Journal of Engineering Sciences, Assiut University, Vol. 39, No 1, pp. 99-111, January 2011

SUPPORT OF FSIG WIND FARM CONNECTED TO THE GRID DURING FAULTS

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(Received November23, 2010 Accepted December 29, 2010)

The penetration of wind power in electrical power system is increased rapidly. Most conventional wind farms are based on fixed speed induction generators FSIG. So it is very necessary and important to study the transient stability ofthe wind farms with FSIC. This paper investigates the impacts of fault occurrence on the stability of wind farm interconnected grid. The behavior of the wind farm during different fault types such as single phase to ground fault, double phase to ground fault and three phase to ground fault is studied. Also, the impacts of reactive power compensator during steady state and fault state conditions are studied. A simulation model of wind farm based on FSIG interconnected grid and equipped with static synchronous compensator STATCOM are developed by MATLAB-SIMULINK toolbox.

KEYWORDS: *Wind Power, FSIG, Fault Types, Wind Farm Protection, STATCOM.*

1. INTRODUCTION

Energy is an essential element to economic and social development. Securing the energy supply is one of the major challenges. An increased world population, an enlarged global economy and higher standards of living all contribute to larger demands for energy. Many countries, including Egypt, are still heavily dependent on oil which will eventually become depleted within a few decades. At the same time, we are facing one of the greatest threats ever climate change. Therefore there is an urgent need for the using of the new renewable energy sources. Wind energy has emerged as the most attractive solution to the world's energy challenges. As a result, wind is the fastest growing energy source in the world today, more and more wind farms are being connected into power systems.

The problem is that, the most currently installed wind turbines are fixed speed wind turbines which utilize the squirrel cage induction generator directly connected to the grid to produce the electricity, these induction generators tend to drain large amounts of VARs from the grid. In steady state operation, these induction generators absorb reactive power for excitation, moreover in the case of short circuit fault in the power system, those wind turbines are easily over speeded and the need of absorbing more extreme reactive power is raised, potentially causing low voltage and there may be stability problems for the power system [1-2]. So it is necessary to examine the responses of these induction generators during the faults and possible impacts on the system stability. In this paper, the impacts of different fault types on 9 MW wind farm interconnected grid are studied by monitoring the active power, reactive power, and bus voltage of the wind farm. Also, the contribution of STATCOM to support the wind farm during different fault types is studied.

2. AERODYNAMIC WIND TURBINE MODEL

The torque and mechanical power extracted from the wind is calculated using the following equation [3]:

$$T_t = \frac{\rho \pi r^2}{2} v^3 C_p(\lambda) / \Omega_t \tag{1}$$

$$P_t = \frac{\rho \pi r^2}{2} v^3 C_p(\lambda) \tag{2}$$

where T_t is the turbine torque (N/m), P_t is the power captured from the turbine (watt), ρ is the air density (kg/m^3), r is the radius of the turbine (m), v is the wind speed (m/s), C_p is the performance coefficient of the wind turbine, λ is the tip speed ratio (the ratio between the blade tip speed and wind speed) and Ω_t is the turbine speed. Wind turbines can be classified as; fixed speed and variable speed wind turbines depending on the turbine operation mode. Most of fixed speed wind turbines are powered by squirrel cage induction generators (SCIG) directly connected to the network. Since the rotor of the squirrel cage induction generators often runs at constant speed, the wind turbine of this type is called a fixed speed wind turbine. In order to prevent the induction generator from being damaged at high wind speed, the turbine blades is often designed at lower efficiency during high wind speed (stall control), or the angle of the blades can be actively adjusted according to the wind speed (pitch angle control).

3. DRIVE TRAIN MODEL

Figure 1 shows the equivalent two mass drive train model of wind turbine. This model is simple and it is considered as more exact simulation model [4-5]. This model consists of two main masses, turbine mass and generator mass. It includes turbine inertia J_T, generator inertia J_G (N m s^2 /rad), turbine friction damping D_T, generator friction damping D_G (N m s/rad) and shaft stiffness K_{sh} (N m/rad). All parameters and variables are referred to turbine side.

$$T_T - K_{sh}(\theta_T - \theta_G) - D_T \omega_T = J_T \frac{d\omega_T}{dt} \tag{3}$$

$$K_{sh}(\theta_T - \theta_G) - T_G - D_G \omega_G = J_G \frac{d\omega_G}{dt} \tag{4}$$

$$T_{sh} = K_{sh}(\theta_T - \theta_G) \tag{5}$$

where T_T, T_G and T_{sh} are turbine, generator and shaft torques (N m), ω_G is the generator angular speed (rad/s), θ_T and θ_G are turbine and generator angular positions (rad) [6].

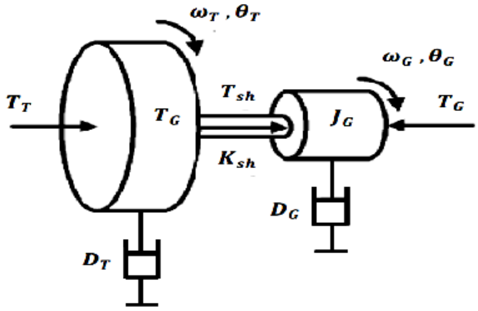

Fig. (1) Two mass drive train model of wind turbine

4. ELECTRICAL SYSTEM MODEL

Most of fixed speed wind turbines are powered by squirrel cage induction generators (SCIG) directly connected to the grid and the power extracted from the wind is limiting using the stall effect. For this kind of generator, the steady-state generated active P_e and reactive power Q_e are approximately given by [3].

$$p_e = 3\frac{P}{2}\frac{R_r}{S\,\omega_e}\frac{V^2\,\Omega_r}{(R_S + R_r/S)^2 + (\omega_e)^2(L_{LS} + L_{Lr})^2} \tag{6}$$

$$Q_e = 3\frac{V^2}{\omega_e L_m}\frac{V^2\,\omega_e(L_{LS} + L_{Lr})}{(R_S + R_r/S)^2 + (\omega_e)^2(L_{LS} + L_{Lr})^2} \tag{7}$$

where P is the number of poles, Lm is the magnetizing inductance, R_r and R_s are the stator and rotor side resistances, Ω_r is the electrical rotor speed, ω_e is the line frequency, V is the stator voltage, L_{Ls} and L_{Lr} are leakage inductances and $S=(\omega_e-\omega_r)/\omega_e$ is the slip. All the electrical quantities are referred to the stator side. In general the induction generators has many advantages, such as a robust design, no need for maintenance, well enclosed and produced in large series, a low price and can withstand over-loads. But the major disadvantage is the uncontrollable reactive power consumption of the induction generator. In order to compensate for the reactive power consumption, shunt capacitor banks are used for compensating the reactive power consumption of the induction generator at no-load [7]. Squirrel cage induction generators can become easily unstable under low voltage conditions, as low terminal voltage lead to: larger rotor slip, larger reactive power consumption, further lowering of terminal voltage, and this may lead to disconnecting the turbine. So that the wind turbines can be equipped with a controllable source of reactive power, e.g. a STATCOM or SVC, to deliver the reactive power required to accelerate the voltage restoration [8].

5. STATCOM OPERATION

The STATCOM is designed using a power electronic voltage source converter VSC as shown in Figure 2. The function of the VSC is a fully controllable voltage source matching the system voltage in phase, frequency, and with amplitude which can be continuously and rapidly controlled, so as to be used as the tool for reactive power control. The VSC can inject or absorb reactive power to/from the bus where it is connected via a coupling transformer.

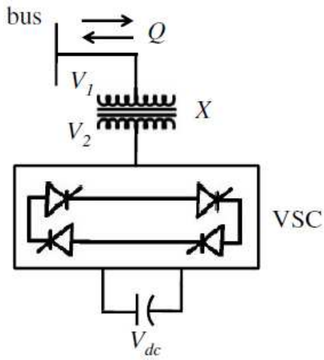

Fig. (2) A controllable voltage source VSC.

The control system can be designed to maintain the magnitude of the bus voltage constant by controlling the magnitude and phase shift of the VSC output voltage. With the VSC voltage and the bus voltage, the output of the VSC can be expressed as follows:

$$P = \frac{V_1 V_2}{X} \sin\delta \tag{8}$$

$$Q = \frac{V_1 V_2}{X} \cos\delta - \frac{V_1^2}{X} \tag{9}$$

where, P and Q are the active and reactive power of the VSC respectively. V1 and V2 are the bus voltage and VSC voltage respectively. X is the reactance of the coupling transformer and δ is the phase difference between the voltages V1 and V2. If the AC voltage V2 generated by the VSC is higher (or lower) than the system voltage V1, the STATCOM generates (or absorbs) reactive power [6].

6. CASE STUDY

6.1 Studied System Description

Figure 3 shows a single line diagram of a typical fixed speed wind power plant under study. A simulation model of a wind farm consisting of six 1.5 MW wind turbines is connected to a 25 kV distribution system exports power to a 120 kV grid through a 25 km 25 kV feeder. The 9 MW wind farm is simulated by three pairs of 1.5 MW wind turbines. Wind turbines use squirrel-cage induction generators (SCIG). 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 (9m/s). Fixed Capacitor banks connected at each wind turbine low voltage bus (400 KVAR for each pair of 1.5 MW turbines) which supplies the constant no load demand. Each wind turbine has a protection system monitoring voltage, current and generator speed. The set parameters of the protection system are illustrated in appendix A. The simulation model is carried out using the MATLAB SimPowerSystems toolbox.

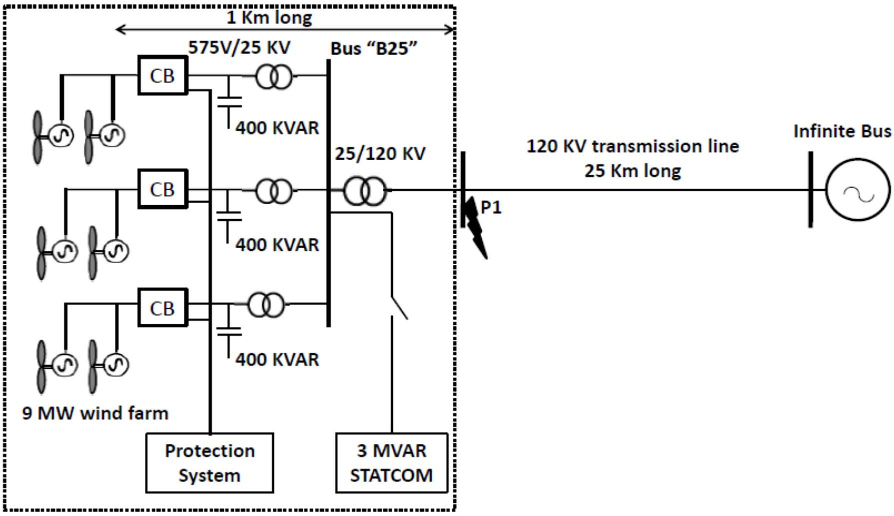

Fig. (3) Single line diagram of the studied system.

The bus B25 is the main bus (collected bus) of the studied wind farm which connects the wind farm with the grid, so this bus is taken as the monitoring point for all studied cases. The total exported (generated) active power from the wind farm to the grid, the total absorbed reactive power from the grid and the terminal voltage at the main bus B25 of the wind farm are monitored.

6.2 Simulation Steps Illustrate

First the system is studied at the steady state and then at the fault state. At these cases, the bus voltage, active and reactive powers are recorded during abnormal values (trigged by events). The behavior of the wind power plant is recorded during fault events, including pre-faults and post-fault events. Within the fault duration it can be assumed that the wind speed does not change, the studied wind speed is the nominal speed 9 m/s, so the wind turbines operate at nominal values. The duration of the fault is usually less than nine cycles (tfault < 150 ms) [9], so the fault duration time is taken as 88 ms. In fault state, the behavior of the wind farm during fault occurrence is monitored under the different fault types: single phase to ground, double phase to ground and three phase to ground events. To study the effect of reactive power compensation at each case of the studied cases, the system is monitored twice, one without STATCOM connection, and the other with connection of 3 MVAR STATCOM. At each case of the studied cases, the fault occurs at the 15th second of the simulation time and its duration is 88 ms.

7. SIMULATION RESULTS

7.1 Steady State Operation

To study the effect of STATCOM during steady state operation, the operation of the wind farm is monitored twice one without STATCOM connected to the main bus of the wind farm and the other when a 3 MVAR STATCOM is connected. Figure 4 shows that the reactive power absorbed by wind farm from the gird is 3.77 MVAR in the case of without STATCOM and it decreases to 1.99 MVAR when the STATCOM is connected. Figure 5 shows the main bus voltage of the wind farm is 0.945 pu when the STATCOM is disconnected and it increases to 0.986 pu when the STATCOM is connected to the main bus of the wind farm. Also, the generated active power is increased from 8.649 to 8.664 MW by connecting the STATCOM as shown in Fig. 6. It is clear that, the STATCOM decreases the absorbed reactive power from the grid by wind farm generators and enhances the bus voltage of the wind farm.

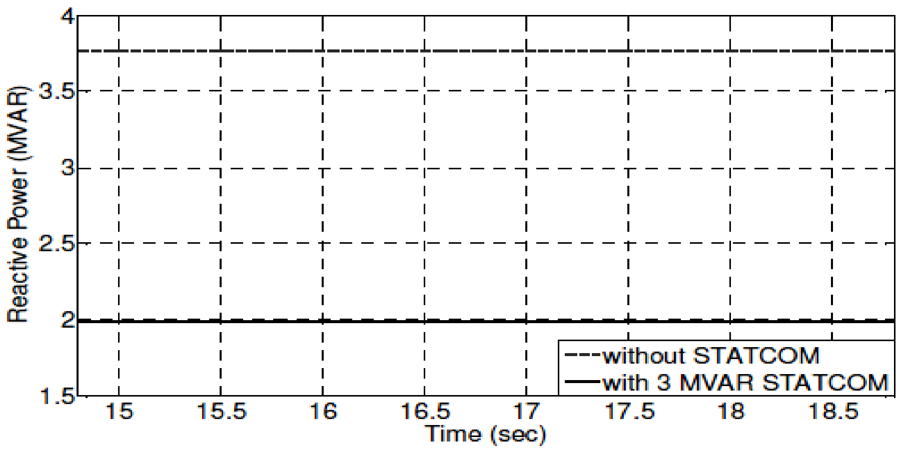

Fig. (4) The reactive power at bus B25during steady state operation.

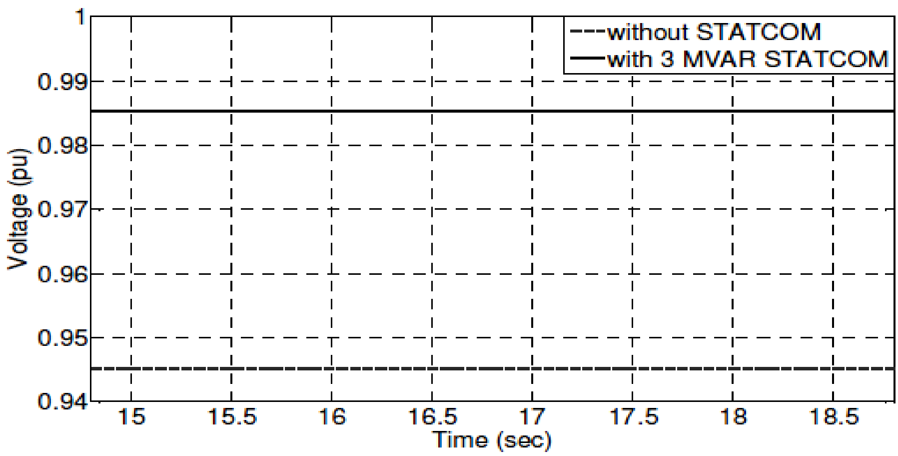

Fig. (5) The voltage of bus B25 during steady state operation.

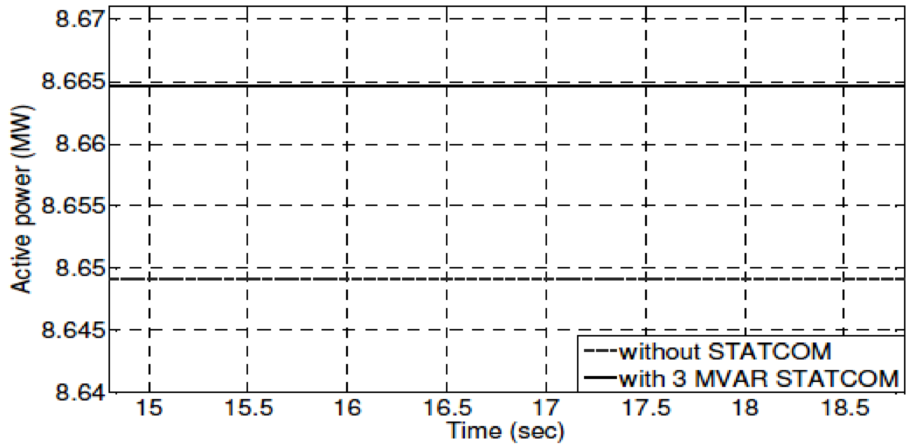

Fig. (6) The active power at bus B25 during steady state operation.

7.2 Effect of Single Phase to Ground Fault

To study the behavior of the wind farm during fault occurrence, a single phase to ground fault occurs at the point P1 for a duration time of 88 ms. Also, to observe the effect of STATCOM on power system stability during fault occurrence, the main bus voltage, active power, and reactive power are monitored twice: with and without STATCOM. Figure 7 shows the bus voltage variation during the single phase to ground fault. During fault period the voltage decreases to 0.802 pu when the STATCOM is disconnected. But it is decreased to 0.854 pu when the STATCOM is connected. It shows that the STATCOM acts as a voltage support for the wind farm during faults by injecting reactive power to the main bus. The voltage values during the faults is above the under voltage protection threshold (0.75 pu with delay time less than 100 ms). Therefore the wind farm stays in service and the system returns back to steady state after removing the fault.

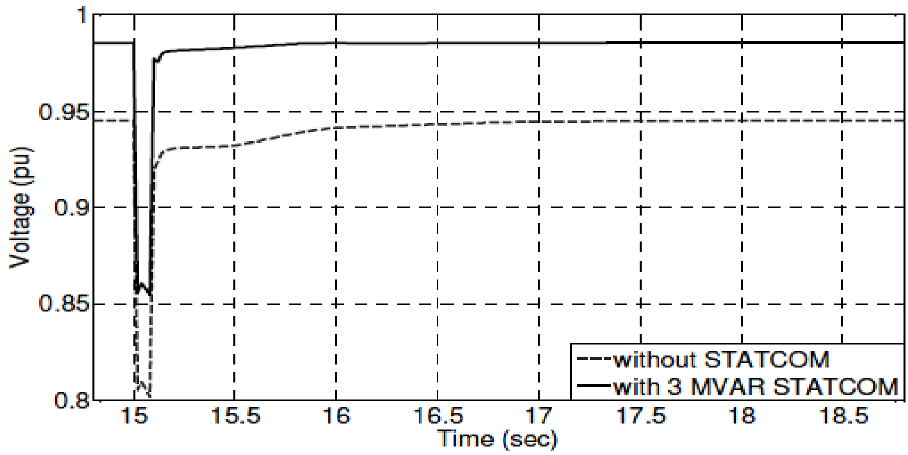

Fig. (7) The voltage of bus B25 during single phase to ground fault.

Figure 8 shows the total exported active power from the wind farm to the grid. During fault period the total exported active power decreases, this decreasing in the case of without STATCOM is 7.8329 MM. When the STATCOM is connected the exported active power decreases to 7.98 MW. Figure 9 shows the total absorbed reactive power from the grid during the single phase to ground fault. During fault period the total absorbed reactive power decreased to 0.902 MVAR when the STATCOM is disconnected, while decreased to -1.56 MVAR when the STATCOM is connected. At post fault period the total absorbed reactive power from the grid increased, this increasing in the case of without STATCOM is 4.4041 MVAR. But when the STATCOM is connected the absorbed reactive power increased to 2.1831 MVAR. Finally, after the end of post fault period, the system returns back to steady state operation either with or without STATCOM.

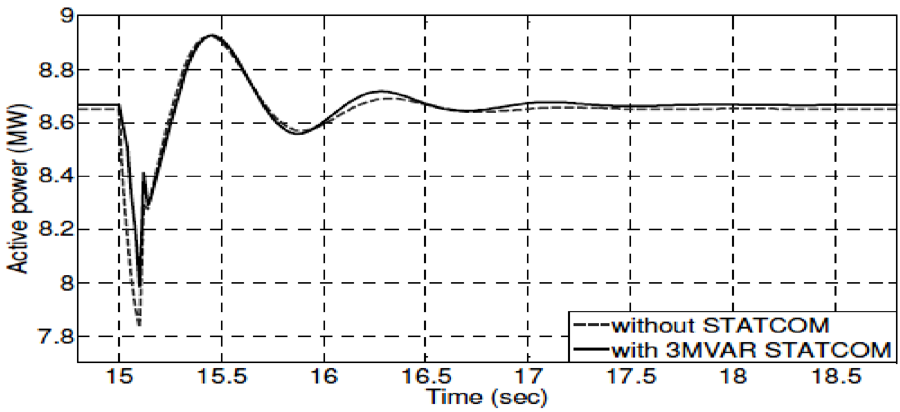

Fig. (8) The active power at bus B25 during single phase to ground fault.

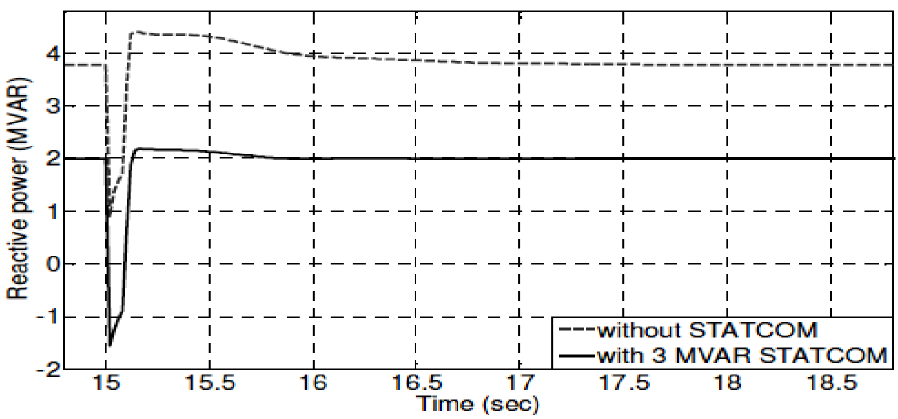

Fig. (9) The reactive power at bus B25 during single phase to ground fault.

7.3 Effect of Double Phase to Ground Fault

In this section the variations of bus voltage, active power and reactive power in case of double phase to ground fault occurs at the point P1 with 88 ms duration time are studied. As shown in Fig. 10 during fault period the bus voltage decreases to 0.443 pu when the STATCOM is disconnected and it decreases to 0.473 pu when the STATCOM is connected. Although the bus voltage is decreased than the under voltage value of the protection system, the wind farm stays in sevice because the under voltage duration time is less than the protection delay time.

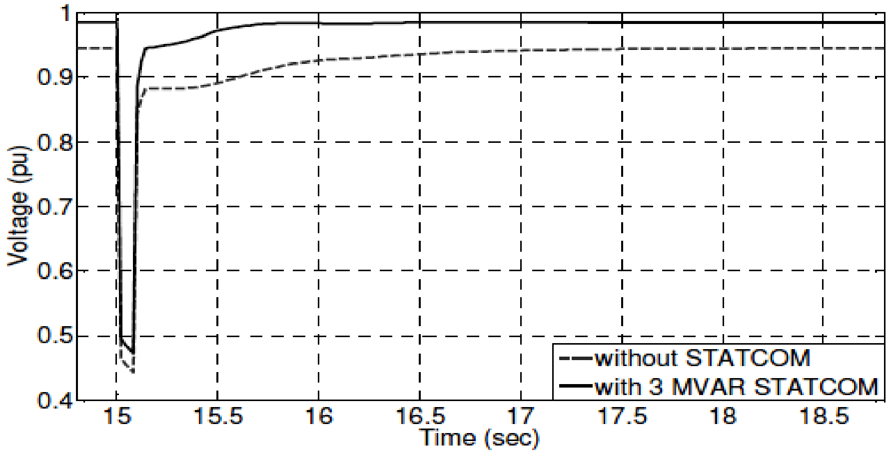

Fig. (10) The voltage of bus B25 during double phase to ground fault.

Figure 11 shows the total exported active power from the wind farm to the grid. During the fault period the total exported active power decreases to 3.96 MW in case of without STATCOM. When the STATCOM is connected the exported active power decreases to 4.05 MW. Figure 12 shows the total absorbed reactive power from the grid during the double phase to ground fault. During fault period the total absorbed reactive power is decreased to 2.07 MVAR when the STATCOM is disconnected, while it decreases to 0.8 MVAR when the STATCOM is connected. At post fault period the total absorbed reactive power from the grid increases to 6.22 MVAR in case of without STATCOM. But when the STATCOM is connected, the absorbed reactive power increased to 3.81 MVAR.

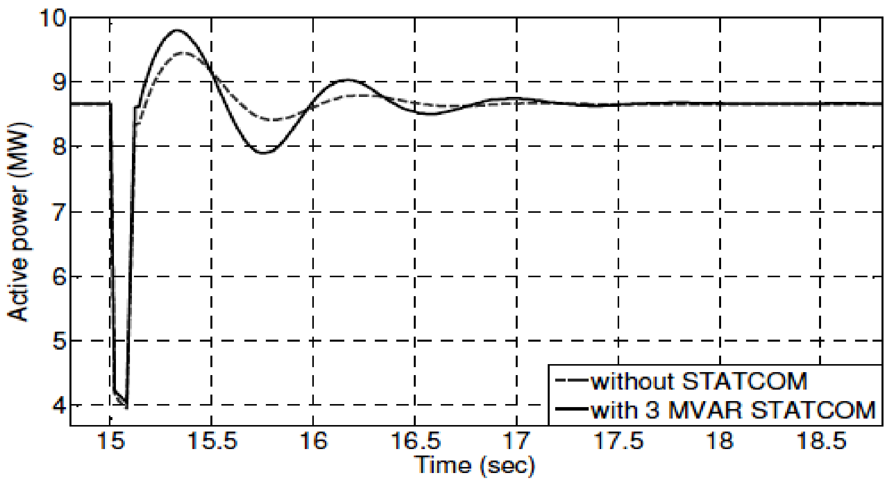

Fig. (11) The active power at bus B25 during double phase to ground fault.

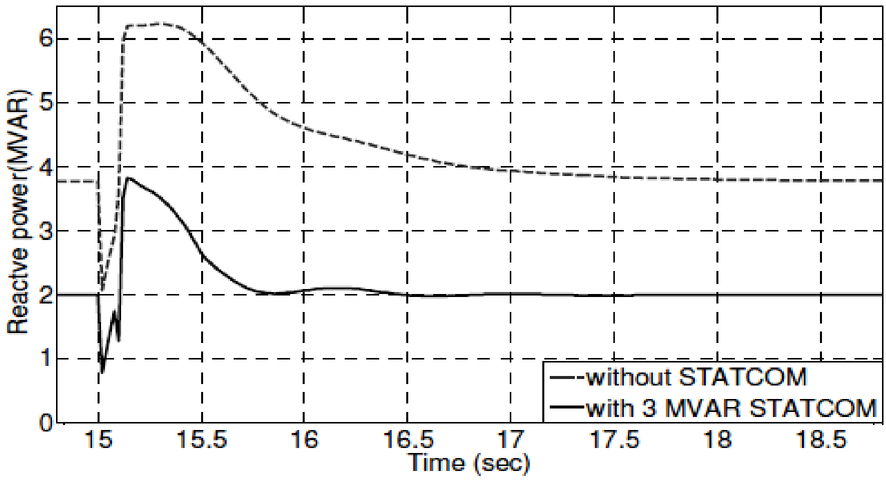

Fig. (12) The reactive power at bus B25 during double phase to ground fault.

7.4 Effect of Three Phase to Ground Fault

In this section the variations of bus voltage, active power and reactive power in the case of a three phase to ground fault are studied. The fault occurs at the point P1 with 88 ms duration time. As shown in Fig. 13 during fault period the bus voltage falls to zero when the STATCOM is disconnected. In this case the protection system trips the wind farm because the under voltage duration time exceeding the protection delay time. As shown in Fig. 14 there is no generated active power of the wind farm. Figure 15 shows the measured reactive power at bus B25 is -1.2 MVAR which it is the total generated reactive power by the static capacitor banks.

When the STATCOM is connected to the system during the fault, the bus voltage falls to zero but its duration time is less than the protection system delay time. Therefore, the wind farm stays in service and the system returns back to steady state after removing the fault as shown in Fig. 15.

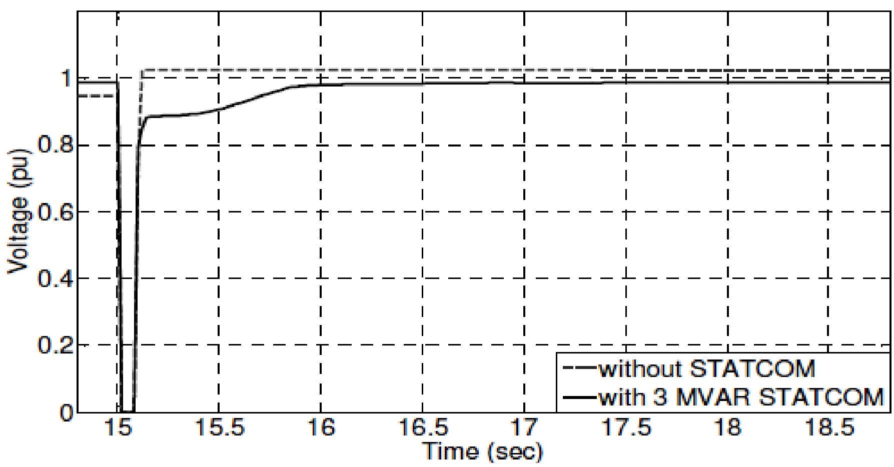

Fig. (13) The voltage of bus B25 during three-phase to ground fault.

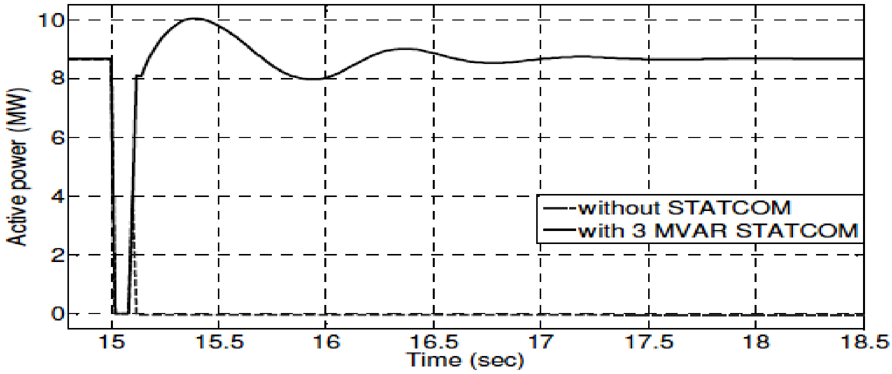

Fig. (14) The active power at bus B25 during three-phase to ground fault.

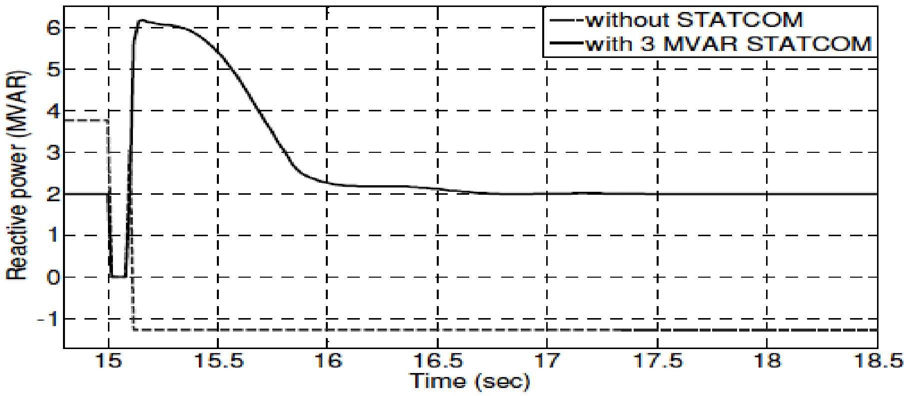

Fig. (15) The reactive power at bus B25 during three-phase to ground fault.

8. CONCLUSIONS

A simulation model of 9 MW SCIG wind farm interconnected grid is investigated. The effect of different fault types on the stability of the protected wind farm is studied. The impacts of the static synchronous compensator STATCOM on the stability of the system during fault events are studied. The wind farm terminal voltage, the exported active power and the absorbed reactive power are monitored in steady state and fault state conditions. A single phase to ground, double phase to ground and three-phase to ground faults are applied at the wind farm terminal for duration time of 88 ms. It is noticed that in cases of single phase to ground fault and double phase to ground fault, the wind farm can stay connected to the grid either in the case of with or without STATCOM. Also, the system returns back to steady state after removing the faults. In case of three-phase to ground fault the wind farm cannot stay connected to the grid when the STATCOM is disconnected, where the wind farm terminal voltages falls to zero and its duration time is increased than the protection system delay time. But by connecting the STATCOM the wind farm terminal voltage can return back to a value more than the under voltage threshold in a time less than the protection delay time. Finally, the STATCOM operates as a reactive power support and thus improves the overall operation of the whole wind farm by reducing the absorbed reactive power from the grid and raising the voltage of the main wind farm bus.

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APPENDIX A

Table A.1: The protection set parameters of SCIG wind turbine

Parameter	Minimum value (pu)	Maximum value (pu)	Delay time (sec)
AC under/over voltage	0.75	1.1	0.1
Under/over rotor speed	1	1.05	5
Parameter	Maximum value (pu)		Delay time (sec)
AC current	1.1		10
AC current unbalance	o.4		0.2
Voltage unbalance	0.05		0.2

دعم محطات الرياح التى تولد الكهرباء باستخدام المولدات الحثية ذات السرعة الثابتة المتصلة بالشبكة خلال القصر

في ظل الزيادة المستمرة لأستخدام طاقة الرياح في توليد الكهرباء و التوسع في بناء المزيد من مزارع الرياح التى تولد الكهرباء باستخدام المولدات الحثية ذات القفص السنجابي. و من المعروف ان المولدات الحثية عموما تعمل على سحب كمية كبيرة من القدرة الغير فعالة من الشبكة المتصلة عليها (حيث انه في الحالات العادية التي لايحدث فيها قصر، تقوم المولدات الحثية بسحب كمية كبيرة من القدرة الغير فعالة اللازمة لعملية الاثارة او الحث المطلوبة لعمل هذه المولدات)، اما في حالة حدوث قصر على الشبكة، فان المولدات الحثية في هذة الحالة تسحب المزيد من الكميات الضخمة جدا من القدرة الغير فعالة و التى هي اكبر من الكمية التى تسحبها في الحالات العادية، مما يؤدي الي حدوث انخفاض للجهد و بالتالى يؤثر على استقرار نظم القوى الكهربية على الشبكة. يقدم هذا البحث دراسة تاثيرات مزارع الرياح (التي تستخدم المولدات الحثية ذات القفص السنجابي لتوليد الكهرباء) على استقرار نظم القوى الكهربية عند حدوث قصر على الشبكة، حيث انة تمت دراسة حدوث القصر فى مختلف الحالات و الظروف، و تلك الحالات المختلفة تم عملها بهدف دراسة تأثير: توصيل/عدم توصيل معوض قدرة غير فعالة خارجي (المعادل التزامني السكوني)، نوع القصر.