Improvement of Power Quality using STATCOM in a DFIG based Wind Farm

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ABSTRACT
Problem of power quality is quite severe in wind energy conversion systems using induction generators. For power generation from wind induction generator are found to be the most appropriate choice. Major problem is seen in voltage profile and frequency deviations with changing natural conditions such as wind speed and variation in load. The transient response is actually a critical dynamic characteristic of doubly fed induction generator-based wind turbines, especially in the presence of fast transient events, such as, fault in power system. This paper presents a comparative study of stabilizing a DFIG (Doubly Fed Induction Generators) based wind farm using its own frequency converters and using a STATCOM (Static Synchronous Compensator) during wind speed change and grid fault.Simulation results show that for dynamic reactive power compensation, when, STATCOM is a used at a point of interconnection of wind farm and the network, the system absorbs the generated wind reactive power while maintaining its voltage level.

Keywords
Wind energy, DFIG, Power Quality, Smart grid, STATCOM

1. INTRODUCTION
Growth of wind power generation is likely to influence the operation and planning of the existing power system networks. Because integration of wind power in power systems causes problem of voltage regulation and reactive power compensation. It is increasingly important that wind generation continue to operate during periods of short circuit fault in the grid. The penetration of wind power has reached levels high enough to affect the quality and stability of the grid [1][6]. According to grid codes issued by utilities, tripping of wind turbines following grid fault is not allowed. Besides to provide voltage support to the grid, mandatory reactive current supply is necessary [4]. Main services in a power system are power-frequency control and voltage control. These services must be provided by each generator connected to the grid. In order to provide the ancillary service of voltage, generators must have some reactive power capability as required by the corresponding grid codes [7].Recently, the most widely used variable wind turbine is the Doubly Fed Induction Generator type (DFIG) because it can operate at a wider range of speed depending on the wind speed or other specific operation requirements. Thus it allows for a better capture of wind energy, and dynamic slip control and pitch control may contribute to rebuilding the voltage at the wind turbine terminals and maintaining the power system stability after clearance of an external short-circuit fault [11][13] . In addition, DFIG have shown better behavior concerning system stability during short-circuit faults in comparison to IG, because of its capability of decoupling the control of output active and reactive power. On the other hand, Static Synchronous Compensators (STATCOM) can be use to provide reactive power to stabilize a wind farm also. There are various voltage source or current source inverter based on FACTS devices for flexible power control damping of power system and stabilization of wind generators, but in this paper STATCOM based on a voltage source converter (VSC) PWM technique is used to stabilize the DFIG [1][3]. This paper presents a comparative analysis of the use of DFIGs frequency converters or STATCOM to stabilize a wind farm. Simulation model of wind turbine with DFIG developed in MATLAB is presented.

2. WIND POTENTIAL AND CONVERSION
In recent years, the environmental pollution has become a major concern in people daily life and a possible energy crisis has led people to develop new technologies for generating clean and renewable energy. Wind power along with solar energy, hydropower and tidal energy are possible solutions for an environmentally-friendly energy production. Among these renewable energy sources, wind power has the fastest growing speed (approximately 20% annually) in the power industry. With the concern of environmental pollution, wind power is being established in many countries by way of government-level policy. It is reported that by 2020, Europe will achieve 20% of power consumed in there supplying by large-scale offshore wind farms [2]. Besides, Europe is now planning for enlarging the capacity of the large-scale offshore wind farms to more than 30 GW power by 2015. Besides Europe, other countries such as China and USA also have promising offshore wind power resources and similar plans for wind farm installation.The development of wind power in India began in the 1990's, and has progressed steadily in the last few years. As per February 2013, India has 18634 MW of installed capacity of wind power. The main requirement for wind power installation is land and grid infrastructure availability. There are reports which indicates India have total wind power access of around 45,000 MW assuming 1% land availability for wind farms requiring @12 ha/MW in sites having wind power density in excess of 200W/sq.m. at 50 m hub-height.India is targeting to add 15000MW in the 12th Five Year Plan Period.

2.1 Aerodynamic Conversion
The process of how the wind turbine system generates electrical power will be briefly summarized as follows:

1) The wind strikes the wind turbine blades, causes them to spin and further makes the low-speed shaft rotate
2) The rotating low-speed shaft transfers the kinetic energy to the gearbox, which has the function of stepping up the rotational speed and rotating the high-speed shaft

3) The high-speed shaft causes the generator to spin at high speed which is close to the rated speed of the generator
4) The rotating generator converts the mechanical power to electrical power.

Usually, the output voltages of the generator are low, and hence there will be the need for a transformer to step up the generator output voltage for the purpose of directly connecting to the grid.The wind turbine always operates with different dynamics, from minimum wind speed to maximum wind speed, and the operating regions of the wind turbine can be illustrated by their power curve shown as in Figure 1.

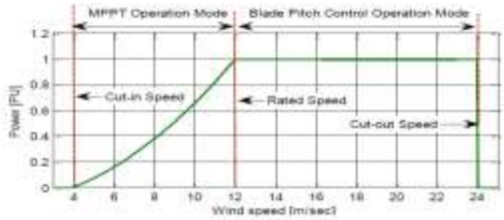

Fig 1: Power verse wind speed curve

Some of the available power in the wind is converted by the rotor blades to mechanical power acting on the rotor shaft of the wind turbine. For steady-state calculations of the mechanical power from a wind turbine, the so called *Cp* (*λ, β*) curve can be used.

The mechanical Power by wind turbine:

$$P_{mec\,h} = \frac{1}{2}\rho A_r C_p(\lambda,\beta) w^3 \qquad (1)$$

$$\lambda = \frac{\Omega_r r_r}{w} \qquad (2)$$

C_p is power coefficient, λ is tip speed voltage, β is the pitch angle, w is wind speed, ρ is the air density, A_r is area swept by rotor, Ω_r is the rotor speed, r_r is the rotor turbine radius.

In Fig. 2, *Cp* (*λ, β*) curve and the shaft power as a function of the wind speed for rated rotor speed, i.e., a fixed-speed wind turbine can be seen. In Fig. 3 the solid line corresponds to a fixed pitch angle, *β*, while dashed line corresponds to a varying β (active stall) [4][11].

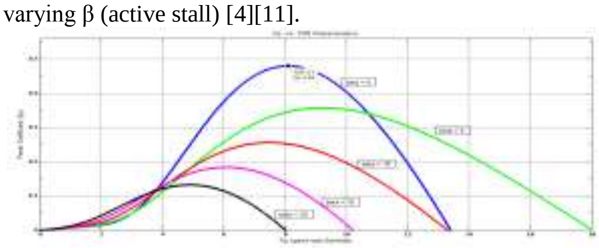

Fig 2: The power coefficient, *Cp*, as a function of the tip speed ratio, *λ*.

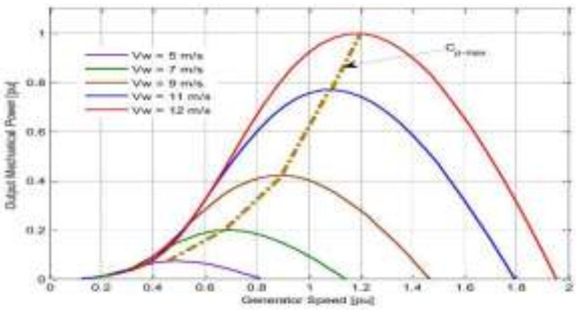

Fig 3: Turbine output power characteristic for different wind speeds.

3. DOUBLY FED INDUCTION GENERATOR

Wind turbines use a doubly-fed induction generator (DFIG) consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. The optimum turbine speed producing maximum mechanical energy for a given wind speed is proportional to the wind speed. Another advantage of the DFIG technology is the ability for power electronic converters to generate or absorb reactive power, thus eliminating the need for installing capacitor banks as in the case of squirrel-cage induction generator.

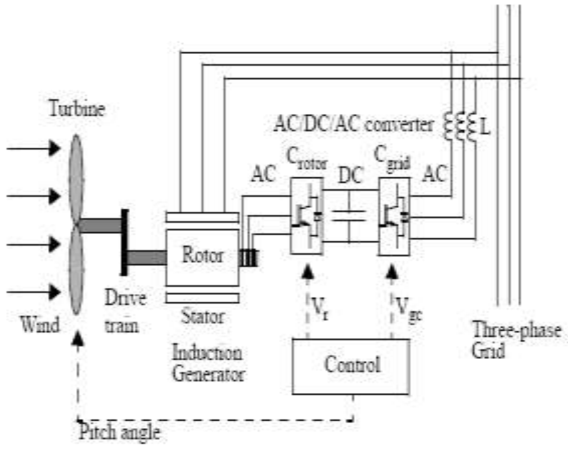

Fig 4: Basic diagram of DFIG with converters

Where Vr is the rotor voltage and Vgc is grid side voltage. The AC/DC/AC converter is basically a PWM converter which uses sinusoidal PWM technique to reduce the harmonics present in the wind turbine driven DFIG system.
The mechanical power and the stator electric power output are computed as follows:

$$P_r = T_m * w_r \qquad (3)$$

$$P_s = T_{em} * w_s \qquad (4)$$

For a loss less generator the mechanical equation is:

$$J\frac{dw_r}{dt} = T_m - T_{em} \qquad (5)$$

In steady-state at fixed speed for a loss less generator

$$T_m = T_{em} \text{ and } P_m = P_s + P_r \qquad (6)$$

and it follows that:

$$P_r = P_m - P_s = T_m w_r - T_{em} w_s = -sP_s \qquad (7)$$

Where,
s is defined as the slip of the generator
Generally the absolute value of slip is much lower than 1 and, consequently, P_r is only a fraction of P_s. Since Tm is positive for power generation and since w_s is positive and constant for a constant frequency grid voltage, the sign of P_r is a function of the slip sign. P_r is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). For super synchronous speed operation, P_r is transmitted to DC bus capacitor and

tends to raise the DC voltage. For sub-synchronous speed operation, P_r is taken out of DC bus capacitor and tends to decrease the DC voltage. C_{grid} is used to generate or absorb the power P_{gc} in order to keep the DC voltage constant. In steady-state for a lossless AC/DC/AC converter P_{gc} is equal to P_r and the speed of the wind turbine is determined by the power P_r absorbed or generated by C_{rotor}. The phase-sequence of the AC voltage generated by C_{rotor} is positive for sub-synchronous speed and negative for super synchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip. C_{rotor} and C_{grid} have the capability for generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals.

Dynamic simulation of DFIG in terms of dq winding is as follows:

1. Voltage equations:

Stator Voltage Equations

$$V_{qs} = p\lambda_{qs} + w\lambda_{qs} + r_s i_{qs} \quad (8)$$

$$V_{ds} = p\lambda_{ds} - w\lambda_{qs} + r_s i_{qs} \quad (9)$$

Rotor Voltage Equations**:**

$$V_{qr} = p\lambda_{qr} + (\omega-\omega_r)\ \lambda_{ds} + r_s i_{qr} \quad (10)$$

$$V_{dr} = p\lambda_{dr} - (\omega-\omega_r)\ \lambda_{qr} + r_s i_{dr} \quad (11)$$

Power Equations:

$$P_s = 3/2\ (V_{ds} I_{ds} + V_{qs} I_{qs}) \quad (12)$$

$$Q_s = 3/2\ (V_{qs} I_{ds} + V_{ds} I_{ds} \quad (13)$$

Torque Equation:

$$T_g = -3\ p/4\ (V_{ds} I_{qs} - V_{qs} I_{ds}) \quad (14)$$

2. Flux Linkage Equations:

Stator Flux Equations:

$$\lambda_{qs} = (L_{is} + L_m)\ i_{qs} + L_m I_{qr} \quad (15)$$

$$\lambda_{ds} = (L_{is} + L_m)\ i_{ds} + L_m I_{dr} \quad (16)$$

Rotor Flux Equations:

$$\lambda_{qr} = (L_{ir} + L_m)\ i_{qr} + L_m I_q \quad (17)$$

$$\lambda_{dr} = (L_{ir} + L_m)\ i_{dr} + L_m I_{ds} \quad (18)$$

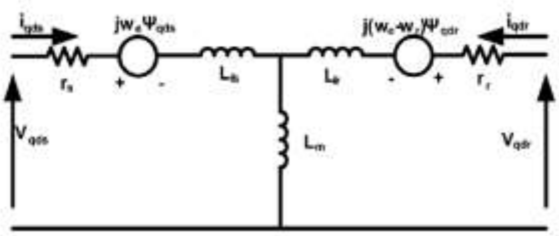

Fig. 5: Complex synchronous equivalent of a DFIG

4. REACTIVE COMPENSATION SYSTEM FOR WIND FARMS

The random and intermittent nature of wind power makes the large-scale wind farms connected to the gird present some unwanted effects at the connection points. The most prominent is voltage fluctuations, in severe case voltage collapse. Voltage fluctuation was mainly caused by the sharp change of reactive power demand. The voltage fluctuation at the wind power connected points is common to see, that means the dynamic voltage stability challenge has to face. To maintain the voltage produced at the stator equal to the ac power network voltage, a specific magnetic flux value must be maintained in the machine (more precisely at the stator terminal) [5]. This can be achieved by applying a voltage to the generator rotor winding that is proportional to the frequency of the voltage applied to the rotor winding (this ensure the V/f ratio constant and a constant magnitude flux value in the machine). The value of the V/f ratio is generally set so that the reactive power at the stator Q_{stator} is equal to zero.Additionally SVC, STATCOM or other FACTS (Flexible AC Transmission System) devices utilizing power electronics to provide dynamically variable import and export capability are also used to provide fast and smooth responses under the different operating scenarios.

STATCOM reactive power compensation principle

STATCOM circuit topology can be divided into two types: voltage source converter （VSC）STATCOM and current source converter (CSC) STATCOM. In general the efficiency of CSC topology is relatively lower than the VSC. The VSC topologies are preferred in STATCOM applications. For large scale wind farm application, higher voltage rating ones are desirable. This paper adopts voltage source STATCOM as a dynamic reactive power compensator. The simplified equivalent circuit of a VSC-STATCOM connected to an ac source is shown in Fig.6, where V_S represents the ac power source, V_S^i, represents controllable ac output voltage of the STATCOM, *Xs* and R_s are the interfacing reactance and resistance.

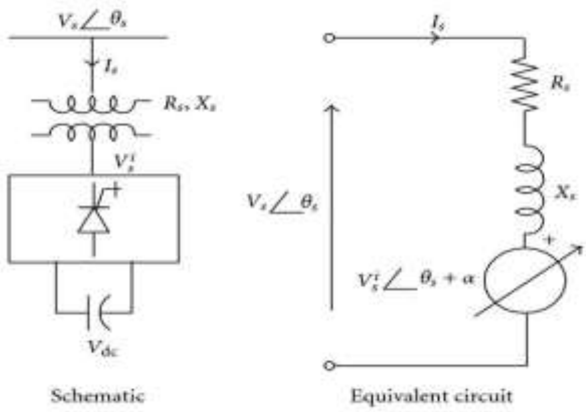

Fig 6: Basic Model of a STATCOM

The voltage drop across *XL* and *R* is $V_l = V_S - V_S^i$ and the current *Is* flown through them related to it too. This current can be leading or lagging the source voltage, phasor diagrams shown in Fig.7 and Fig.8 show their relations.

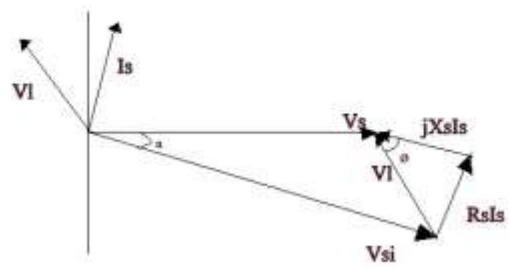

Fig.7 Capacitive reactive power vector graph of STATCOM

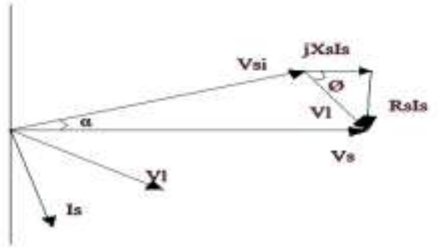

Fig.8 Inductive reactive power vector graph of STATCOM

Assuming that the positive direction of power transmission is from the grid to the STATCOM, if *Xs* >> *Rs*, the active power *P* and reactive power *Q* to the STATCOM can be deduced from Fig.7 and Fig.8:

$$P = \frac{V_s V_s^i \sin\alpha}{X_s} \quad (19)$$

$$Q = \frac{V_s^i (V_s \cos\alpha - V_s^i)}{X_s} \quad (20)$$

The equation (1) and (2) clearly indicate that the active power *P* and reactive power *Q* can be controlled by adjusting the STATCOM output voltage amplitude V_s^i and the phase difference α between V_S and V_s^i. The polarity of α determines the direction of active power, and the amplitude difference of V_S and V_s^i determines reactive power direction [8][9].

5. PROPOSED MODEL

In the proposed model 1.5 MW wind-turbines has been used. Wind turbines uses doubly fed induction generators (DFIG). The stator winding is connected directly to network. The 1.5 MW wind turbine is simulated to the 50 Hz grid and the rotor is driven by a variable-pitch wind turbine. In order to generate power the DFIG speed must be slightly above the synchronous speed. Speed varies approximately between 1pu at no load and 1.005 pu at full load. Each wind turbine has a protection system monitoring voltage, current and machine speed. Reactive power absorbed by the DFIGs is partly compensated by V/f ratio constant and a constant magnitude flux value in the machine. The value of the V/f ratio is generally set so that the reactive power at the stator Q_{stator} is equal to zero. . The rest of reactive power required to maintain the bus voltage close to 1pu by a 10-Mvar STATCOM. The turbine mechanical power as function of turbine speed is displayed for wind speeds ranging from 5 m/s to 12 m/s. The nominal wind speed yielding the nominal mechanical power (1pu) is 12 m/s. The wind turbine model and the STATCOM model are phasor models that allow transient stability type studies with long simulation times.

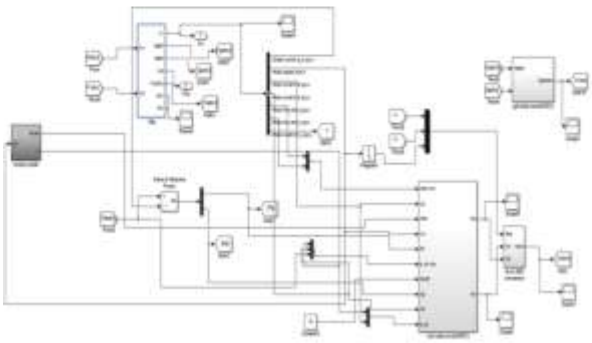

Fig.9: Wind farm model

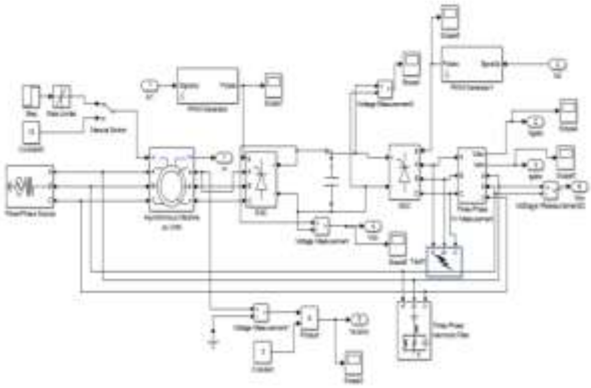

Fig 10: DFIG Block

6. SIMULATION RESULTS AND DISCUSSION

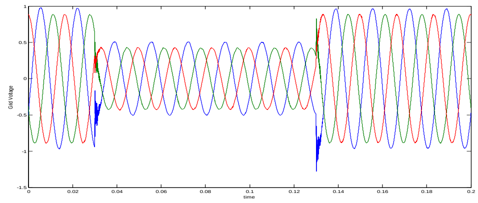

Fig 11: Grid Voltage (pu)

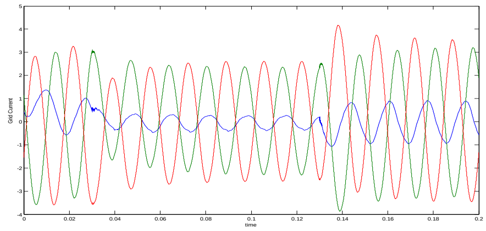

Fig 12: Grid Current (pu)

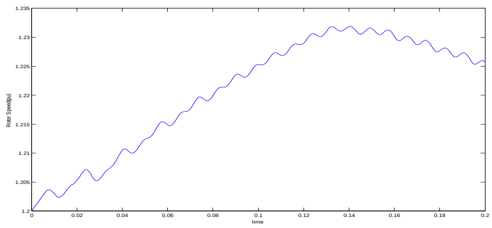

Fig 13: Rotor speed (pu)

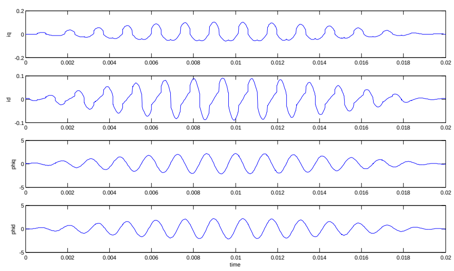

Fig 14: Rotor current and flux

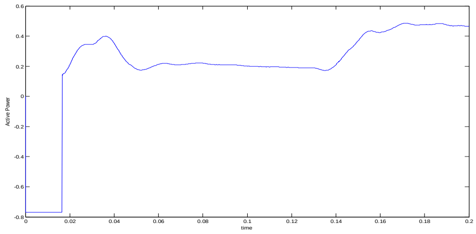

Fig 15: Rotor Active Power (pu)

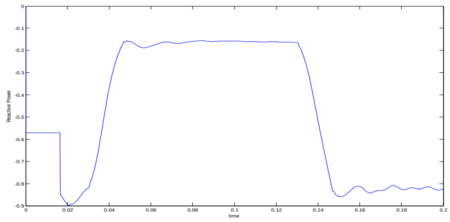

Fig 16: Rotor Reactive Power (pu)

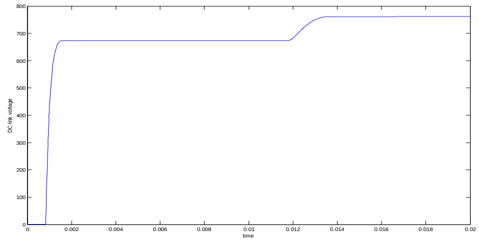

Fig 17: DC link voltage using PI controller

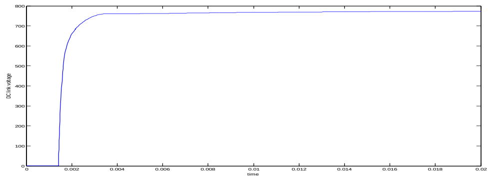

Fig 18: DC link voltage using Fuzzy controller

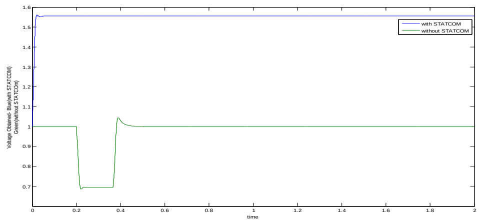

Fig 19: Voltage obtained- Blue (with STATCOM), green (without STATCOM)

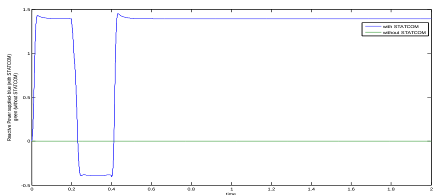

Fig 20: Reactive Power supplied- yellow (with STATCOM), purple (without STATCOM)

We can observe that when fault occurs at 0.2 sec, voltage sag occurs around 30%, at that time reactive power generated by STATCOM is -0.27 pu, while for the conventional circuit it is almost zero. Also the maximum capacitive power generated by a STATCOM decreases linearly with voltage decrease (constant current). This ability to provide more capacitive power during a fault is one important advantage of the STATCOM.

7. CONCLUSION

This paper explores the possibility of connecting a STATCOM to the wind power system in order to provide efficient control. In this paper, the wind turbine modeled is a DFIG that is an induction machine which requires reactive power compensation during grid side disturbances. An appropriately sized STATCOM can provide the necessary reactive power compensation when connected to a weak system. A simulation study shows the comparison of voltage regulation with DFIG's frequency converters and with the STATCOM. It is concluded that additional voltage/var support provided by an external device STATCOM can significantly improve the wind turbines fault recovery by more quickly restoring voltage characteristics.

8. REFERENCES

[1] Dianguo Xu, Rui Li, Yicheng Liu, Yongqiang Lang, "Reactive power analysis and control of doubly fed induction generator wind farm", IEEE, 13th European Conference on Power Electronics and Applications, 2009, pp. 1 – 10

[2] Renewable Energy Akshay Urja, Volume 6, Issue 5 & 6, June 2013, Newsletter of the Ministry Of New And Renewable Energy, Government Of India

[3] L. Xu and P. Cartwright "Direct active and reactive power control of DFIG for wind energy generation", *IEEE Trans. Energy Convers.*, 2006, vol. 21, no. 3, pp.750 -758 .

[4] Erlich, H. Wrede and C. Feltes, "Dynamic Behaviour of DFIG- Based Wind Turbine During Grid Faults", IEEJ Trans. Vol. 128, No 4, pp. 396, 2008.

[5] Molinas M, Suul J.A., Undeland T, "A simple method for analytical evaluation of LVRT in wind energy for induction generators with STATCOM or SVC" IEEE, Power Electronics and Applications, 2007 European Conference, 2007, pp. 1 – 10.

[6] A. D Hasan, G. Michalke, "Fault ride-through capability of DFIG wind turbines", Renewable Energy Vol. 32, pp. 1594-1610, 2007.

[7] D. Santos-Martins, S. Arnaltes, J. L. Rodriguez Amenedo, "Reactive power capability of doubly fed asynchronous generators", Electric power systems research, Vol.78, pp. 1837-1840, 2008.

[8] Jingmei Fang, Gengyin Li, Xuefeng Liang, Ming Zhou, "An optimal control strategy for reactive power in wind farms consisting of VSCF DFIG wind turbine generator systems", IEEE, Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 2011, 4th International Conference, July 2011, pp. 1709 – 1715.

[9] Masaud, T, Sen P.K, "A comparative study of the implementation of STATCOM and SVC on DFIG-based wind farm connected to a power system" , Power and Energy Society General Meeting, 2012, IEEE, pp.1-6.

[10] Guowei Cai, Qi Sun, Cheng Liu, Pengfei Li, "A new control strategy to improve voltage stability of the power system containing large-scale wind power plants", IEEE, 4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 2011, Weihai, Shandong pp. 1276 – 128.

[11] S. Santos, H. T. Le, "Fundamental time-domain wind turbine models for wind power studies", Renewable Energy, Vol. 32, pp. 2436-2452, 2007.

[12] B. H. Chowdhury, S. Chellapilia, "Doubly-fed induction generator control for variable speed wind power generation", Electric Power System Research, Vol. 76, pp. 786-800, 2006.

[13] H. Karim-Davijani, A. Sheikjoleslami, H. Livani and M. Karimi- Davijani, "Fuzzy Logic Control of Doubly Fed Induction generator Wind Turbine", World Applied Science Journal, Vol. 6, No. 4, pp. 499-508, 2009.

[14] Sun, Z. Chen and F. Blaabjerg, «Transient Stability of DFIG Wind Turbines at an External Short Circuit Fault», Wind Energy Journal, Vol. 8, pp. 345-360, 2005.

[15] Y. Zou , M. Elbuluk and Y. Sozer "A complete modeling andsimulation of induction generator wind power systems", *Proc.IEEE Ind. Appl. Soc. Annu. Meeting*, pp.1 -8, 2010

[16] Enrique Santacana, Gary Rackliffe,Le tang, and Xiaoming,"Getting Smart", IEEE power & energy magazine, April. 2010.

[17] A. Tapia, G. Tapia, J. X. Ostolaza, and J. R. Saenz, "Modeling And Control Of A Wind Turbine Driven Doubly Fed Induction Generator," *IEEE Trans. Energy Conversion*, Vol. 18, No. 2, June. 2003, pp. 194-204.

[18] A. Adamczyk, R. Teodorescu, R. N. Mukerjee, and P. Rodriguez, "Overview of facts devices for wind power plants directly connected to the transmission network," IEEE International Symposium on Industrial Electronics (ISIE), pp. 3742-3748, 2010.