Stability Enhancement of DFIG-based Variable Speed Wind Turbine with a Crowbar by FACTS Device as Per Grid Requirement

Kenneth E. Okedu*

*Department of Electrical and Electronic, Faculty of Engineering, University of Port Harcourt, Nigeria

‡ Corresponding Author; Kenneth E. Okedu,Department of Electrical and Electronic, Faculty of Engineering, University of Port Harcourt, Nigeria, kenokedu@yahoo.com

Received: 22.05.2012 Accepted:19.06.2012

Abstract- A crowbar protection switch is normally considered to protect the power converter of doubly fed induction generator (DFIG) during grid fault. However, the crowbar protection has some adverse effects on the operation of DFIG as to deteriorate the independent controllability of real and reactive powers. This paper investigates the effect of connecting FACTS (Flexible AC Transmission System) device such as a STATCOM (Static Synchronous Compensator) to the point of common coupling (PCC) of a wind farm composed of DFIG. Simulation results in power system computer aided design/electromagnetic transient including DC (PSCAD/EMTDC) show that a FACTS device can effectively enhance the performance of the DFIG, when it is disconnected by the crowbar switch during grid fault by providing additional reactive power to the system, thus improving the voltage instability performance of the DFIG and the wind farm as well. A comparative study of stabilizing a wind farm with variable speed wind turbine generator system that use DFIG as the wind generator and FACTS was also carried out in this study. Simulation results in PSCAD/EMTDC also show that the wind farm could be effectively stabilized with both systems, but at a reduced cost with the proposed DFIG system.

Keywords- Crowbar, doubly fed induction generator (DFIG), FACTS, grid codes, grid faults, wind energy.

1. Introduction

The increasing size of wind turbine and wind farms resulted in new interconnection rules called grid codes. Today, there is need to control wind power, both in active and reactive power, and to be able to stay connected with the grid when grid faults happen. The doubly fed induction generator (DFIG) has the largest world market share among the commercial available wind turbine generator systems since the year 2002 [1], because of its ability to provide variable speed operation and independent active and reactive power control in a cost-effective way.

It is increasingly important that electrical power generation using wind energy continue to operate during periods of short circuit fault in the grid as per recent wind farm grid code. The penetration of wind power to the grid has reached levels high enough to affect the quality and stability of the grid [2]. According to grid codes set by utilities, tripping of wind turbine generators systems (WTGSs) following grid fault is not allowed. Besides to provide voltage support to the grid, mandatory reactive current control is necessary. Main ancillary 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.

DFIG has shown better behaviour concerning system stability during short-circuit faults in comparison to induction generator (IG) [3], because of its capability of decoupling the control of output active and reactive powers. The superior dynamic performance of the DFIG results from the frequency converter which typically operates with sampling and switching frequencies of above 2 kHz [4].

Crowbar protection is often adopted to protect the rotor side converter (RSC) which is basically a voltage source converter (VSC) from transient overcurrent during grid fault. The severe problems are not the transient overcurrent, but the DC voltage instability in the back-to-back VSC. In the case of a weak power network and during a grid fault, the grid side converter (GSC) cannot provide sufficient reactive power and voltage support due to its small power capability, and there might be a risk of voltage instability. As a result, utilities, typically, immediately disconnect the wind turbines from the grid to prevent such a contingency and reconnect them when normal operation has been restored. Therefore, voltage instability is a crucial issue in maintaining uninterrupted operation of wind turbines equipped with DFIGs. With the rapid increase in penetration of wind power to the grid, tripping of many wind turbines in a large wind farm during grid fault may influence the overall power system stability.

The problem of voltage instability can be solved by using dynamic reactive power compensation. There are various voltage source or current source inverter based on flexible ac transmission system (FACTS) devices for flexible power control damping of power system and stabilization of wind generators [5, 6]. Shunt connected flexible ac transmission system (FACTS) devices, such as static var compensator (SVC) and the static synchronous compensator (STATCOM), have been widely used to provide high-performance steady-state and transient voltage control at the point of common coupling (PCC). The application of a SVC or a STATCOM to a wind farm equipped with fixed-speed wind turbines (FSWTs) and squirrel-cage induction generators (SCIGs) for steady-state voltage regulation and for short-term transient voltage stability is already reported in [6, 7].

This paper presents the use of a STATCOM to improve the stability of a wind farm composed of DFIG during grid fault. A crowbar protection switch is connected to the DFIG and is triggered if the DC-link voltage, E_{dc}, exceeds its maximum set point value, thus making the DFIG to behave like a conventional IG during the grid fault, hence loosing controllability of both active and reactive power. The STATCOM is used to support the DFIG during the crowbar period and helps to handle the necessary reactive power demand to avoid voltage instability. Simulations are carried on using laboratory standard power system simulation package designed by Manitoba HVDC research laboratory center in Canada, named PSCAD/EMTDC (power system computer aided design and electromagnetic transient including DC) [8].

2. Model of the Considered System

The model system for this study is shown in Figure 1, where the crowbar switch is connected across the rotor of the DFIG. The rating of the DFIG considered is 50MW. The DFIG is assumed to be made up of many smaller ratings of DFIG, but the aggregated model is used for simulation purpose. The parameters of the DFIG used for this study are shown in Table 1[9].

The crowbar switch is triggered if the E_{dc-max} value as shown in the excitation parameters in Table 2 [10] is exceeded. Thus, the comparator shown in Figure 1 sends a signal to switch on the transistors switches during the grid fault, thereby protecting the power converter by disconnecting the rotor side converter of the DFIG system. The FACTS device which is the STATCOM is connected to the PCC to boost the system stability.

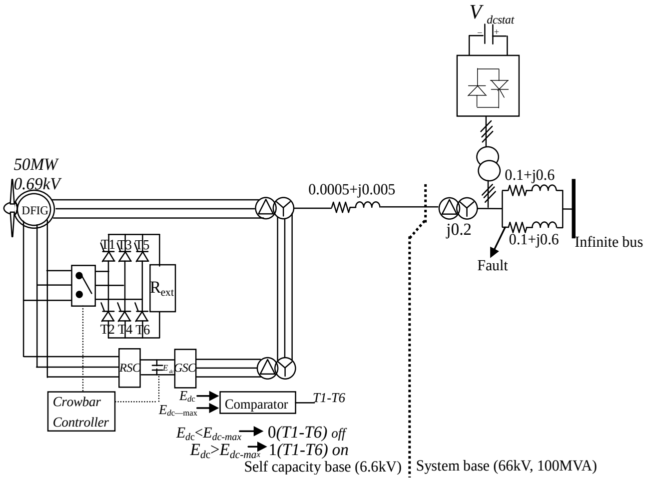

Fig. 1. Model of the considered system

From Figure 1, during grid fault, when the DFIG system is disconnected by the crowbar in order to protect its vulnerable power converters, the STATCOM performs the action of providing more reactive power to the system. Thus, the DFIG voltage instability problem is mitigated with the support of the STATCOM as shown in the simulation results discussed in section 7.

Table 1. DFIG parameters

Generator Type	DFIG
Rated voltage	690V
Stator resistance	0.01pu
Stator leakage reactance	0.15pu
Magnetizing reactance	3.5pu
Rotor resistance	0.01pu
Rotor leakage reactance	0.15pu
Inertia constant	1.5sec

Table 2. Parameters of excitation circuit of DFIG

DC link voltage	1.5kV
DC link capacitor	50,000 μF
Device for power converter	IGBT
PWM carrier frequency	2kHz
Upper limit of DC voltage (E_{dc-max})	1.65kV (110%)
Lower limit of DC voltage (E_{dc-min})	0.75kV (50%)
Short circuit parameter of protective device for over voltage	0.2 ohm

3. Wind Turbine Model

The captured power from the wind can be expressed as eqn. (1). Tip speed ratio λ, and power coefficient, C_p, can be expressed in terms of the eqns. (2) to (4) as shown below [9, 11].

$$P_{wt} = 0.5\rho C_p(\lambda,\beta)\pi R^2 V_w^{\ 3}[W] \tag{1}$$

$$C_p(\lambda,\beta) = 0.5(\Gamma - 0.022\beta^2 - 5.6)e^{-0.17\Gamma} \tag{2}$$

$$\lambda = \frac{\omega_{wt} R}{V_w} \tag{3}$$

$$\Gamma = \frac{R(3600)}{\lambda(1609)} \tag{4}$$

The torque coefficient and the turbine torque are expressed as follows.

$$C_t = \frac{C_p(\lambda)}{\lambda} \tag{5}$$

$$T_M = 0.5\rho C_t(\lambda)\pi R^3 V_w^{\ 2} \ \text{[NM]} \tag{6}$$

Where, P_{wt} is the extracted power from the wind, ρ is the air density kg/m^3, R is the blade radius [m], V_w is wind speed [m/s], blade pitch angle is β deg, ω_{wt} is the rotational speed [rad/s] of wind turbine, and T_M is the wind turbine output torque [Nm]. The wind turbine characteristics [12] for the DFIG is shown in Figure 2. In Figure 2, the wind turbine characteristics in terms of turbine power and the rotor speed are shown. The dotted lines show the locus of the maximum power point trajectory of the turbine which is used to determine the output power reference P_{ref} of the DFIG.

Equations (7) and (8) are used to obtain the regulation of the active power according to P_{ref} as shown in Figure 3. The optimum rotor speed ω_{ropt} is given in equation (9) and the maximum rotor speed chosen is 1.3pu.

$$P_{ref1} = 0.1571V_w - 1.035 \ \text{[pu]} \tag{7}$$

$$P_{ref2} = 0.2147V_w - 1.668 \ \text{[pu]} \tag{8}$$

$$\omega_{wt\_opt} = 0.0775V_w \ \text{[pu]} \tag{9}$$

The power extracted from the wind can be limited by pitching the rotor blades. The PI controller is usually used to achieve the angle control in such a way that the pitch controller shown in Fig. 4 controls the angle when the turbine speed exceeds 1.3pu for the case of DFIG operating in variable speed mode. In order to get a realistic response in the pitch angle control system, the servomechanism is expressed with a delay system with time constant, T_{servo} and limiters for the pitch angle and its rate of change, as shown in Figure 4. The rate of change limitation is very important during a grid fault, because it decides how fast the aerodynamic power can be reduced in order to prevent over-speeding during fault [13]. Therefore, considering the realistic scenario for a heavy mechanical system, the rate limiter must be incorporated to simulate the pitch controller. The pitch rate limiter of ± 10deg./sec. is used for the pitch controller in this study.

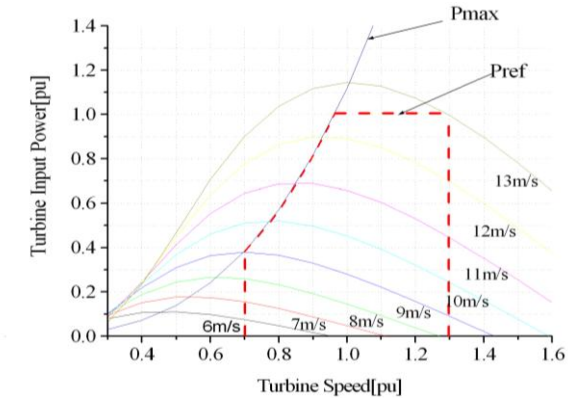

Fig. 2. Turbine characteristic with maximum power point tracking (for DFIG VSWT)

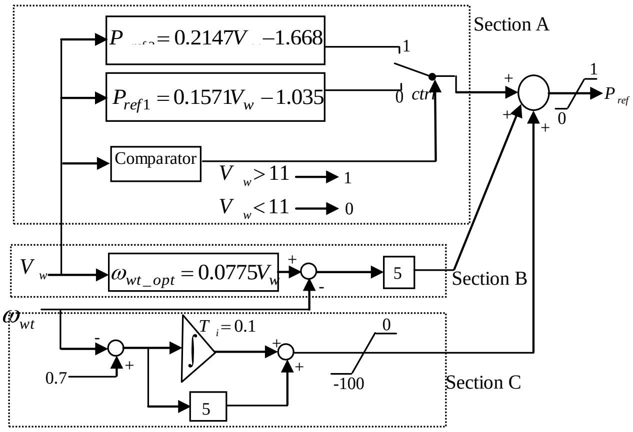

Fig. 3. Control block to determine active power reference for DFIG P_{ref}

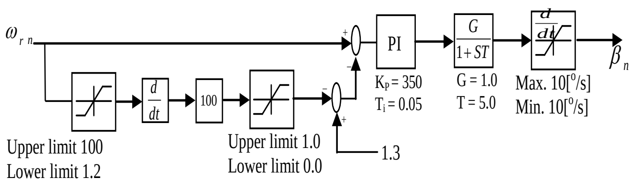

Fig. 4. Pitch controller for DFIG Variable Speed Wind Turbine

4. Grid Codes

The most worrying problem that wind farm must face is a voltage dip in the grid during grid fault. The magnitude of the voltage is controlled by the reactive power exchange, since in most networks the reactive power is proportional to the voltage ($Q\alpha\Delta V$). Figure 5 displays the typical requirement for fault-ride through grid code. The wind farm must remain connected even if the voltage drops suddenly for the short duration, defined by the retained voltage r.m.s value shown by the solid line, and the duration of the fault are also shown in the curve [14]. Figure 6 shows the required reactive current support from the generating plants during voltage dip.

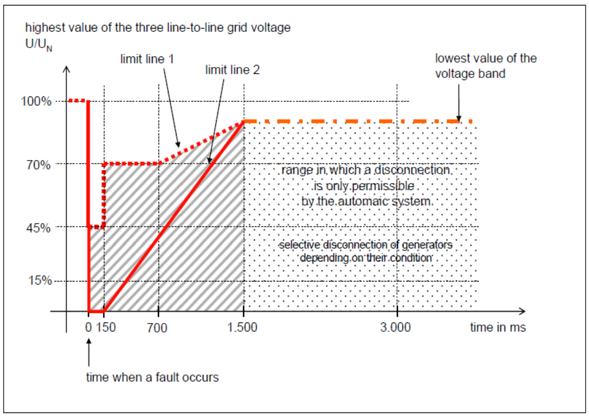

Fig.5. Fault ride through requirement for wind farm

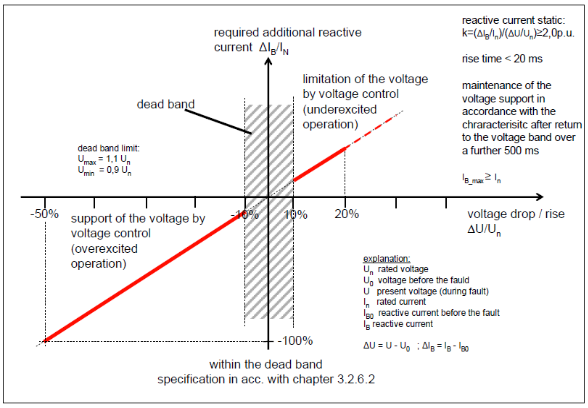

Fig. 6. The Rule of voltage support during grid fault as set by E.ON NETZ

5. DFIG Wind Turbine Control System

The control system and the configuration of the DFIG are shown in Figures 7a-7d. The control system of the DFIG is made up of the rotor side converter (RSC) and the grid side converter (GSC) [15]. The rotor side converter controls the terminal (grid) voltage to 1.0 pu. The d-axis current controls the active power, while the q-axis current controls the reactive power. After dq0-to-abc transformation, V_{dr}^{*} and V_{qr}^{*} are sent to the PWM signal generator and V_{abc}^{*} are the three-phase voltages desired at the rotor side converter output.

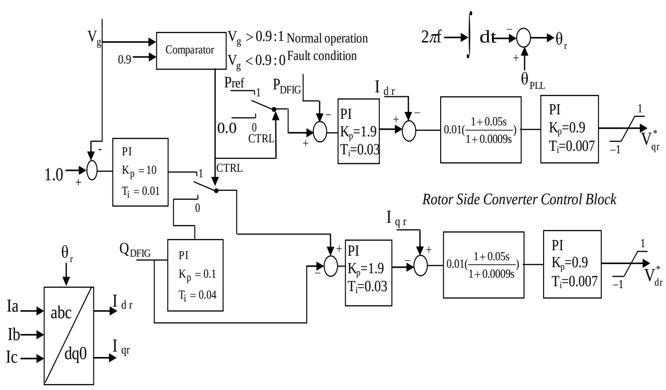

Fig. 7a. Rotor side converter control block for DFIG system

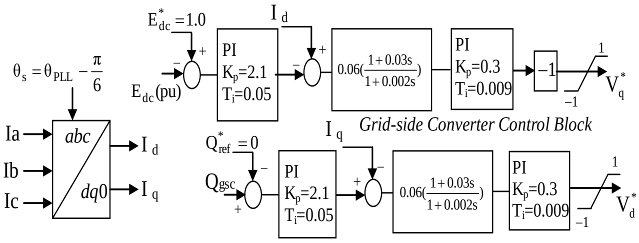

Fig. 7b. Grid side converter control block for DFIG system

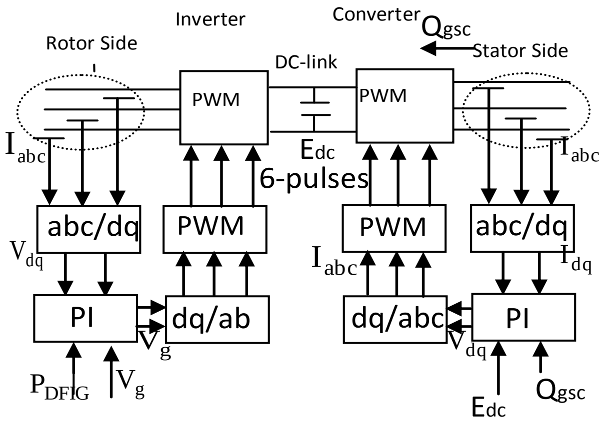

Fig. 7c. DFIG configuration system

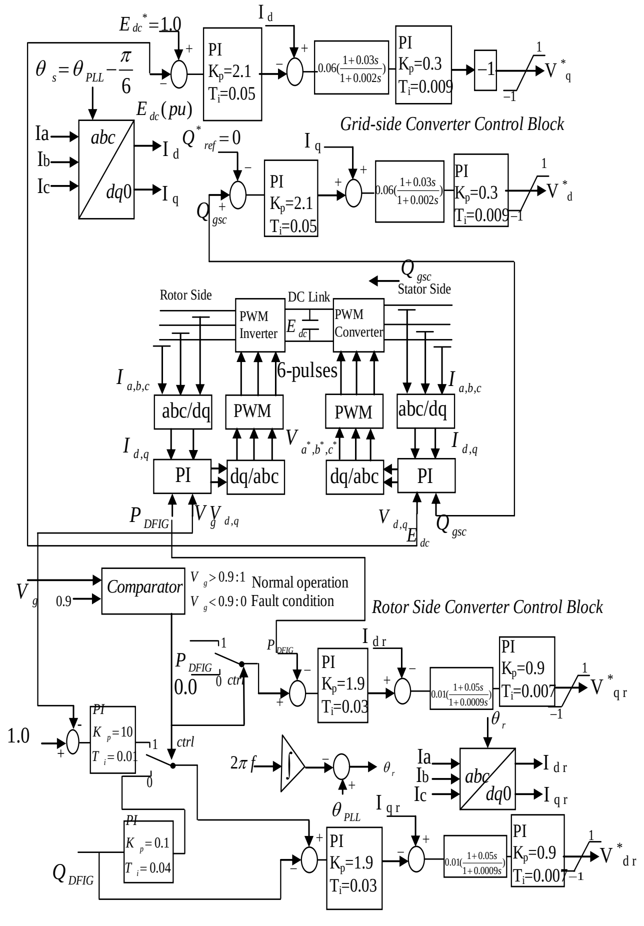

Fig. 7d. Complete DFIG control system

The GSC of the DFIG system is used to regulate the DC-link voltage (E_{dc}) to 1.0pu. The d-axis current controls the DC-link voltage, while the q-axis current controls the reactive power of the grid side converter. After a dq0- to-abc transformation, V_q^* and V_d^* are sent to the PWM signal generator. Finally V_{abc}^* are three voltages at the GSC output for the IGBT's switching.

6. FACTS (STATCOM) Control System

STATCOM can enhance the transient stability and significantly minimize the blade-shaft torsional oscillation of wind turbine generators [16, 17]. The reactive power of a STATCOM is provided by voltage source converter (VSC). The VSC converts the DC voltage into a three-phase output ac voltage with desired amplitude, frequency and phase. The control scheme and switching strategy for the STATCOM is shown in Figure 8, while Table 3 shows the parameters of the STATCOM as given in [6].

Table 3. Parameters of STATCOM

DC link voltage	6.6kV
Dc link capacitor	50,000μF
Device for power converter	IGBT
PWM carrier frequency	1050Hz
Rated Power	20MVA
Rated Voltage	3.50kV

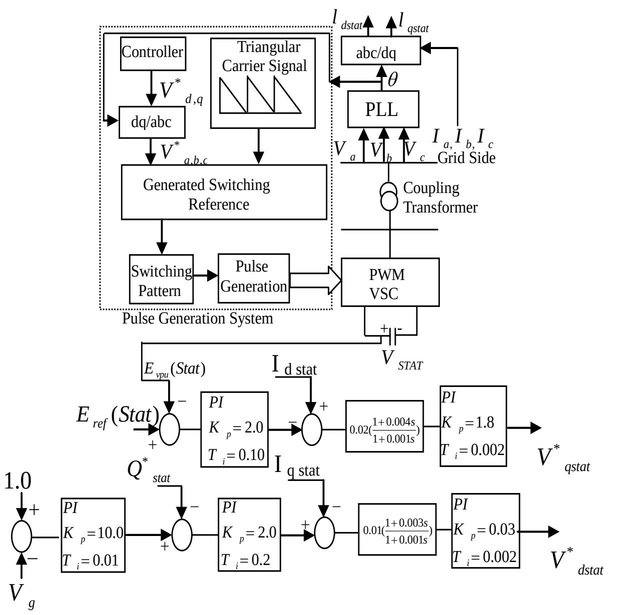

Fig. 8. Control block and switching strategy of STATCOM

From Figure 8, the d-axis current of the STATCOM corresponds to and controls the q-axis reference voltage of the STATCOM, while the q-axis current corresponds to and controls the d-axis reference voltage of the STATCOM. The generated reference voltage are then compared with a triangular carrier signal which is then the effective switching signals for the insulated gate bipolar transistors (IGBTs).

7. Simulation Results and Discussion

7.1. Stability enhancement of DFIG with FACTS device

Simulation analyses for a three-line-to-ground (3LG) fault as shown in Figure 1 were performed to show the effect of the crowbar switch in protecting the DFIG during grid fault, and for cases, where STATCOM is connected to the PCC and with no STATCOM connected. In the fault analysis, it is seen that the DFIG is generating its rated power under a constant wind velocity of 15m/sec. The simulation is carried out using PSCAD/EMTDC, and the fault was considered to occur at 0.1sec. The circuit breakers on the faulted line were opened and reclosed at 0.2 sec and 1.0 sec respectively. The simulation time step for the study is 0.00001 sec and some of the simulation results for 3 sec duration are shown in Figures 9 to 12. The simulation result in Figure 9 shows the effect of the crowbar switch from which it is clear that high DC-link voltage due to high rotor currents experienced during the grid fault can be avoided when crowbar protection is considered.

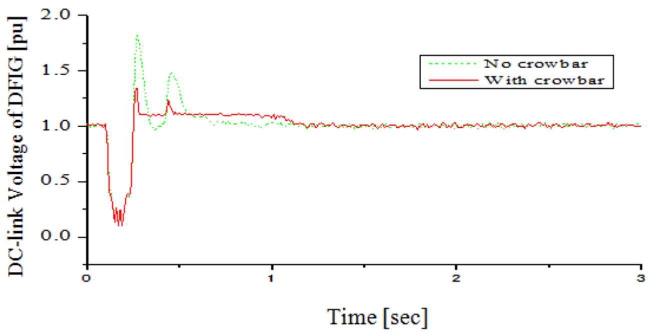

Fig. 9. DC-link voltage of DFIG (3LG)

Also, in Figure 10, the terminal voltage instability of the DFIG caused by the disconnection of the RSC system from the generator rotor by the crowbar switch during grid fault could be improved with STATCOM connected at the PCC. This is because the STATCOM handles the reactive power demand of the system and maintains the voltage at the desired level considering the grid requirement in Figure 5.

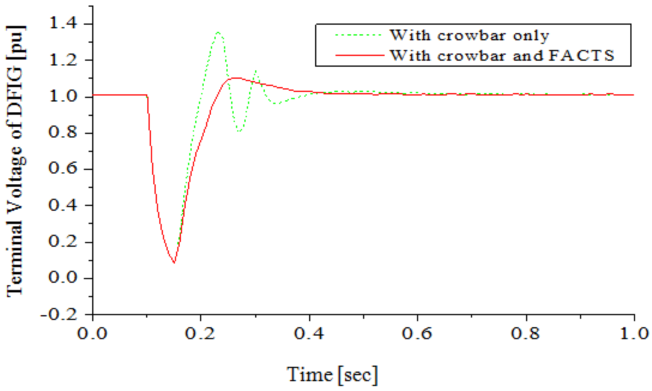

Fig.10. Terminal voltage of DFIG (3LG)

Figures 11 and 12 respectively show the response of the DC-link voltage and the reactive power of the STATCOM during the grid fault. It could be seen from Figure 12 that about 0.25pu of the reactive power from the STATCOM is needed to stabilize the system.

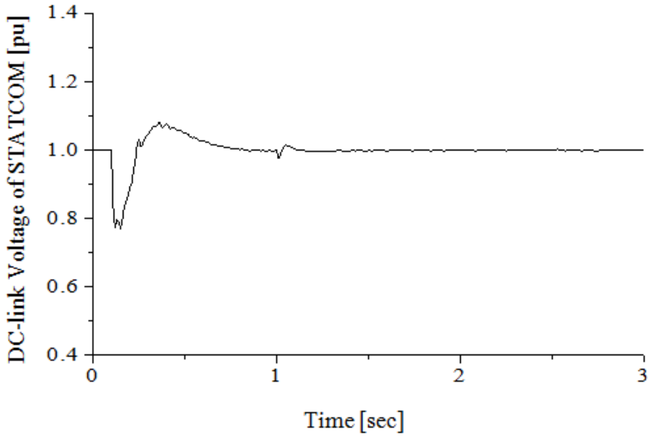

Fig.11. DC-link voltage of STATCOM

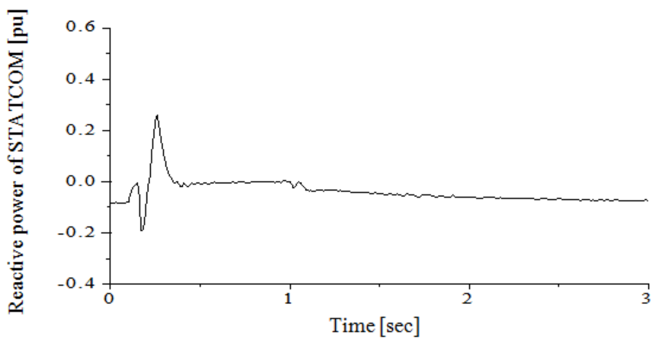

Fig.12. Reactive power of STATCOM (3LG)

7.2. Comparative study of the proposed DFIG system and FACTS device

The model systems considered in this analysis are shown in Figures 13-15. In the first case, the wind farm is composed of 2 aggregated DFIGs and IGs each of capacity 12.5MVA. The wind farm capacity in this case is 50MVA. The two DFIGs (25MVA) are 50% of the wind farm as shown in Figure 13. For the second case, the wind farm is composed of only 2 aggregated IGs each of capacity 12.5MVA, without any reactive compensation device connected at the point of the common coupling (PCC) as shown in Figure 14. The total capacity of the wind farm in this case is 25MVA. The third case (Figure 15) considers a wind farm of two aggregated IGs each of capacity 12.5MVA, with a STATCOM connected at the PCC. The parameters of the DFIGs have already been given in Table 1, while Table 4 shows the parameters of the IGs [11].

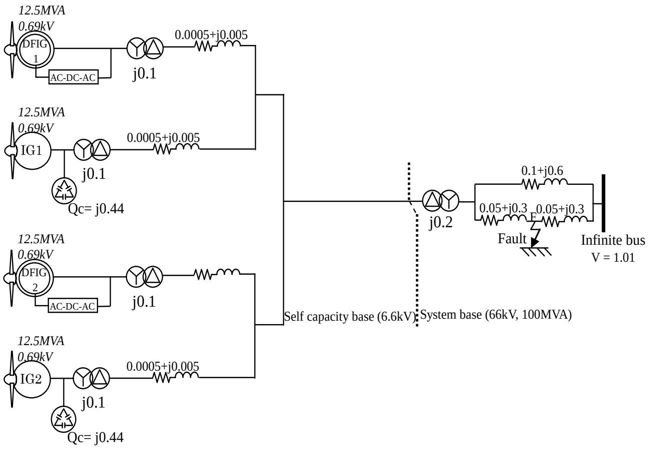

Fig.13. Wind farm model for DFIGs and IGs (Case 1)

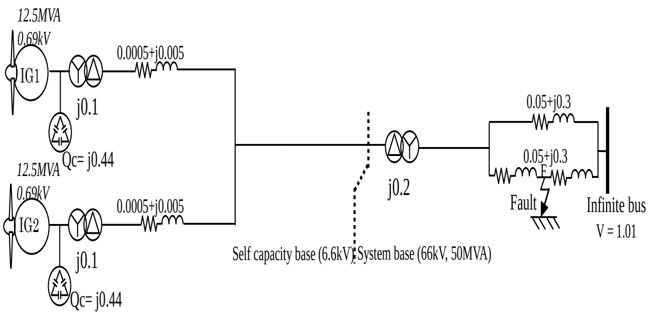

Fig.14. Wind farm model for only IGs (Case 2)

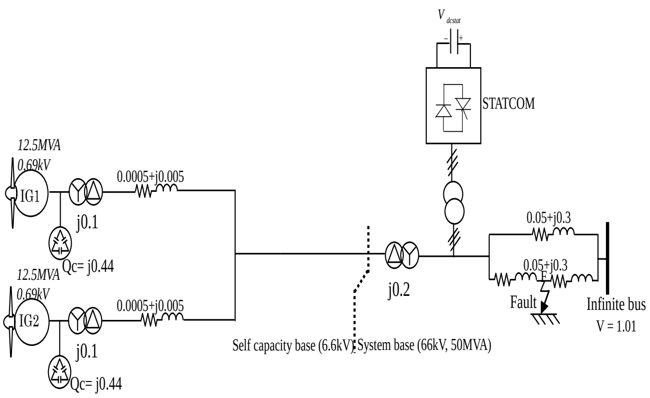

Fig.15. Wind farm model with STATCOM (Case 3)

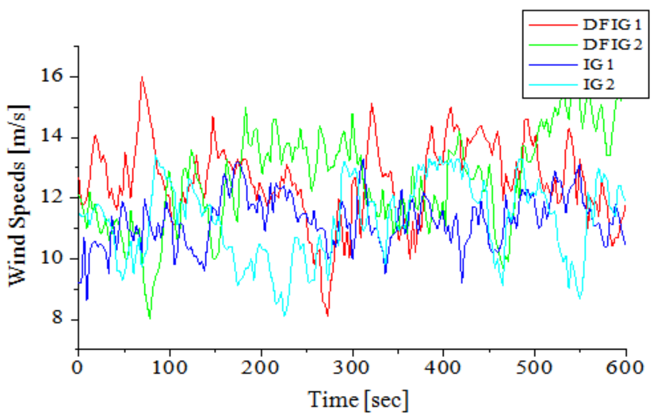

Fig.16. Wind speed data for DFIGs and Igs

Simulations are also carried out for three cases with different real wind speed data obtained from Hokkaido Island, Japan, for each generator (Figure 16) based on the model systems in Figures 13-15. The response of the wind farm terminal voltage to wind speed change for all cases are shown in Figure 17. The wind farm responses during grid fault are given in Figures 18-22, where simulations were run for 10sec., with three-phase, two line to line and a line to ground faults applied at 0.1sec, and the circuit breakers on the faulted line were opened and reclosed at 0.2sec and 1.0sec respectively.

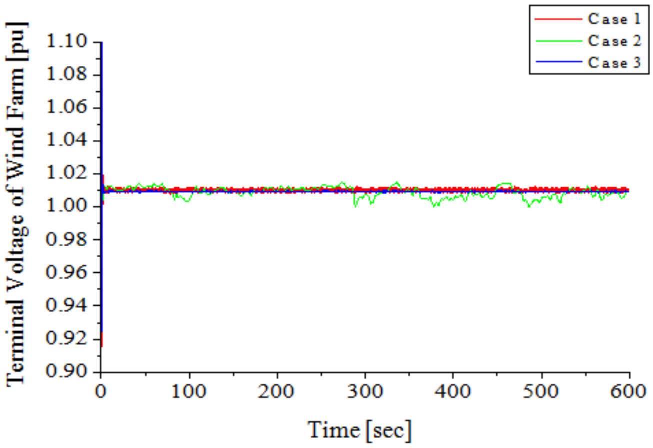

Fig.17. Terminal voltage of wind farm (Dynamic analysis)

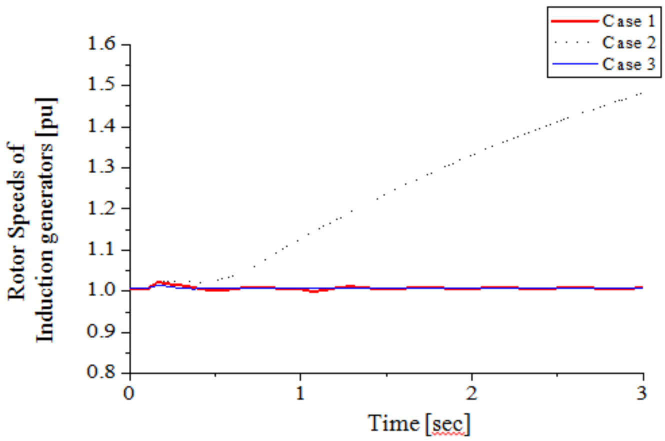

Fig.18. Rotor speed of induction generators (3LG)

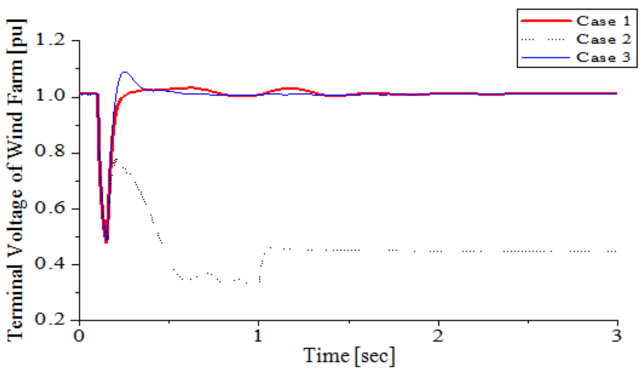

Fig.19. Terminal voltage of wind farm (Transient analysis for 3LG)

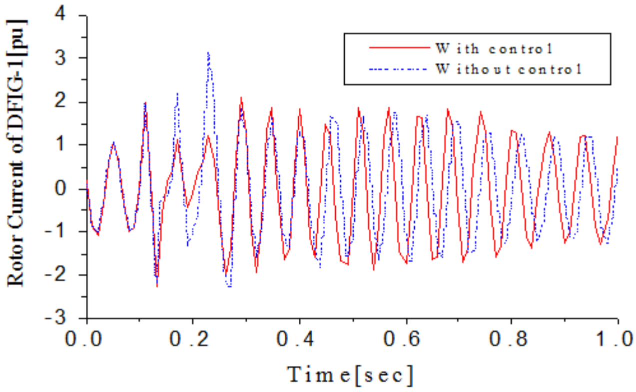

Fig.20. Rotor current of DFIG-1 (3LG)

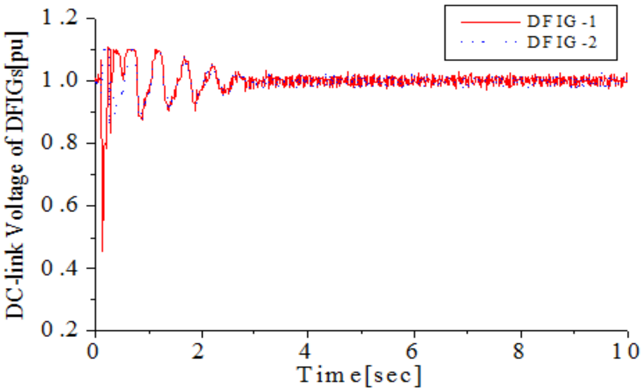

Fig. 21. DC link voltage of DFIG-1 and DFIG-2 (2LS)

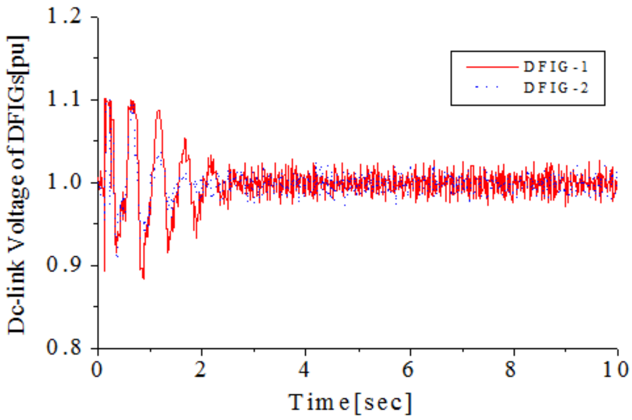

Fig. 22. DC link voltage of DFIG-1 and DFIG-2 (1LG)

From Figure 17, the terminal voltage of the grid connected wind farm remains constant despite the wind change for the dynamic analysis for cases 1 and 3 respectively. This is because reactive power is been supplied to the system by the proposed DFIG control and the FACTS device respectively. However, for case 2, where no reactive compensation is provided, the terminal voltage of the grid connected wind farm is unstable. In Figure 18, it could be seen that the rotor speed of the induction generator become unstable (case 2) during transient because of no reactive power compensation, compared to cases 1 and 3. The response of the terminal voltage of the wind farm during transient condition is shown in Figure 19. Though in cases 1 and 3, the terminal voltage was able to follow the grid requirement stipulated in Figure 5, but better performance of the terminal voltage during transient was achieved in case 1.

However, when no reactive power compensation was considered (case 2), the terminal voltage of the wind farm was not able to follow the grid requirement.

Figure 20 shows the response of rotor current of DFIG-1, from which it can be observed that, when the control strategy of limiting the rotor current of the RSC of the DFIG by the proposed method is employed, the rotor current could be maintained within two times of its nominal value during the grid fault, though it is over three times of that value when no control was implemented.

The responses of the DC-link voltage of the DFIGs for two line-to-line (2LS) and one line to ground faults (1LG) respectively are given in Figures 21 and 22 respectively.

The simulation results show that the DFIGs and the STATCOM (cases 1 and 3) systems can effectively stabilize the wind farm by providing/absorbing necessary reactive power to/from the system. However, the proposed DFIGs system seems to be more advantageous because, apart from generating electric power at steady state, it can also stabilize the wind farm during dynamic and transient conditions

8. Conclusion

The effect of connecting flexible ac transmission system (FACTS) device to the point of common coupling (PCC) of a wind farm composed of doubly fed induction generator (DFIG) has been investigated. The FACTS can greatly enhance the performance of the DFIG, when its power converter is disconnected from the rotor with a crowbar switch during grid fault in order to protect the DC-link voltage from damage. The FACTS device provides additional reactive power to the system, thus improving the performance of the terminal voltage of the DFIG by reducing the voltage instability caused by the grid fault.

A comparative analysis of using the proposed DFIGs method and static synchronous compensator (STATCOM) which is a FACTS device to stabilize a wind farm has also been reported. The proposed DFIGs system offer more advantage than that of the STATCOM system because it generates electric power in steady state and at the same time, stabilizes the wind farm during network disturbance, through provision of reactive power by their power converters at reduced cost, without external reactive power compensation compared to the STATCOM system.

Appendix

T_M	Aerodynamic torque of wind turbine
π	Pie
ω_{wt}	Wind turbine speed
R	Radius of the wind turbine
V_w	Wind speed
C_p	Power coefficient of wind turbine
λ	Lambda (Tip speed ratio of wind turbine)
P_{wt}	Power of the wind turbine
ρ	Air density
Γ	Gamma
PI	Proportionate integral controller
K_p	Gain constant of PI controller
T_i	Time constant of PI controller
IGBT	Insulated gate bipolar transistor
PWM	Pulse width modulation
E_{dc}	DC-link voltage of DFIG
V_{dstat}	DC-link voltage of STATCOM

References

[1] Y. Zhou, P. Bauer, J. A. Ferreira, and J. Pierik, “Operation of grid-connected DFIG under unbalanced grid voltage condition”, IEEE Transaction on Energy Conversion, vol. 24, no. 1. Pp. 240-246, 2009.

[2] S. Heir, Grid Integration of Wind Energy Conversion Systems, ISBN: 0471-97143, 1998.

[3] A. D. Hassan and G. Michalke, “Fault ride-through capacity of DFIG wind turbines”, Renewable Energy, vol. 32, pp. 1594-1610, 2007.

[4] I. Erlich, H. Wrede, and C. Feltes, “Dynamic behavior of DFIG-based wind turbine during grid faults”, IEEJ Trans. Industrial Application, vol. 128, no. 4, pp. 396-401, 2008.

[5] M. R. I. Sheikh, S. M. Muyeen, R. Takahashi, and J. Tamura, “Smoothing control of wind generator output fluctuations by PWM voltage source converter and chopper controlled SMES”, European Transactions on Electrical Power ETEP, vol. 21, no. 1, pp. 680-697, 2011.

[6] S. M. Muyeen, M. A. Mannan, M. H., R. Takahashi, and J. Tamura, “Stabilization of wind turbines generator system by STATCOM”, IEEJ Transaction on Power and Energy, vol. 126-B, no. 10, pp. 1073-1082, 2006.

[7] J. A. Suul, M. Molinas and T. Undeland “STATCOM-based indirect torque control of induction machines during voltage recovery after grid faults”, IEEE Trans. on Power Electronics, vol. 25, no. 5, pp. 1240-1250, 2010.

[8] PSCAD/EMTDC Manual, Manitoba HVDC research center, 1994-2005 editions.

[9] K. E. Okedu, S. M. Muyeen, R. Takahashi, and Junji Tamura, “Stabilization of wind farms by DFIG-based variable speed wind generators”, International Conference of Electrical Machines and Systems (ICEMS), Seoul, South Korea, October, 2010.

[10] K. E. Okedu, S. M. Muyeen, R. Takahashi, and J. Tamura, “Comparative study between two protection schemes for DFIG-based wind generator”, International Conference of Electrical Machines and Systems (ICEMS), Seoul, South Korea, October, 2010.

[11] R. Takahashi, J. Tamura, M. Futami, M. Kimura and K. Idle, “A new control method for wind energy conversion system using double fed synchronous

generators", IEEJ Trans. Power and Energy, vol. 126, no. 2, pp. 225-235, 2006.

[12] O. Wasynczuk, D. T. Man, and J. P. Sullivan, "Dynamic behavior of a class of wind turbine generator during random wind fluctuations", IEEE Trans. on Power Apparatus and Systems, vol. PAS-100, no. 6, pp. 2837-2845, 1981.

[13] M. Garcia-Garcia, M. P. Comech, J. Sallan, and A. Liombart, "Modeling wind farms for grid disturbance studies", Renewable Energy, vol. 33, pp. 2109-2121, 2008.

[14] E.ON NETZ GmbH, Grid connection regulation for high and extra high voltage, 2006.

[15] K. E. Okedu, S. M. Muyeen, R. Takahashi, and J. Tamura, "Participation of FACTS in stabilizing DFIG with crowbar during grid fault based on grid codes", IEEE-GCC conference and exhibition, pp. 365-368, February, 2011, Dubai.

[16] L. Zhang, C. Shen, M. L. Crow, L. Dong, S. Pekarek, and S. Atcitty, "Performance indices for the dynamic performance of FACTS and FACTS with energy storage", Elect. Power Component and System, vol. 33, no. 3, pp. 299-314, 2005.

[17] K. E. Okedu, S. M. Muyeen, R. Takahashi, and J. Tamura, "Comparative study of wind farm stabilization using variable speed generator and FACTS device", IEEE-GCC conference and exhibition, pp. 569-572, February, 2011, Dubai.