However each of the TSO's issues a number of different requirements. Some of them are described below in the following manner.

The active power/frequency control demands that the active power deviation around actual output should stay in accordance with a voltage/frequency diagram stated in

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grid codes. Several regulation techniques are defined in the grid codes. A power/frequency characteristic, or droop characteristic controls the slope of active power production. This control shall be adjusted according to TSO demands [1].

Nowadays the wind power plants are required to be able to fulfill the reactive power and voltage control demands. Due to the current penetration level of Wind Power in the grid must provide the reactive power exchange with the grid. The exchange rate and level is specified by the TSO. The given range defines for each operation set point the minimal amount of reactive power (lagging or leading) in respect to produced active power.

In every national grid codes a set of requirements are imposed to cope with problems arising due to rapid voltage changes/jumps, voltage flicker and harmonics. These requirements are more important on medium voltage levels, especially where the wind power penetration level is high. Rapid voltage changes refer to sudden increase/decrease in the value of RMS voltage at the PCC. Flicker is a term used for defining the unsteadiness of visual sensation in the light source, cause by voltage fluctuations. These variations occur due to switching of capacitors, lines, cables transformers etc. in the system. For harmonic disturbance the indicator Dn denotes the level of distortion for each individual harmonic:

$$Dn = (Un/Ul) * 100\% \tag{1}$$

Which should be less than 1.0% at PCC for every $1 < n < 51$. The total harmonic effective distortion (THD) is defined as:

$$THD = 100\sqrt{\sum_{n=2}^{50}\left(\frac{U_n}{U_l}\right)^2}\% \tag{2}$$

and it should have a value less than 1.5% at PCC.

Wind Turbines Capabilities with Respect to Grid Codes: Fixed Speed Wind Turbine is a concept that uses a Squirrel Cage Induction Generator directly connected to grid. Therefore the speed of this WT is fixed by the grid frequency. Due to this fixed speed, the wind fluctuations are converted in power fluctuations which will cause voltage variations in weaker grids. Having large numbers of FSWT in a wind farm connected to grid, the reactive power consumption will be large. This reactive power can be compensated by adding capacitor banks to each individual WT, for achieving a PCC power factor close to

unity. This type of WT lacks power electronic interfaces; therefore reactive power control is not possible. The tracking of optimum active power and assuring power quality cannot be fulfilled. In case of a grid fault there is a large amount of fault current contribution, thus the turbines need to rely on protection devices (over current, over- and under voltage, over and under frequencies). As a result FSWTs cannot meet grid code demands without any form of external support such as FACTS devices.

Power Flow Control in Transmission Lines: Active and reactive power in a transmission line depend on the voltage magnitudes and phase angles at the sending and receiving ends as well as line impedance. To facilitate the understanding of the basic issues in power flow control using VSC-based FACTS controllers, the simple model shown in Fig. 2(a) is used. The sending and receiving ends are connected by an equivalent reactance X, assuming that the resistance of high voltage transmission lines is very small. The receiving end is modeled as an infinite bus with a fixed angle of 0°.

For the receiving end side;

$$SR = PR + j QR \tag{3}$$

$$PR = (VS*VR \sin{^*})/X \tag{4}$$

$$QR = VS*VR(\cos{^*} - VR)/X \tag{5}$$

Similarly, for the sending end

$$Ps = VSVR \sin{^*}/ X \tag{6}$$

$$= Pmax \sin{^*} \tag{7}$$

$$Qs = VS (VS-VR \cos{^*})/X \tag{8}$$

The equations for sending and receiving end active power flows, PS and PR, are equal because the system is assumed to be a lossless system. As it can be seen in Fig. 2 (b), the maximum active power transfer occurs, for the given system, at a power or load angle * equal to 90°. Maximum power occurs at a different angle if the transmission losses are included. The system is stable or unstable depending on whether the derivative dp/d * is positive or negative. The steady state limit is reached when the derivative is zero. In practice, a transmission system is never allowed to operate close to its steady
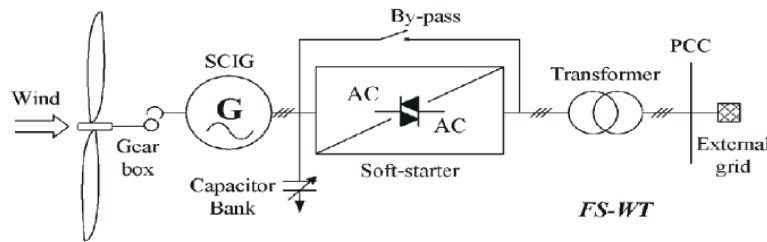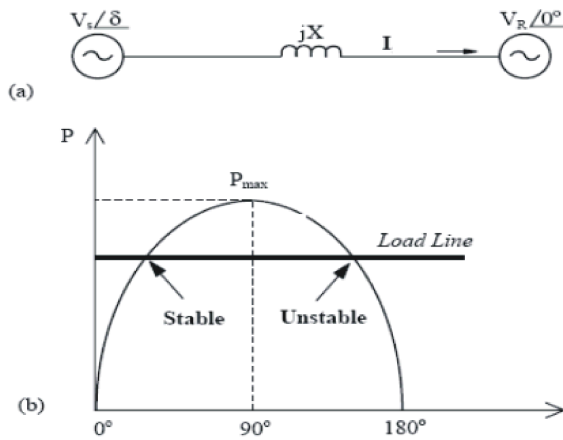
Fig. 1:

Fig. 2: (a) Equivalent Circuit Model (b) Power Angle Curve of a Lossless Line

state limit, as certain margin must be left in power transfer in order for the system to be able to handle disturbances such as load changes, faults and switching operations. Fig. 2(b), the intersection between a load line representing sending end mechanical (wind turbine) power and the electric load demand line defines the steady state value of *; a small increase in mechanical power at the sending end increases the angle.

For an angle above 90°, increased demand results in less power transfer, which accelerates the generator and further increases the angle, making the system unstable; on the left side intersection, however, the increased angle * increases the electric power to match the increased mechanical power. In determining an appropriate margin for the load angle, the concepts of dynamic or small signal stability and transient or large signal stability are often used. Typical power transfers correspond to power angles below 30°; to ensure steady state rotor angle stability, the angles across the transmission system are usually kept below 45°.

Eq. (4) and Eq. (6) shows that the real or active power transfer depends mainly on the power angle and inspection of Eq. (5) and Eq. (7) shows that the reactive power requirements of the sending and receiving ends are

excessive at high angles and high power transfers. It is also possible to conclude that reactive power transfer depends mainly on voltage magnitudes, which flows from the highest voltage to the lowest voltage, while the direction of active power flows depends on the sign of the power angle.

Eq. (4) to Eq. (7) show that the power flow in the transmission line depends on the transmission line reactance, the magnitudes of sending and receiving end voltages and the phase angle between the voltages. The concepts behind FACTS controllers are to enable control of these parameters in real-time and, thus, vary the transmitted power according to system conditions. The ability to control power rapidly, within appropriately defined boundaries, can increase transient and dynamic stability, as well as the damping of the system. For a given power flow, a change of X also changes the angle between the two ends. Regulating the magnitudes of sending and receiving ends voltages, VS and VR can also control power flow in a transmission line. However, these values are subject to tight control due to load requirements that limit the voltage variations to a range between 0.95 and 1.05 p.u. and hence cannot influence the power flows in a desired range.

Hence, the regulation of voltage magnitude has much more influence over the reactive power flow than the active power flow. Of the FACTS controllers, the STATCOM has the ability to increase/decrease the terminal voltage magnitude and, consequently, to increase/decrease power flows in the transmission line. FACTS controllers can be used to control steady state active and reactive power flow, but it should be also noted that these fast controllers could have pronounced, positive impact on transient and dynamic conditions in a power system if designed properly. The STATCOM has the ability to control reactive power absorption/generation and since its time response is very fast, sometimes even less than one cycle, it can be used to effectively prevent the problem of voltage stability in FSWTs.
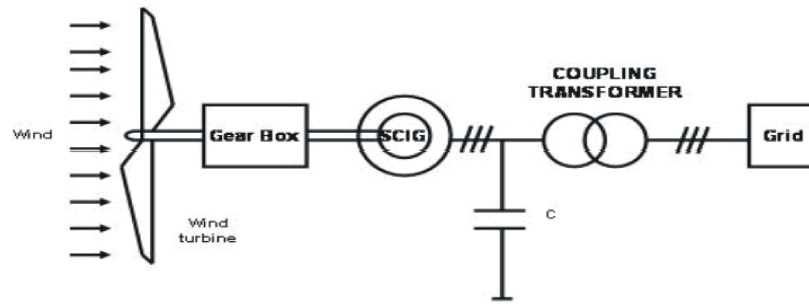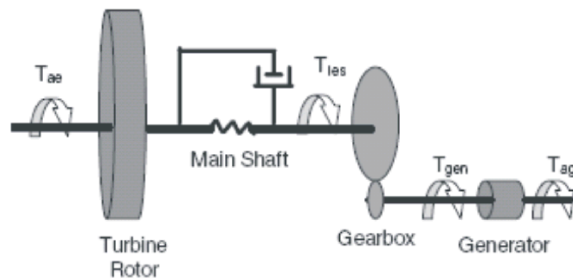
Fig. 3: Grid connected FSWT

Fig. 4: Drive Train Model

Wind Turbine Model: The dynamic stability of induction generators directly connected to a grid as shown in Fig. 3 depends on the characteristic of the generator, the grid configuration and the characteristic of the disturbance.

Wind farms with induction generators generate real power and consume reactive power [2]. 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. The most commonly used dynamic reactive compensators are the thyristor-based

Static Var Compensator (SVC) and the voltage source converter (VSC) based Static Synchronous Compensator (STATCOM). Compared to the SVC, the STATCOM is able to provide faster and smoother dynamic voltage control because of its rapid and continuous response characteristics. Therefore, it is more suitable for voltage flicker mitigation at the connection point of the wind farm.

In order to evaluate the improvement of the stability conditions that a STATCOM can produce in the system with a wind farm connected to a weak grid, power system simulation have been performed in MATLAB/ SIMULINK. A sketch of the power system that has been studied is outlined as drive train model as shown in Fig. 4.

In this model it is known that a wind turbine with squirrel-cage induction generator has a relatively soft coupling between the turbine rotor and the induction generator rotor this means that a two mass representation of the shaft would be recommended. One mass is representing the turbine and another representing the generator rotor. In case of non-representation of the shaft by two-mass model, that is, the shaft is represented by a lumped-mass model, the result would give an oversimplified representation of the wind turbine shaft system, but the behavior of the frequency deviation follows the expected average frequency curve. Considering that the study will compare cases with or without the STATCOM a simpler representation of the shaft has been used in the study, which means, a single mass representation [3].

Statcom Topology: The STATCOM is based on a solid - state voltage source implemented with an inverter and connected in parallel to the power system through a coupling reactor. A STATCOM consists of an inverter and a DC capacitor as shown in Fig. 5. With this arrangement, this device can supply both leading and lagging vars with a small energy storage device.

The AC current is the result of interaction of the converter output voltage with the AC system and can have any phase relationship with respect to the voltage. It is always a combination of two controlled switches and one uncontrolled switch conducting and vice versa. The converter supplies real power from its DC capacitor to the AC system if the converter output voltage leads the corresponding AC system voltage whereas the converter absorbs real power from the AC system if the converter output voltage is made to lag the AC system voltage. The amount of exchanged real power is typically small in
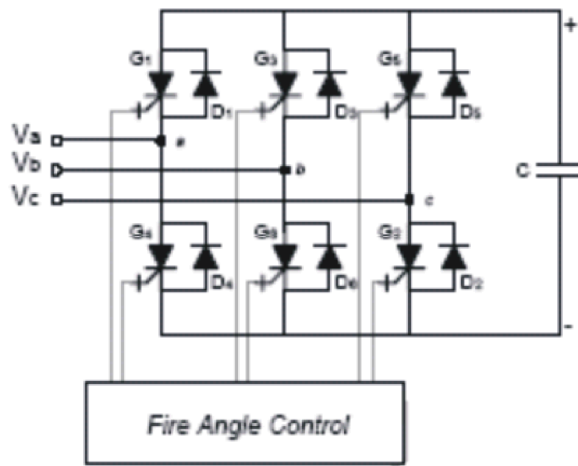
Fig. 5: STATCOM Inverter

Fig. 6: Equivalent Circuit Model

steady state; hence, the firing angle is also small. The real power that is being exchanged by the transmission system must be supplied or absorbed at its DC terminals by the DC energy storage. In contrast, the reactive power exchange is internally generated or absorbed by the voltage-sourced converter, without the DC energy storage device playing any part in it [4].

If two sources V1 with a phase angle of * and V2 with a phase angle of 0 are connected together by means of an inductive link of impedance (R +j X) ohms as shown in Fig. 6 and if the active power flowing into the source V2 is constrained to be zero (because this represents the STATCOM situation) the power delivered by the source V1 (which will not be zero and it will be equal to the power absorbed by the resistance in the link) and the reactive power delivered to the link by the source V2 will be given by the following relations (Assuming * is small and R << X).

Active power delivered by V1,

$$P = (V1^2/ R) **^2 \tag{9}$$

Reactive power delivered by V2,

$$Q =(V1*V2)/R* * \tag{10}$$

Also,

$$Q = V2 (V2-V1)/X \tag{11}$$

where the powers are for one phase and voltages have phase values. These relations can be used up to about 20 degrees for *. Active Power drawn from the source V1 is independent of sign of phase angle (only V1 can supply losses in R because of the zero active power constraint at V2) whereas the reactive power delivered by V2 is directly proportional to the phase angle. In the STATCOM context, the source V1 is the power system voltage at the bus where the STATCOM is connected, V2 is the AC voltage generated by the inverter in the STATCOM, R is the total loss resistance in the link comprising the winding losses in the link inductor, interface magnetic, the inverter switches and snubber etc. It is also possible to derive the following useful relationships in this context. The phase angle of V1 with respect to V2.

$$* = (R/X)*((V2-V1)/V1) \tag{12}$$

This shows that the relative phase angle is linearly related to the voltage magnitude difference (for small differences) and hence the reactive power delivered by V2 is proportional to the voltage magnitude difference. Thus Q is proportional to * or equivalently to (V2-V1). In the STATCOM, the required AC voltage source V2 is generated by inverting the DC voltage, which is assumed available across the capacitor in the DC side [5]. But if the active power which goes into the inverter from the mains is kept zero, the initially charged capacitor will soon discharge down to zero due to active power losses in the inverter which the D.C. side will have to supply. The DC side voltage will remain constant (or at least controlled) if the power drawn from mains is just enough to supply all the losses which take place everywhere due to the flow of demanded reactive current. The DC side capacitor voltage is,

$$Vdc = (V1/K)*(1-(X/R))* * \tag{13}$$

where V1 is the rms phase voltage of AC mains, k is a constant, which also absorbs the modulation index of PWM process in the Inverter.VSC transforms, through appropriate switching sequence, DC voltage at its DC terminals into an AC voltage of controllable frequency, magnitude and phase angle at its terminals. The output voltage could be fixed or variable, at a fixed or variable frequency. For FACTS application purposes, it is always assumed that the output voltage wave form has a fixed
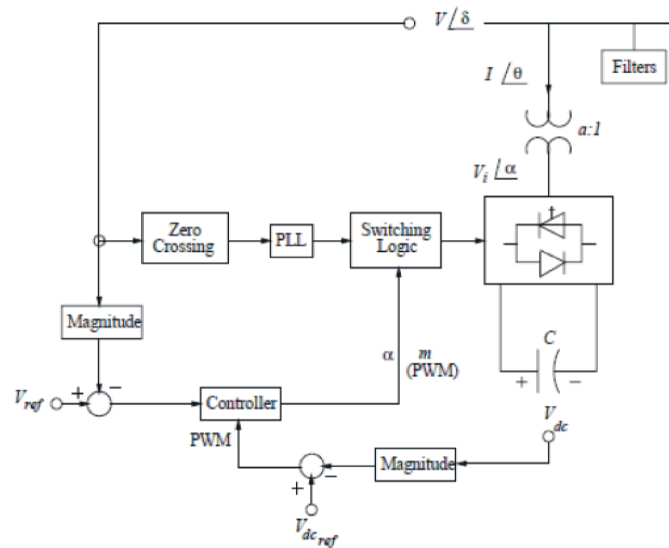
Fig. 7: Control Strategy of STATCOM

frequency equal to the fundamental frequency of a power system to which the converter is connected, as high voltage and power harmonics could create many problems [6].

Statcom Control Strategy: Fig. 7 shows the block diagram of control scheme implemented in STATCOM. A STATCOM is configured to keep the reactive power delivered by the source at a zero value as long as the reactive demand is within the STATCOM rating. The control of STATCOM reactive power is by " and m control. The source side voltages and currents are sensed and the reactive power is calculated by analog/pulse circuitry. This calculated value is compared with the desired value (usually zero) and the error is processed in a Proportional-Integral-differential Controller. The error output decides the phase shift needed in the inverter output in order to develop the required DC bus voltage such that the inverter output voltage magnitude will be sufficient to make the Inverter deliver the var required by the load. The inverter is gated by a fixed PWM pattern optimized for eliminating chosen harmonics (usually fifth, seventh, eleventh etc; triple harmonics need not be eliminated since they do not result in current flows in a three wire system).

The PWM technique is commonly employed to generate high quality output waveforms by relatively low power converter used in wind power applications. With this technique, the output of each converter pole is switched several times during a fundamental cycle between the positive and negative terminals of the DC source. PWM requires a considerable increase in the number of switch operations ,thereby it generally increases the switching losses of the converter. However, the always increasing switching frequency of modern solid-state power switches used in FACTS controllers made possible the use of PWM in high power applications.

The aim of the PWM control scheme is to maintain constant voltage magnitude at the point of common coupling, under system disturbances. The control system only measures the rms voltages at the PCC, i.e., no reactive power measurements are required. With these converters, the ac output voltage can be controlled, by varying the width of the voltage pulses.

Test System and Comments on Results: In order to evaluate the improvement of the stability conditions that a STATCOM can produce in the system with a wind farm connected to a weak grid, power system simulation is performed in MATLAB/ SIMULINK as shown in Fig. 8. A 3 MW wind farm consisting of single Squirrel Cage Induction Generator (SCIG) driven by Fixed Speed Wind Turbine (FSWT) is connected to a power grid through a step-up transformer and a power line. The Wind Turbine Generator (WTG) with a rated power capacity of 33MW is considered here. A STATCOM is shunt connected at the 25kV bus (the high voltage terminal of the transformer) to provide dynamic reactive compensation [7].

To reduce the size of the STATCOM, a fixed capacitor bank is used to supply about 400 Kvar reactive power at the nominal voltage condition. The parameters
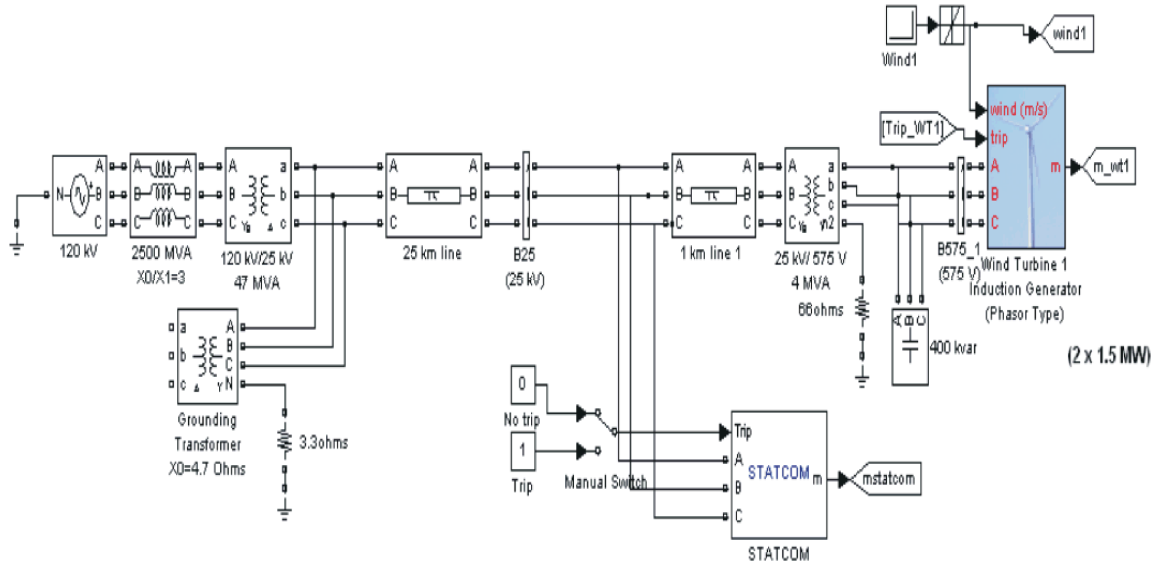
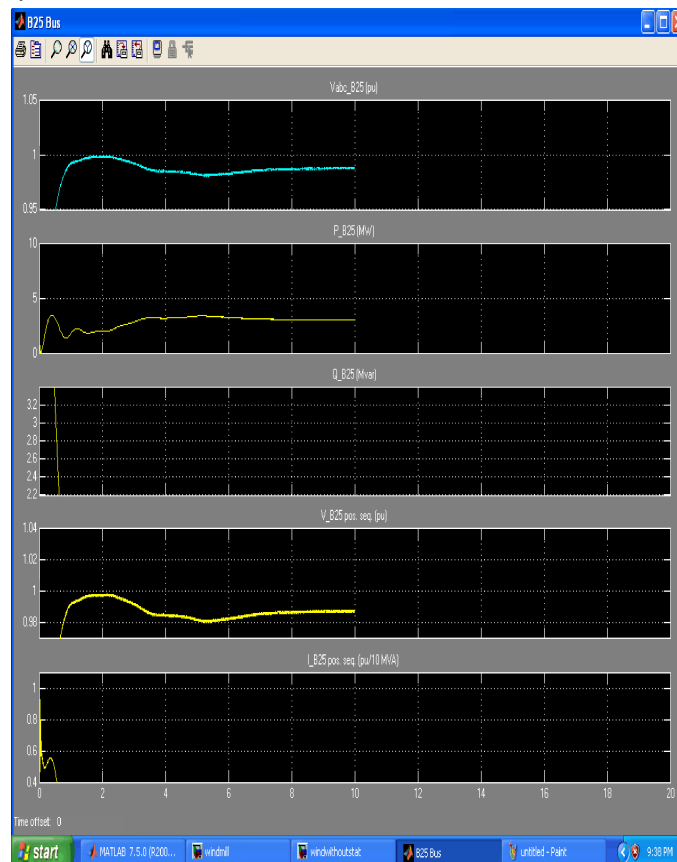Fig. 8: Diagram of the test system

Fig. 9: Voltage, real power, reactive power and current at bus B25 without STATCOM

of the system components are as follows. SCIG: rated power = 33MW, rated stator voltage = 575 V, stator resistance = 0.004843 pu, rotor resistance = 0.004377 pu, stator leakage inductance = 0.1248 pu, rotor leakage inductance = 0.1791 pu, magnetizing inductance =6.77 pu.
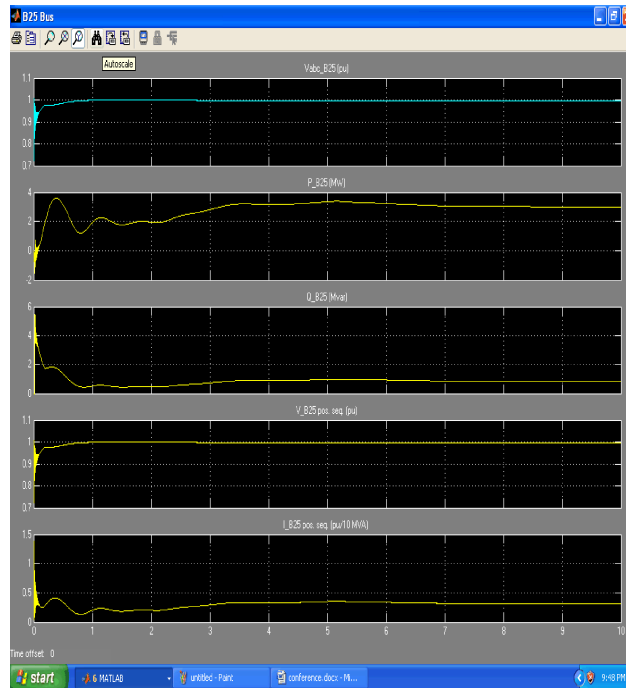
Fig. 10: Voltage, real power, reactive power and current at bus B25 with STATCOM
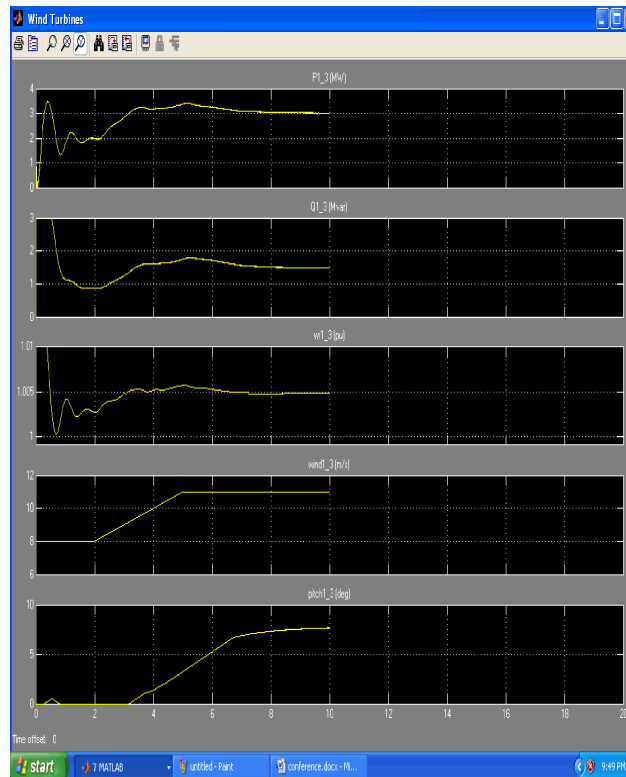

Fig. 11: Real power, reactive power, generator speed, wing speed and pitch angle of wind turbine without STATCOM

In order to evaluate the improvement of the stability conditions that a STATCOM can produce in the system with a wind farm connected with induction generators [8], different power system simulations have been performed in MATLAB/ SIMULINK model as shown in the simulation results are as shown from Fig. 9 Fig. 15.
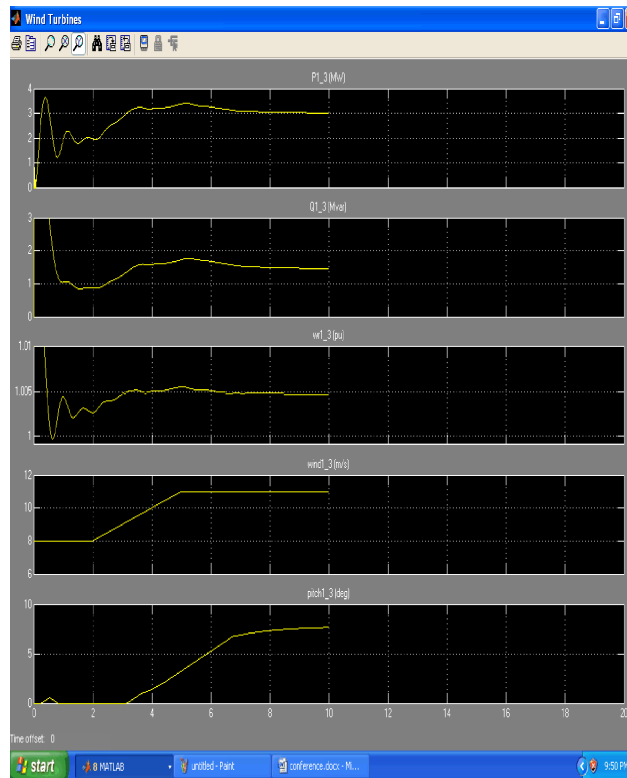
Fig. 11: Real power, reactive power, generator speed, wing speed and pitch angle of wind turbine with STATCOM

CONCLUSION

This paper has analyzed the transient stability limits of a wind farm with squirrel-cage induction generators. It has been analyzed that the squirrel-cage induction generators used in constant-speed turbines can lead to voltage and rotor instability. The study has demonstrated that an additional active voltage / Var support produced by a STATCOM can significantly improve the recovery of wind turbines from voltage collapse since this device can make a faster restoration of the voltage, improving the stability limit conditions of the induction generators [9]. It is found in the simulation results that the STATCOM can provide a major increase in the transient stability margin of power systems that integrate wind generation. The experimental results provide a clear qualitative verification of transient margin increase in the wind energy conversion system with STATCOM when compared to the system without the STATCOM support. The STATCOM is an optimum candidate for providing ride through in wind farms equipped with asynchronous generators directly connected to the grid. Voltage fluctuations during normal operations can be mitigated and voltage instability during islanding operation can be prevented by using dynamic reactive compensation [10].

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