DYNAMIC PERFORMANCE IMPROVEMENT OF FIXED SPEED INDUCTION GENERATOR BASED WIND FARM USING STATCOM DURING FAULT

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Abstract— This paper presents the impact of fault on the stability of fixed speed induction generator (FSIG) based wind farm connected to interconnected power system. The improvement in dynamic performance of FSIG based wind farm by control strategy applied to Static Synchronous Compensator (STATCOM) is presented in this paper under balanced and unbalanced fault. The effect of fault location and its duration times are studied for for L-G, L-L-G, L-L-L-G faults type. The simulation results are carried out using MATLAB-simulink environment. The influence of fault location and its duration on Bus voltage, Active power and Reactive power is demonstrated the control strategy using STATCOM is investigated in terms of regulation reactive power regulation and transient stability of the wind farm during disturbance.

Index Terms — FSIG, STATCOM, Wind farm, Transient stability

I. INTRODUCTION

The use of wind power has increased significantly over recent decades and its integration with the power system is now an important topic of study. India ranks fifth amongst the wind energy producing countries of the world after USA, China, Germany and Spain. One of the major issues concerning a wind farm interconnection to a power grid concerns its dynamic stability on the power system. In the past, wind turbines used to disconnect during faults on the grid, which leads to dynamic instability of the system. Therefore various countries across the globe have imposed grid code regulations while integrating wind farm to the power system these are important code is Low Voltage Ride Through (LVRT) capability. Two of the objectives are enhancement of reactive power capability during disturbance and fault ride through capability during faults [1, 2].

The wind energy conversion system (WECS) could be operationally classified into fixed speed and variable speed wind turbine generating system (WTGS). In the early stage of wind power generations, most wind farms were equipped with fixed speed induction generators (FSIG). The operation of FSIG is fairly simple but it is unable to extract maximum power at varying wind speed as its slip can be varied in a very small range.

Fixed speed wind turbines utilize squirrel cage induction generator directly connected to the grid to produce the electricity. These induction generators which are usually connected at weak end of a grid or at distribution networks draw large amount of reactive currents during disturbances such as faults. When a grid fault occurs, the system voltage together with the wind turbine terminal voltage will drop in a very short time. The electromagnetic torque also drops instantaneously since it is proportional to the square of the terminal voltage, while the mechanical torque is remain unchanged at the moment. So the unbalance of electromagnetic torque and mechanical torque will result in rotor speed acceleration. At the same time, it will also reduce the output electrical power from the wind turbines, if there is no sufficient electrical power to balance the mechanical power, the power surplus then leads to rotor acceleration, which also lead to reactive power consumption.[3] Therefore, the stability becomes an important problem.

For the reason that this specified generator cannot supply adaptable reactive power its need to help the voltage recover it needs reactive power support from external compensation devices such as STATCOM. Furthermore it is economically convenient to handle the fault, without disconnecting the wind turbine from the grid. It is necessary to examine the responses of SCIG wind farm during the faults and possible impacts on the system stability. In this paper, the impacts of fault location and its duration time on 12 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 locations and durations are studied [4].

This paper is organized in six sections. Section II describes mathematical modeling of FSIG. Section III deals with STATCOM as reactive power compensation device. Section IV present proposed test system. Section V presents results and discussion. Section VI concludes the result of the work.

II. MATHEMATICAL MODELLING OF FSIG

A. Induction Generator Model

Assumptions:

The following assumptions are made while modelling the induction generator.

(1) Stator current is negative when flowing toward the machine, i.e. generator convection is used

(2) Equations are derived in the synchronous reference frame

(3) q-axis is 900 ahead of the d-axis.

The stator of the induction machine carries three-phase windings. The windings produce a rotating magnetic field which rotates at synchronous speed. The dynamic equations for stator and rotor in d-q reference frame rotating at synchronous speed [5],[6],[8] are described in (1)-(3).

Stator Voltage Equations:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = R_s \begin{bmatrix} -i_{ds} \\ -i_{qs} \end{bmatrix} + \omega_s \begin{bmatrix} -\varphi_{qs} \\ \varphi_{ds} \end{bmatrix} + \frac{1}{\omega_b}\frac{d}{dt}\begin{bmatrix} \varphi_{ds} \\ \varphi_{qs} \end{bmatrix}$$
(1)

Rotor Voltage Equations:

$$\begin{bmatrix} v_{dr} \\ v_{qr} \end{bmatrix} = R_r \begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} + s\omega_s \begin{bmatrix} -\varphi_{qr} \\ \varphi_{dr} \end{bmatrix} + \frac{1}{\omega_b}\frac{d}{dt}\begin{bmatrix} \varphi_{dr} \\ \varphi_{qr} \end{bmatrix}$$
(2)

Flux Equations:

$$\varphi_{ds} = -X_{ss}i_{ds} + X_m i_{dr}$$
$$\varphi_{qs} = -X_{ss}i_{qs} + X_m i_{qr}$$
$$\varphi_{dr} = X_{rr}i_{dr} - X_m i_{ds}$$
$$\varphi_{qr} = X_{rr}i_{qr} - X_m i_{qs}$$
(3)

where v_{ds} and v_{qs} are d- and q-axis stator voltages, respectively, v_{dr} and v_{qr} are d- and q-axis rotor voltages, respectively, i_{ds} and i_{qs} are d- and q-axis stator currents, respectively, i_{dr} and i_{qr} are d- and q-axis rotor currents respectively, R_s is stator resistance, R_r is rotor resistance, φ_{ds} and φ_{qs} are d- and q-axis stator fluxes, respectively, φ_{dr} and φ_{qr} are d- and q-axis rotor fluxes, respectively, ω_s is synchronous speed, ω_b is the base speed, X_{ss}, X_{rr}, and X_m stator reactance, rotor reactance and self magnetizing reactance, repectively.

The expression for the stator and rotor currents as the state variables are obtained by substituting the flux equations (3), into the stator and rotor voltage equations (1),(2).

B. Wind Turbine Model

To complete the induction generator state model, it is necessary to combine the equations that describe electrical voltage and current components of the machine with swing equation that provides rotor speed as state variable. In power system studies, drive trains are modelled as a series of rigid disks connected via mass less shafts.

For accurate representation of drive train, wind turbine shaft and generator rotor coupled together via gear box which cannot be considered stiff. Therefore, the interaction between the wind turbine and generator rotor makes the shaft motion more complex than one mass model. The dynamics of the drive train which actually comprises of turbine, gearbox, shafts and other mechanical components of WT can be represented as two mass model i.e one mass for the wind turbine and the other for the generator rotor. The dynamic equations which represent two mass model of drive train obtained from Newton's equations of motion for rotational speed and shaft torsion are expressed in (4)-(7).

$$\frac{d\omega_t}{dt} = \frac{1}{2H_t}(T_m - T_{sh}) \quad (4)$$

$$\frac{d\theta_{tw}}{dt} = \omega_b(\omega_t - \omega_r) \quad (5)$$

$$T_{sh} = K_{sh}\theta_{tw} + D_{sh}\frac{d\theta_{tw}}{dt} \quad (6)$$

$$\frac{d\omega_r}{dt} = \frac{1}{2H_g}(T_m - T_e) \quad (7)$$

Where H_t = inertia constant of turbine, H_g = inertia constant of generator, ω_t = WT angle speed, θ_{tw} = shaft twist angle, K_{sh} = shaft stiffness coefficient, D_{sh} = damping coefficient, T_{sh} = shaft torque.

T_m and T_e are given by (8) and (13).

$$T_m = \frac{C_{p(pu)}{V_{w(pu)}}^3}{\omega_{r(pu)}} \quad (8)$$

$$V_{w(pu)} = \frac{V_w}{V_{w\_base}} \quad (9)$$

$$C_{p(pu)} = \frac{C_p}{C_{p\_nom}} \quad (10)$$

where

$$C_p = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right) e^{-c_5\lambda_i} + c_6\lambda \quad (11)$$

$$\lambda_i = \frac{1}{\frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}} \quad (12)$$

Where, ρ = air density, R= WT blade radius, V_w = wind speed, β =blade pitch angle, λ= blade tip speed ratio, C_p= power coefficient. T_e in terms of the state variables

$$T_e = X_m(i_{dr}i_{qs} - i_{qr}i_{ds}) \quad (13)$$

C. Pitch Controller

The pitch angle of the wind turbine blade is controlled to maintain the rotating speed of the WT to prevent overrated power production during strong wind conditions. Generally, the reference of the pitch angle βref is kept zero when wind speed is below rated value. When wind speed is higher than rated value, the power limitation feature is activated by adjusting the pitch angle using the pitch controller [7]. The control equation is given by (14)

$$\frac{d\beta}{dt} = K_p\frac{T_m - T_{sh}}{2H_t} + K_i\Delta\omega_t \quad (14)$$

Where, K_p and K_i are the proportional and integrating gains of the WT speed regulator, respectively. $\Delta\omega_t$ is the deviation of the WT rotating speed [9].

III. STATCOM AS REACTIVE POWER COMPENSATION DEVICE

A STATCOM provides the desired reactive power by exchanging the instantaneous reactive power among the phases of the ac system. The mechanism by which the converter internally generates and/or absorbs the reactive power can be understood by considering the relationship between the output and input powers of the converter. The STATCOM can be used to maintain certain voltage level at PCC under heavy loading conditions. In its simplest form, the STATCOM is made up of a coupling transformer, a voltage source inverter (VSC) and a DC energy storage device.

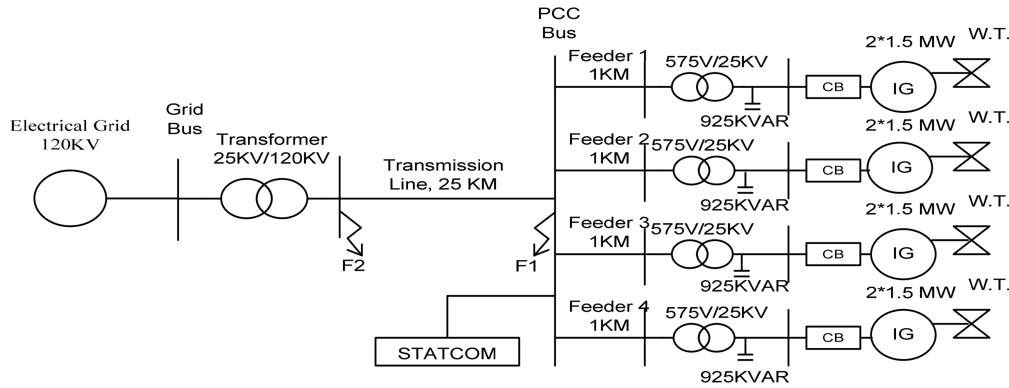


Fig.1 Schematic diagram of grid connected wind farm

The energy storage device is a relatively small DC capacitor, and hence the STATCOM is capable of only capacitor, and hence the STATCOM is capable of only reactive power exchange with the transmission system. The difference between the converter output voltage and the PCC bus voltage basically determines the flow of reactive power through the coupling transformer to or from the system [10].

IV. Test System

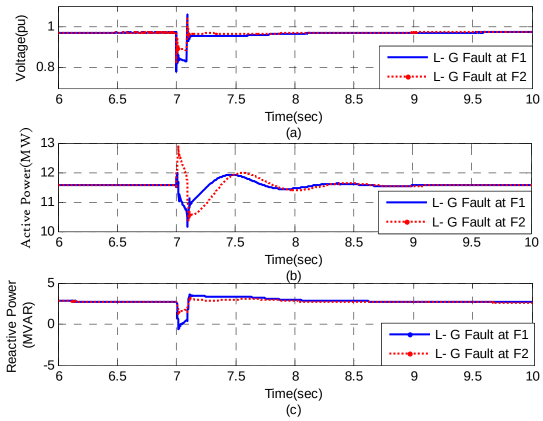
Fig.1 shows the schematic diagram of the fixed speed induction generator based WECS consisting of eight 1.5 MW wind turbines is connected to a 25 kV distribution system exports power to a 120 kV grid through a 25 kV feeder. The main data of SCIG and system parameters are described in Appendix. The 12 MW wind farm is simulated by four pairs of 1.5 MW SCIG wind turbines. The stator winding of SCIG 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). Fixed capacitor banks 925 KVAR are connected at low voltage bus of each wind turbine. This supplies the constant no load demand. A 3 MVAR STATCOM is connected at the main bus B25. The bus B25 is the main bus of the wind farm which connects the wind farm with the grid. The wind farm must stay connected during fault, with the voltage at interconnection point dropping to zero for the duration of nine cycles (150 ms based on 60 Hz frequency) [11]. This time is generally needed for the transmission system protective equipment to clear the fault. Therefore, to study the effect of fault duration it must not exceed than 150 ms.

V. RESULTS AND DISCUSSION

The effect of fault location and its duration on the stability of the wind farm connected interconnected power system are studied for different fault types such as single line to ground fault, double line to ground fault, and three-line to ground fault. To study the effect of fault location on the behavior of the wind farm, the operation of the wind farm under different fault types are monitored twice, one when the fault occurs at the first fault location F1 about 1 km from wind turbines, and the other when the fault occurs at the second fault location F2 about 26 km from wind turbines. Also, to study the effect of fault duration time on the behavior of the wind farm, the operation of the wind farm under different fault duration times is monitored when the fault occurs at the point F1.

A. Effect of fault location

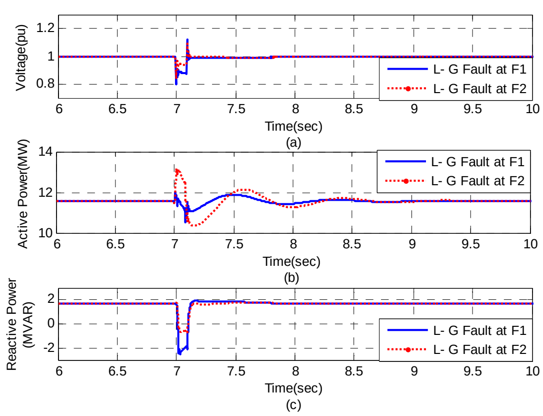
Fig.2 shows the variation of wind farm terminal voltage, generated active power, and absorbed reactive power when a single line to ground fault occurs at the points F1 and F2. During fault period, the voltage of the main bus B25



(a)Voltage at PCC, (b) Active Power, (c) Reactive Power

Fig.2 Single line to ground fault at different fault location –without STATCOM

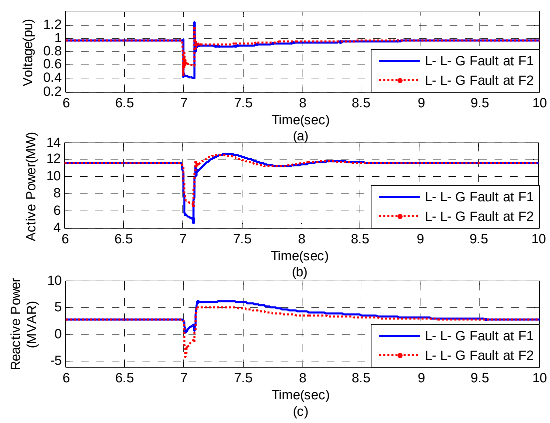
is decreased to 0.78 pu when the fault occurs at point F1, and it decreases to 0.81 pu when the fault occurs at point F2. Also, the total exported active power at bus B25 decreases to 10.17 MW when the fault occurs at point F1, and it decreases to 10.35 MW when the fault occurs at point F2. After fault clearance, the total absorbed reactive power from the grid is increased; this increasing when the fault occurs at point F1 is 2.655 MVAR while in the case of second fault location F2, it is increased to 2.646 MVAR. As shown in Fig. 2, it is clear that the wind power plant has the ability to stay connected under this fault condition without STATCOM connection either when the fault occurs at F1 or F2.



(a)Voltage at PCC, (b) Active Power, (c) Reactive Power

Fig.3 Single line to ground fault at different fault location –with STATCOM

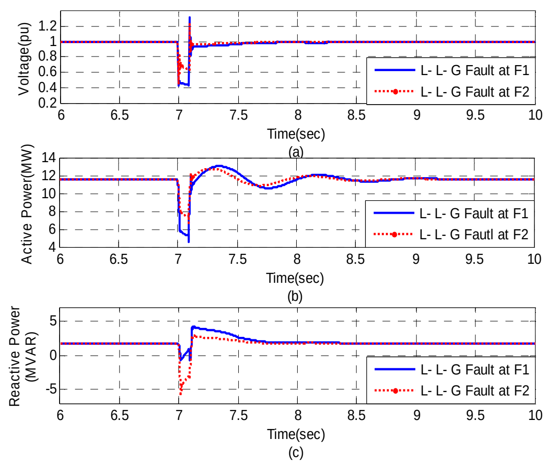
Fig. 3 shows the variations of wind farm terminal voltage, generated active power and absorbed reactive power in case of single line to ground fault which occurs at points F1 and F2 in case of STATCOM connecting. During fault period, the voltage of the main bus B25 is decreased to 0.82 pu when the fault occurs at point F1, and it decreases to 0.84 pu when the fault occurs at point F2. Also, the total exported active power at bus B25 decreases to 10.6 MW when the fault occurs at point F1, and it decreases to 12.5 MW when the fault occurs at point F2. After fault clearance, the total absorbed reactive power from the grid is increased; this increasing when the fault occurs at point F1 is 1.691 MVAR while in the case of second fault location F2 it is increased to 1.693 MVAR. It is clear that, the STATCOM enhances the wind farm terminal voltage. Also the absorbed reactive power from the grid is decreased.



(a)Voltage at PCC, (b) Active Power, (c) Reactive Power

Fig.4 Double line to ground fault at different fault location –without STATCOM

Fig. 4 shows the variation of wind farm terminal voltage,generated active power and absorbed reactive power in case of double line to ground fault occurs at the points F1 and F2. During fault period, the voltage of the main bus B25 is decreased to 0.40 pu when the fault occurs at point F1, and it decreases to 0.43 pu when the fault occurs at point F2. Also, the total exported active power at bus B25 decreases to 4.53 MW when the fault occurs at point F1, and it decreases to 6.28 MW when the fault occurs at point F2. After fault clearance, the total absorbed reactive power from the grid is increased; this increasing when the fault occurs at point F1 is 2.74 MVAR, while in the case of second fault location F2 it is increased to 2.69 MVAR. As shown in Fig. 4, it is clear that the wind power plant has the ability to stay connected to grid in case of double line to ground fault without STATCOM connection, either when the fault occurs at the first fault location F1 or when the fault occurs at the second fault location F2, then at the both cases after fault clearance, the system returns back to steady state operation as the pre-fault fault period.

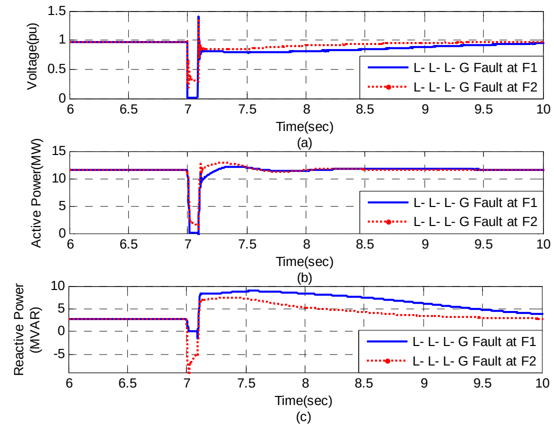


(a)Voltage at PCC, (b) Active Power, (c) Reactive Power

Fig.5 Double line to ground fault at different fault location –with STATCOM

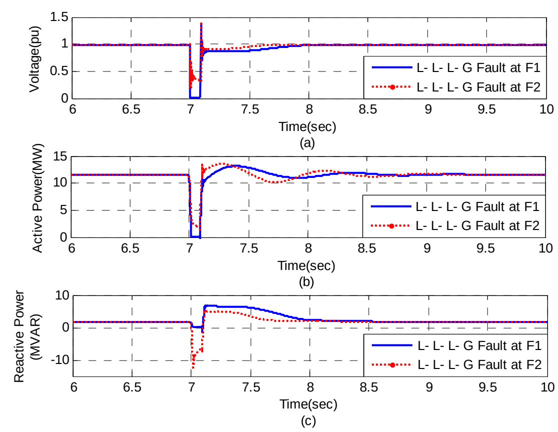
Fig. 5 shows the variation of wind farm terminal voltage, generated active power and absorbed reactive power when a double line to ground fault occurs at the points F1 and F2 in case of STATCOM connecting. During fault period, the voltage of the main bus B25 is decreased to 0.43 pu when the fault occurs at point F1, and it decreases to 0.5 pu when the fault occurs at point F2. Also, the total exported active power at bus B25 decreases to 5.5 MW when the fault occurs at point F1, and it decreases to 7.5 MW when the fault occurs at point F2. After fault clearance, the total absorbed reactive power from the grid is increased; this Increasing when the fault occurs at point F1 is 1.697 MVAR while in the case of second fault location F2 it is increased to 1.692 MVAR.

As shown in Fig. 6 when the system operates without STATCOM, the main bus voltage falls to zero when the fault occurs at point F1, and it decreases to 0.2 pu when the fault occurs at point F2. Also, the total exported active power at bus B25 falls to zero when the fault occurs at point F1, and it decreases to 1.5 MW when the fault occurs at point F2. After fault clearance, the total absorbed reactive power from the grid is 2.64 MVAR when the fault occurs at point F1. When the fault occurs at point F2, the absorbed reactive power is increased to 2.63 MVAR. It is clear that wind power plant has the ability to stay connected to the grid in case of L-L-L-G fault without STATCOM either faults occurs at F1 or F2.



(a)Voltage at PCC, (b) Active Power, (c) Reactive Power

Fig.6 Three- line to ground fault at different fault location –without STATCOM



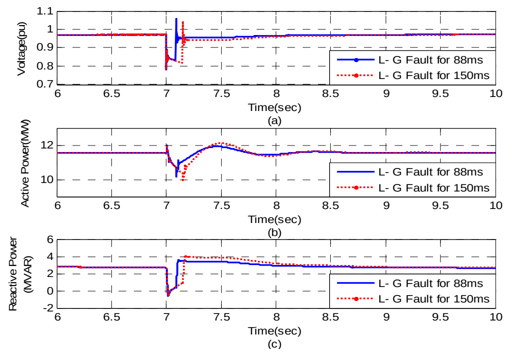
(a)Voltage at PCC, (b) Active Power, (c) Reactive Power

Fig.7 Three- line to ground fault at different fault location –with STATCOM

Fig. 7 shows the effect of three-line to ground fault on the wind farm behavior when the STATCOM is connected. During fault period, the voltage of the main bus B25 is fall to zero when the fault occurs at point F1 and it decreases to 0.2 pu when the fault occurs at point F2. Also, the total exported active power at bus B25 falls to zero when the fault occurs at point F1, and it decreases to 2 MW when the fault occurs at point F2. After fault clearance, the total absorbed reactive power from the grid is increased; this increasing when the fault occurs at point F1 and F2 is 1.69 MVAR. The STATCOM improve the voltage profile at the PCC and increases the active power. Wind farm absorbed reactive power from the grid is decreases.

B. Effect of fault duration

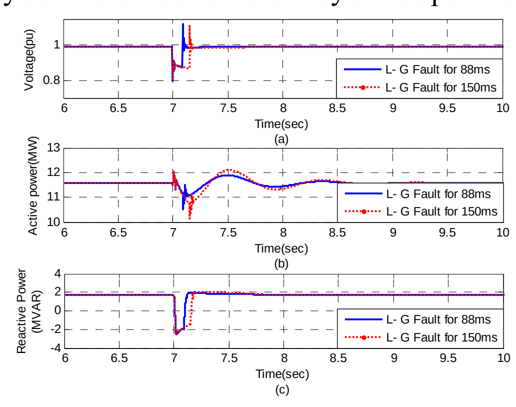
The effect of fault duration time is studied for different fault types, the studied fault occurs at point F1. Fig. 8 shows the behavior of the wind farm when a single line to ground fault occurs for 88 ms and 150 ms duration times. As shown in Fig. 8, during fault period the voltage of the main bus B25 is decreased to 0.7802 pu when the fault duration time is 88 ms or 150ms. Also, the total exported active the case of 88 ms is 10.17 MW and it decreases to 9.8675 MW in the



(a)Voltage at PCC, (b) Active Power, (c) Reactive Power

Fig.8 Single line to ground fault at different fault duration –without STATCOM

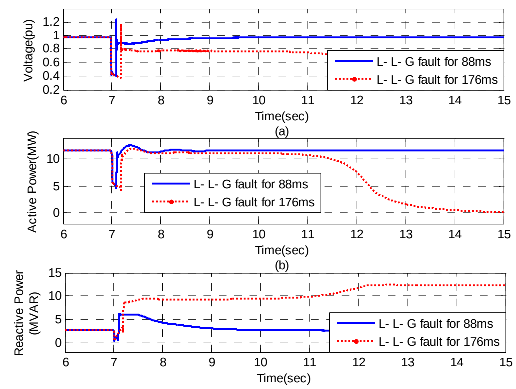
case of 150 ms fault duration. After fault clearance, the total absorbed reactive power from the grid is increased to 2.655 MVAR in the case of 88 ms fault duration, and it increases to 2.669 MVAR in the case of 150 ms fault duration. It is clear that, the wind power plant has the ability to stay connected under this fault condition without STATCOM connection either when the fault occurs for 88 ms or 150 ms, so at both cases the system returns back to steady state operation.



(a)Voltage at PCC, (b) Active Power, (c) Reactive Power

Fig.9 Single line to ground fault at different fault duration –with STATCOM

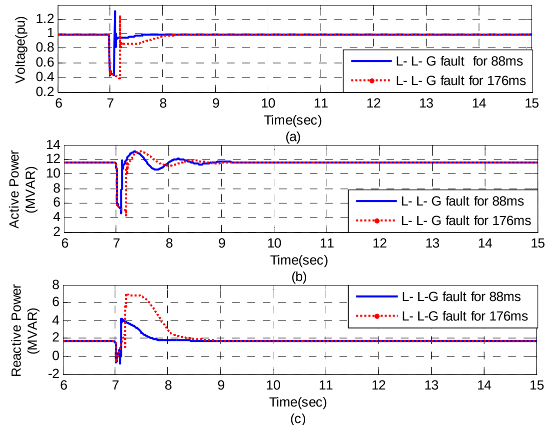
Fig. 9 shows the effect of fault duration time on the behavior of the wind farm in case of STATCOM connecting in case of single line to ground fault. During fault period, the voltage of the main bus B25 is decreased to 0.8 pu when the fault duration is 88 ms or 150 ms. Also, the total exported active power from the wind farm is decreased to 10.6 MW in case of 88 ms fault duration, and it decreases to 10.15 MW in case of 150 ms fault duration. After fault clearance, the total absorbed reactive power from the grid is increased to 1.691 MVAR in case of 88 ms or 150 ms fault duration. It is clear that, in case of single line to ground fault, the wind power farm has the ability to stay connected under this fault condition with and without 3 MVAR STATCOM connection either when the fault occurs for 88 ms or 150 ms. Also, the system returns back to steady state operation after clearing the fault.



(a)Voltage at PCC, (b) Active Power, (c) Reactive Power

Fig.10 Double line to ground fault at different fault duration –without STATCOM

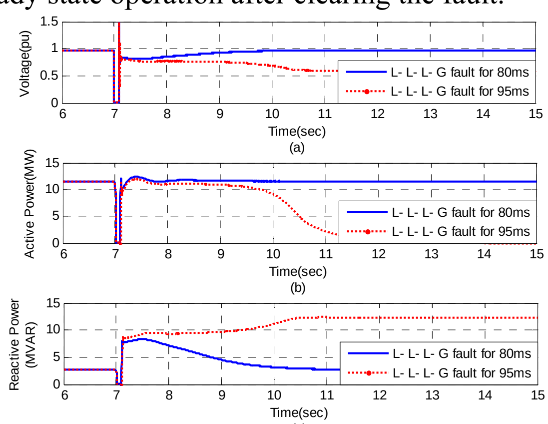
Fig. 10 shows the behavior of the wind farm without STATCOM when a double line to ground fault occurs for 88 ms and 176 ms duration times. As shown in Fig. 11, during fault period the voltage of the main bus B25 is decreased to 0.408 pu when the fault duration times are 88 ms and it is decreased to 0.372 pu when fault duration time is 176 ms. When the fault duration time is equal or more than 176 ms the protection system trips the wind farm and the generated active power falls to zero. After fault clearance, the absorbed reactive power increased to 2.639 MVAR in case of 88 ms fault duration. In case of 176 ms fault duration, the measured reactive power value is 12.24 MVAR. It is clear that When L-L-G fault occurs for 88ms or 176ms, wind farm has ability to stay connected to the grid for fault duration time 88ms and when the fault duration time is equal or more than 176 ms active power falls to zero and trip the wind farm.



(a)Voltage at PCC, (b) Active Power, (c) Reactive Power

Fig.11 Double line to ground fault at different fault duration –with STATCOM

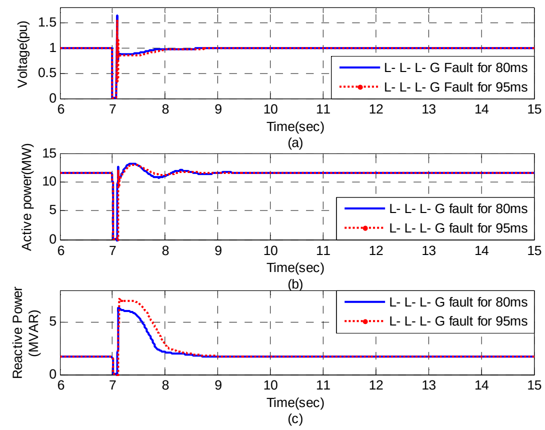
Fig. 11 shows the effect of double line to ground fault duration time on the behavior of the wind farm in case of STATCOM connecting. During fault period, the voltage of the main bus is decreased to 0.43 pu when the fault duration is 88 ms, and it decreases to 0.4 pu when the fault duration time is 176 ms. Also, the total exported active power from the wind farm is decreased to 5.5 MW in case of 88 ms fault duration, and it decreases to 5 MW in case of 176 ms fault duration. After fault clearance, the total absorbed reactive power from the grid is increased to 1.69 MVAR in case of 88 ms and 97 ms fault duration. It is clear that Wind farm has ability to stay connected to the grid for fault duration time 88ms or 176ms and the system returns back to steady state operation after clearing the fault.



(a)Voltage at PCC, (b) Active Power, (c) Reactive Power

Fig.12 Three line to ground fault at different fault duration –without STATCOM

Fig. 12 shows the behavior of the wind farm without STATCOM when a three line to ground fault occurs for 80 ms and 95 ms duration times. During fault period, the voltage of the main bus B25 falls to zero when the fault duration times are 80 ms and 95 ms. When the fault duration time is equal or more than 95 ms the protection system trips the wind farm and the generated active power falls to zero. After fault clearance, the absorbed reactive power increased to 2.636 MVAR for 80 ms fault duration. Where, the measured reactive power value is 12.21 MVAR. It is clear that When L-L-L-G fault occurs for 80ms or 95ms, wind farm has ability to stay connected to the grid for fault duration time 80ms and when the fault duration time is equal or more than 95 ms active power falls to zero and trip the wind farm.



(a)Voltage at PCC, (b) Active Power, (c) Reactive Power

Fig.13 Three line to ground fault at different fault duration –with STATCOM

Fig.13 shows that the effect of three-line to ground fault duration time on the behavior of the wind farm in case of STATCOM connecting. During fault period, the voltage of the main bus and the measured active power nearly falls to zero in cases of 80 ms and 95 ms fault duration times. After fault clearance, the total absorbed reactive power from the grid is increased to 1.695 MVAR in case of 80 ms and 95 ms fault duration. It is clear that Wind farm has ability to stay connected to the grid for fault duration time 80ms or 95ms and the system returns back to steady state operation after clearing the fault.

VI. CONCLUSION

Wind power plant has the ability to stay connected to the grid in case of L-G, L-L-G, L-L-L-G fault without STATCOM either fault occurs at F1 or F2. With STATCOM connection improve the voltage profile at PCC and absorbed reactive power from the grid is decreased and increases the active power during fault period. Wind farm has ability to stay connected for L-G fault occurs for 88ms or 150ms duration when system operates with or without STATCOM. In case of L-L-G fault, when the system operate without STATCOM the protection system trip the wind farm due to under voltage condition in case of fault duration time equal or exceed 176ms. When the STATCOM is connected the system return back to steady state and wind farm can stay connected to the grid. In case of L-L-L-G fault, when the system operates without STATCOM, the protection system trip the wind farm due to under voltage condition in case of fault duration time equal or exceed 95ms. When the STATCOM is connected the system can return back to steady state and the wind farm can stay connected to the grid.

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APPENDIX

Fixed speed induction Parameters	
Rated power (MW)	3
Rated voltage (V)	575
Rated frequency (Hz)	60
Stator resistance (pu)	0.004843
Rotor resistance (pu)	0.004377
Stator leakage inductance (pu)	0.1248
Rotor leakage inductance (pu)	0.1791
Mutual inductance (pu)	6.77

Transmission line parameters	
Positive sequence resistance (ohm/km)	0.1153
Zero sequence resistance (ohm/km)	0.413
Positive sequence inductance (henries/km)	0.00105
Zero sequence inductance (henries/km)	0.00332
Positive sequence capacitance (farads/km)	11.33e-9
Zero sequence capacitance (farads/km)	5.01e-9

STATCOM DATA	
STATCOM rating	3 MVA
DC-link capacitance	375 μF
DC link Voltage	4000 V