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Improvement of Low Voltage Ride through Capability of DFIG based Wind Energy System

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Abstract— Among the different renewable, wind energy system is the most exploited due to its free availability and technological developments. With the increasing penetration of wind energy into power system, the grid codes are become effective which mean wind energy system must insure the uninterrupted operation with voltage control and reactive power compensation improving low voltage ride through capability(LVRT). The doubly fed induction generator (DFIG) based wind energy system is very sensitive to voltage variation and less ability to resist drop in grid voltage. To enhance the LVRT capability of DFIG, one of the series connected Flexible A.C. Transmission Systems (FACTS) device Static Synchronous Compensator (STATCOM) is proposed here. The STATCOM connected between the wind energy system and point of common coupling compensate accurately. When there is voltage difference between normal voltage and fault condition, difference will be generated by inverter modulation thus improving its LVRT. The simulation for 2MW wind energy system is carried out on Matlab/Simulink environment and results are verified.

Key words: LVRT, DFIG, STATCOM

I. INTRODUCTION

Due to increasing climate changes green house effect and limited sources of fossil fuels, more countries are attracted towards renewable energy sources like solar, wind, biogas and fuel cells. Especially wind energy is capable of providing massive power requirement. Large wind farms are planned and installed all over the world. Today's total wind generator installed capacity has crossed 360 GW at the end of December 2014[1].

Typically doubly fed induction generator (DFIG) based wind energy system gaining more popularity because of its inherent advantages. DFIG is variable speed generator and has capability of interdependent control over active and reactive power. DFIG is wound rotor induction generator with the stator is directly connected to constant frequency three phase network and rotor through the back-to-back converters connected to DC linked capacitor[2]. The back-to-back converters consist of IGBT based stator side converter (GSC) and rotor side converter (RSC) as shown in the fig.1. The purpose of RSC is to regulate active n reactive power flow between machine and grid independently and the GSC maintains the DC link voltage constant independent of magnitude and direction of reactive power. The generation of power at variable speeds from sub-synchronous to super-synchronous can be achieved using DFIG increasing power generation. The stator winding provides 70% of power to the grid while only 30% flows from rotor side so converters rating is 20-30% of that generator's size.

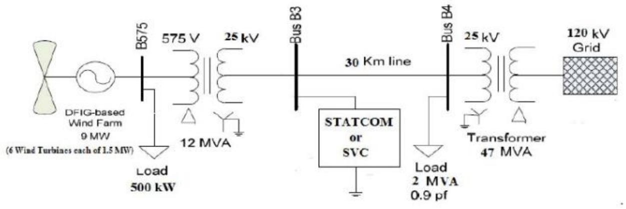

Fig. 1: DFIG based Wind Energy System

A major drawback of DFIG is their operation during grid faults. Faults in power system, even far away from the location of the turbine, can cause a voltage dip at the connection point of wind turbine. The dip in the grid voltage will result in an increase of the current in the stator windings of the DFIG. Because of the magnetic coupling between stator and rotor, this current will also flow in the rotor circuit and the power-electronic converter. This can lead to the destruction of the converter. It is possible to try to limit the current by current-control on the rotor side of the converter; however, this will lead to high voltages at the converter terminals, which might also lead to the destruction of the converter. Therefore, one of the key issues related to DFIG based wind energy system is low voltage ride through capability. Many researchers are working on this issue and they have proposed many techniques. The crowbar technique, one of the solution, in which RSC is blocked and rotor circuit is short circuited for protecting converter from over current in the rotor circuit. The generator operates as a simple wound rotor induction generator producing active power and GSC can be set to control reactive power and voltage. When fault has been cleared and normal voltage and frequency level in power network restored, DFIG starts working normally and RSC reconnects. In this uninterrupted operation mode of DFIG, voltage stability is a crucial issue. In the case of a weak power network and during a grid fault, GSC is not capable of providing sufficient reactive power and voltage support. This can be reason for risk of high voltage collapse. Because of voltage dips, RSC will not restart and generator will be disconnected from the network. The dynamic reactive power compensator can be used. Some researchers suggested the FACTS devices. In this paper, a STATCOM is implemented and investigated how it is helpful to uninterrupted operation of a DFIG based wind energy system.

In this paper, single machine infinite bus system with DFIG wind turbine is taken for simulation study. The behavior of system at three phase fault condition is studied and at that condition STATCOM connected at point of common coupling will support for reactive power and tries to maintain voltage level.

II. MODELLING OF DFIG

The basic configuration of wind turbine with DFIG is shown in fig.1. It consists of wind turbine blades, mechanical shaft system, gearbox and generator and back to back converter with its control system.

A. *Model with Wind Turbine Aerodynamics:*

The mechanical power of the wind turbine can be calculated by

$$P_t = \frac{1}{2}\rho\pi v^3 R^2 C_p(\beta,\lambda)$$

Where R is the radius of the blades, ρ is the air density, ὺ is the wind velocity. The power conversion coefficient (λ, β) can be expressed by (2) as a function of the blade pitch angle β and the tip-speed ratio λ

$$C_p(\beta,\lambda) = C_1\left(C_2\frac{1}{\lambda_i} - C_3\beta - C_4\beta^{C_5} - C_6\right)\left(e^{-C_7\frac{1}{\lambda_i}}\right)$$

Where

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + C_8\beta} - \frac{C_9}{1+\beta^3}$$

The tip-speed ratio λ is defined as

$$\lambda = \frac{\omega_r R}{v}$$

The constant coefficient C_1- C_9 as shown in the appendix are given by[13]

With constant blade pitch angle, the maximum value of the power coefficient Cpmax would be obtained at a particular value of λ , defined as λopt. For maximum power point tracking (MPPT), λ should be maintained at this optimal value. The maximum output power of the wind turbines P_{t_max} can be expressed by

$$P_{t\_max} = \frac{1}{2}\rho\pi R^2 c_{p\_max} v^3$$

Fig.3 shows the relationship between Cp and λ , with constant pitch angle β=0. It can be seen that cpmax=0.44 and λopt=7.2. All the other parameters of the wind turbine are given in the appendix.

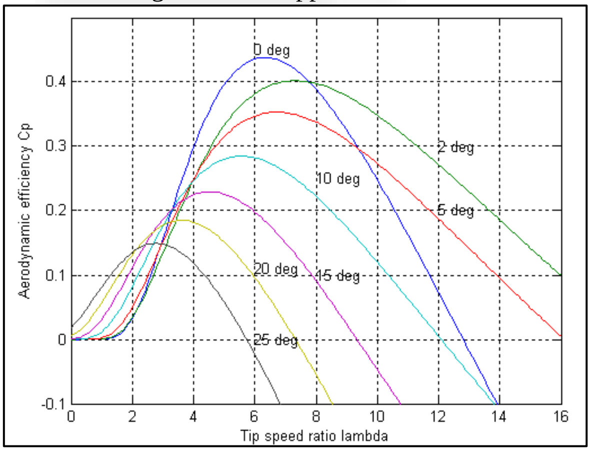

Fig. 2: C_p-λ Curve

B. *Modelling of Induction Generator:*

The steady state model of induction generator can be expressed in following equations. The stator and rotor voltage equations in instantaneous variables transform by applying synchronously rotating reference frame transformation, the voltage equations become

$$v_{ds} = R_s i_{ds} + p\varphi_{ds} - \omega_1\varphi_{qs}$$
$$v_{qs} = R_s i_{qs} + p\varphi_{qs} + \omega_1\varphi_{ds}$$
$$v_{dr} = R_r i_{dr} + p\varphi_{dr} - (\omega_1 - \omega_r)\varphi_{qr}$$
$$v_{qr} = R_r i_{qr} + p\varphi_{qr} + (\omega_1 - \omega_r)\varphi_{dr}$$

Where ωs is the rotational speed of the synchronous references frame,wr is the rotor speed, and the flux linkages are given by

$$\varnothing_{ds} = L_s i_{ds} + L_m i_{dr}$$
$$\varphi_{qs} = L_s i_{qs} + L_m i_{qr}$$
$$\varphi_{dr} = L_r i_{dr} + L_m i_{ds}$$
$$\varphi_{qr} = L_r i_{qr} + L_n$$

In order for the rotor mmf to be in synchronism with the stator mmf, the frequency of the rotor current, wrf must satisfy the slip frequency constant.

The per unit electromagnetic torque equation is given by

$$T_{em} = 1.5n_p(\varphi_{ds}i_{qs} - \varphi_{qs}i_{ds}) = 1.5n_p(i_{qs}i_{dr} - i_{ds}i_{qr})$$

The stator active and recative powers are

$$P_s = 1.5(u_{ds}i_{ds} + u_{qs}i_{qs})$$
$$Q_s = 1.5(u_{qs}i_{ds} - u_{ds}i_{qs})$$

The active and reactive rotor powers are as:

$$P_r = 1.5(u_{dr}i_{dr} + u_{qr}i_{qr})$$
$$P_r = 1.5(u_{dr}i_{dr} + u_{qr}i_{qr})$$

III. STATIC SYNCHRONOUS COMPENSATOR

The static synchronous compensator (STATCOM), the Flexible A. C. Transmission System device is used to generate or absorb reactive power. Usually, the STATCOM is applied to voltage support aims. It basically composts of voltage source converter (VSC), a DC energy storage device, a coupling transformer. The VSC converts the dc voltage across the storage device into a set of three phase ac output voltages. It can continuously generate or absorb reactive power by varying the amplitude of the converter voltage with respect to the line bus voltage so that a controlled current flows through the tie reactance between the STATCOM and the distribution network. When system voltage is low, the STATCOM generates reactive power (STATCOM capacitive). When system voltage is high, it absorbs reactive power (STATCOM inductive). The VSC uses forced-commutated power electronic devices to synthesize its terminal voltage from a DC voltage source. The IGBT based STATCOM model is used. The overall scheme of the STATCOM circuit is shown in fig.3 and the control system block diagram is shown in fig.4.

The real and reactive power injected by the STATCOM is given by the following equations:

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

Where δ is the angle of V_1 with respect of V_2 .In steady state operation, the voltage V_2 generated by the VSC is in phase with V_1 (δ=0), so that only reactive power is flowing (P=0). If V_2 is lower than V_1, Q is flowing from V1 to V2 (STATCOM is absorbing reactive power). On the reverse, if V2 is higher than V1, Q is flowing from V2 to V1(STATCOM is generating reactive power). The reactive power is given by the following equation:

$$Q = \frac{V_1(V_1 - V_2 \cos\delta)}{X}$$

$$Q = \frac{V_1(V_1 - V_2)}{X}$$

IV. SIMULATION RESULTS AND DISCUSSION

The simulation analysis was carried out using Matlab/Simulink software. Different cases studied on the test system shown in fig 1. Here the short circuit fault is considered and its effect on the DFIG based wind energy system connected to the power system. Also the evaluation of the STATCOM has been addressed and analyzed. Results show how STATCOM provides reactive power mitigating transient disturbances.

A. The System Output at Steady State Conditions without STATCOM:

A step wind speed profile has been applied with initial wind speed of 8 m/s and then at t=5s wind speed increases to 14m/s. the control mode of the DFIG based wind energy system was set to voltage regulation mode of reference voltage of 1pu on the base of generator rating at bus B575. At t=5s, the generated active power starts increasing smoothly to reach its rated value of 9 MW.

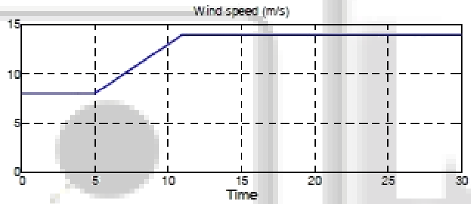

Fig. 3: Wind Speed Profile

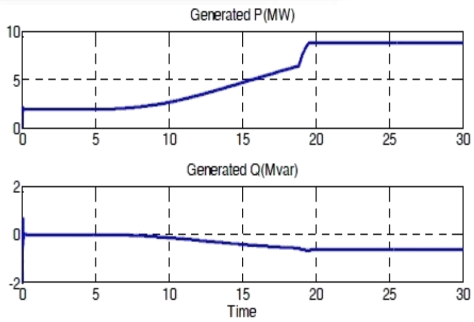

Fig. 4: DFIG Generated Active and Reactive Power

Over that time frame the turbine speed will have increased from 0.8 pu to 1.21 pu. The reactive power is controlled to maintain a 1 pu voltage at bus B575 and the equivalent DC link voltage of the DFIG based wind energy system at 1200V. the overall performance of the system is shown below figs.

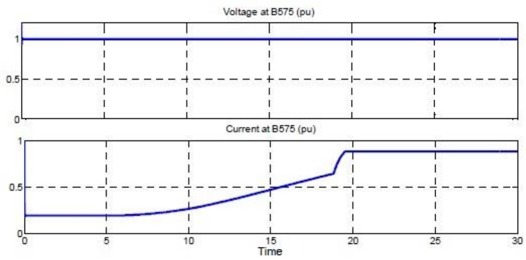

Fig. 5: The Voltage and Current at Point of Common Coupling

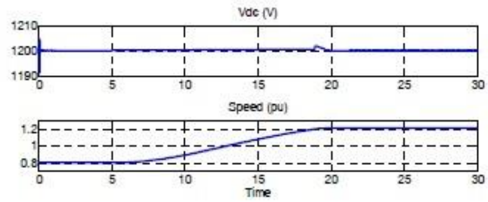

Fig. 6: DC Link Capacitor Voltage and Turbine Speed

B. Single Line To Ground Fault with STATCOM And RSC Blocking:

Grid fault has a significant effect on the wind system even when the fault located far away from the PCC of the wind farm. Voltage sag at PCC leads to over current in the rotor circuit, DC link voltage fluctuations and a change in speed. Therefore, the RSC must be blocked to avoid being destroyed by the over current in the rotor circuit.

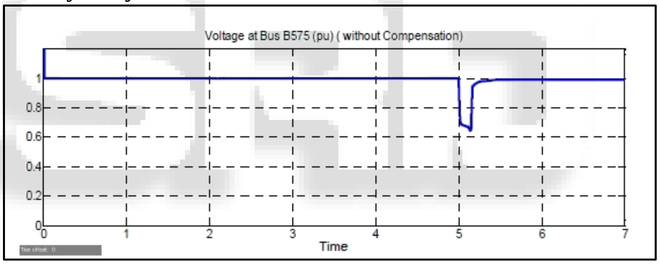

Fig.7: PCC Voltage during SLGF

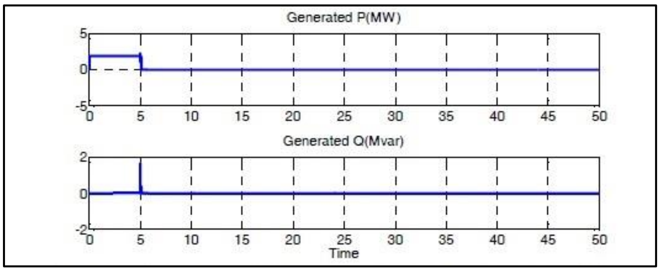

Fig. 8: Interrupted Operation of the Wind Turbine during A SLGF

A temporary single line to ground fault is applied for 9 cycles to the bus B3 at t=5s. the RSC is blocked by setting the control mode of DFIG based wind energy system to a VAR regulation mode with reference reactive power command equal to zero. DFIG will not be able to exchange reactive power with the power system. The protective system of DFIG wind system designed to trip the wind turbine when the voltage at PCC drops to 75%.

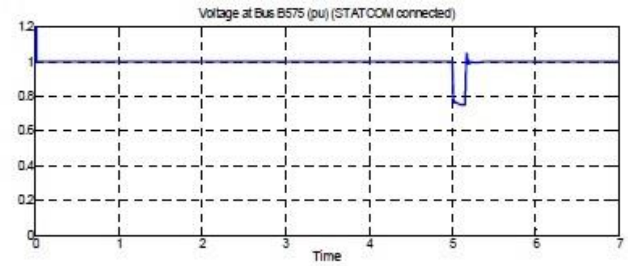

Fig. 9: PCC voltage during SLGF with a STATCOM

Fig.9. shows that the voltage at the PCC (bus B575) during the fault is dropped to 0.65 pu which makes the protective system trips the wind farm where the total active power generated by the wind farm is zero as shown in fig.10. also fig.11 shows that the RSC and GSC are blocked to protect them from the over currents in the rotor circuit, as a result of that, the DFIG based wind energy system does not exchange a reactive power with the power system.

After installation of 10 MVA STATCOM at bus B3 inn Fig.1, it provided the required reactive power to maintain the voltage at the PCC above 75 pu and maintain the wind farm in service during and after the single line ground fault. Fig.11. shows how the voltage at the PCC is improved to 0.79 pu when a STATCOM is connected.

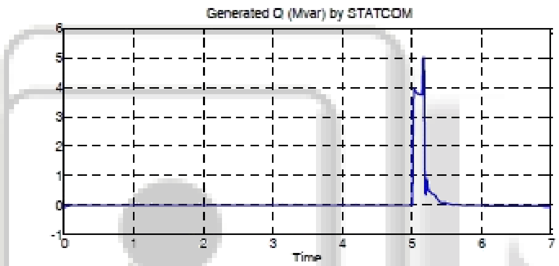

Fig. 10: Reactive Power Injected By the STATCOM during SLGF

Fig.12 shows the reactive power supplied by the STATCOM to maintain the wind energy system in service. The RSC is blocked, and the STATCOM is providing 4MVar reactive power. This could not have been provided by the GSC, which has the rating of 3 MVA, and underlines the need for a STATCOM or some other form of reactive compensation.

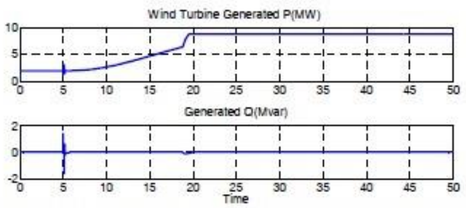

Fig. 11: Uninterrupted Operation of the Wind Turbine with A STATCOM during A SLGF

Fig.13.shows how the wind energy system remain in services during the fault and generates a full 9 MW active power when the STATCOM is connected. While the RSC is blocked and the reactive power command of the GSC is set to zero.

C. Single line to ground fault with STATCOM and RSC blocking:

A temporary line to line fault is applied for 9 cycles to the bus B3(25 kV) at t=5s. The RSC is blocked and reactive power command of the GSC is set to zero.

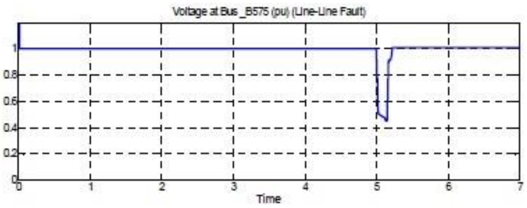

Fig. 12: PCC Voltage during Line To Line Fault

Fig.12 shows that the voltage at the PCC during the fault is dropped to 0.45 pu. It is clear that the line to line fault causes a deeper voltage sag compare with the single line to ground fault. The wind farm is tripped by the protective system due to this significant voltage sag which exceeded the under voltage protection limit of 0.75pu.

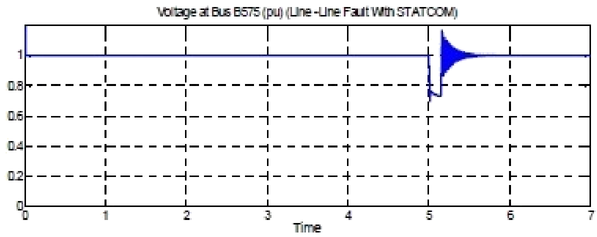

Fig.13: PCC Voltage with STATCOM

After installation of 20 MVA STATCOM at the bus B3 in Fig.1, it provided the required reactive power to maintain the voltage at the PCC above 75 pu and maintain the wind energy system in service during and after the line to line fault. Fig.13. shows how the voltage at the PCC is improved to 0.76 pu when a STATCOM is connected and the PCC voltage is quickly reestablished shortly after the fault has cleared.

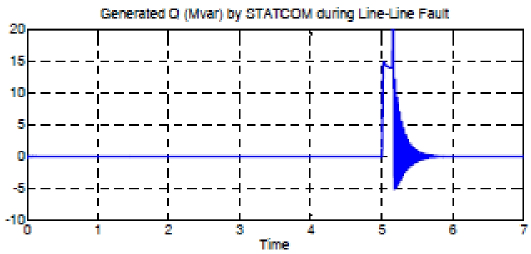

Fig. 14: Reactive Power Injected By the STATCOM

Fig.14. shows the reactive power supplied by the STATCOM to maintain the wind energy system in service. The RSC is blocked, and the STATCOM is providing 15MVar reactive power. The amount of the reactive power injected is much higher than the injected reactive power during the single line to ground fault which is realistic increase due to the different in the voltage sag level in both cases.

Another requirement for the successful uninterrupted operation of the wind turbines is the dc-link voltage stability of variable frequency ac/dc/ac converter (VFC), in the rotor circuit. Fig.17 and Fig.18 show that the overshoot of the DC link voltage has been decreased during the fault from 1315V to 1280 V when the STATCOM is installed. Decreasing the overshoot of the DC link voltage minimize the dangerous of damaging the GSC and helps the RSC to restart when the fault has cleared. In addition, the GSC controller successfully controls the DC-link voltage back to the nominal value of 1200V when the STATCOM is installed.

V. CONCLUSION

Dynamic reactive power compensation is the most successful technique to integrate the DFIG based wind energy system. The STATCOM connected at the PCC is used to provide reactive power support thus improving voltage level. This prevent the tripping of wind energy system during voltage crisis.

From results, it was concluded that the STATCOM produces the required reactive power to maintain the wind energy system in services and produces a better voltage profile independent of wind speed variation.

Wind Turbine		Generator Parameters		Transmission Line Parameters (π Model)	
Rated Capacity	(6 Turbines ×1.5MW) 9 MW	P_{rated}	6G×1.5 MW	r_1	0.1153 Ω/km
Cut –in Wind speed	3.5 m/s	V_{rated}	575 V	r_0	0.413 Ω/km
Cut-out Wind speed	25 m/s	r_s	0.00706	l_1	0.00105 H/km
Rated Wind speed	14 m/s	r_r	0.005	l_0	0.00332 H/km
No. of Blades	3	l_{ls}	0.171	C_1	11.33e-9 F/km
Rotor Diameter	82.5 m	l_{lr}	0.156	C_0	5.01e-9 F/km
Swept area	5346 m^2	L_m	2.9		
Rotor speed	10.1-18.7 rpm	pf	0.9		

Table 1: Appendix

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