Comparative Study between Two Protection Schemes for DFIG-based Wind Generator Fault Ride Through

K. E. Okedu*, S. M. Muyeen, R. Takahashi* and J. Tamura***

Abstract – Fixed speed wind turbine generators system that uses induction generator as a wind generator has the stability problem similar to a synchronous generator. On the other hand, doubly fed induction generator (DFIG) has the flexibility to control its real and reactive powers independently while being operated in variable speed mode. This paper focuses on a scheme where IG is stabilized by using DFIG during grid fault. In that case, DFIG will be heavily stressed and a remedy should be found out to protect the frequency converter as well as to allow the independent control of real and reactive powers without loosing the synchronism. For that purpose, a crowbar protection switch or DC-link protecting device can be considered. This paper presents a comparative study between two protective schemes, a crowbar circuit connected across the rotor of the DFIG and a protective device connected in the DC-link circuit of the frequency converter. Simulation analysis by using PSCAD/EMTDC shows that both schemes could effectively protect the DFIG, but the latter scheme is superior to the former, because of less circuitry involved.

Keywords: DFIG, Grid fault, IG, Protection schemes, Stability, Wind energy

1. Introduction

Low voltage ride through is an important feature for wind turbine systems to fulfill grid code requirements, hence, the increased amount of power from decentralized, renewable energy systems, especially wind energy systems, require strong grid codes to maintain a stable and safe operation of the energy network [1], [2]. According to recent wind farm grid code, wind generators need to continue their operation during a short circuit fault in the grid under some specified conditions. The grid codes cover rules considering the fault ride though behavior as well as the steady state active power and reactive power production. A detailed review of grid code technical requirements regarding the connection of the wind farms to the electrical power system is given in [1], [3]. Voltage instability problems occur in a power system that cannot supply the reactive power demand during disturbances like faults [4], [5].

The doubly fed induction generator (DFIG) has very attractive characteristic as a wind generator because the power processed by the power converter is only a fraction of the total power rating of the DFIG, that is typically 20-30%, and therefore its size, cost and losses are much smaller compared to a full size power converter [6] used in other variable speed wind generators. DFIG can operate at a wider range of speed depending on the wind speed or other specific operation requirements. Thus, it allows a better capture of wind energy [7]-[9]. The dynamic slip control and pitch control are the other salient features which help to augment the system stability [10]. In addition, DFIG have shown better behavior concerning system stability during short-circuit faults in comparison with IG (Induction Generator), because of its capability of decoupling the control of active and reactive power output. The superior dynamic performance of the DFIG results from the frequency converter which typically operates with sampling and switching frequencies of above 2 kHz [11]. At lower voltages down to 0% the IGBTs (Insulated Gate Bipolar Transistors) of the DFIG are switched off and the system remains in standby mode [12]-[15]. If the voltages are above a certain threshold value during fault, the DFIG system can be synchronized very quickly and back in operation again. But, the reaction of DFIGs to grid voltage disturbances is sensitive, as described in [16] and [17] for symmetrical and unsymmetrical voltage dips, and requires additional protection for the rotor side power electronic converter.

On the other hand, IG is used in general as fixed speed wind turbine (FSWT) generator due to their superior

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characteristics such as brushless and rugged construction, low cost, maintenance free and operational simplicity, but requires large reactive power to recover the air gap flux when a short circuit fault occurs in the power system. IG technology has limited ability to provide voltage control, thus require reactive power compensation.

The DFIG might be a good solution to stabilize the IG during grid fault, as this has not been widely reported till date. This study attempts to resolve problems carried out by other researchers in stabilizing the IG using DFIG instead of using external reactive compensation devices like the FACTS (flexible ac transmission systems) which is a more expensive method.

During a grid fault, however, the frequency converter can be damaged due to large rotor currents generated, which causes to rise the DC-link voltage above nominal value. Two types of circuits have been considered for protecting DFIG, that is, a crowbar switch and a protective device [18]. This paper presents a comparative study between these two protection schemes.

2. Wind Turbine Modeling

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 [18]-[20].

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

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

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

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

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_{wtb} 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_{wtb} is the rotational speed [rad/s], and T_M is the wind turbine output torque [Nm]. Figures 1 and 2 show the wind turbine characteristics [21] used in this study for both IG (FSWT) and DFIG (VSWT) respectively.

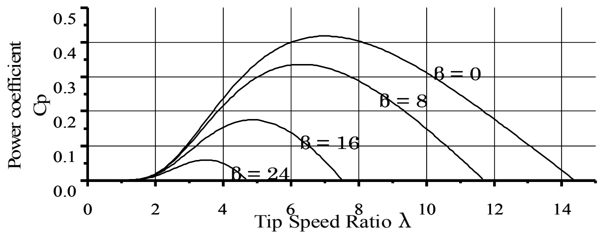

Fig. 1. C_P- λ curves for different pitch angles (for FSWT)

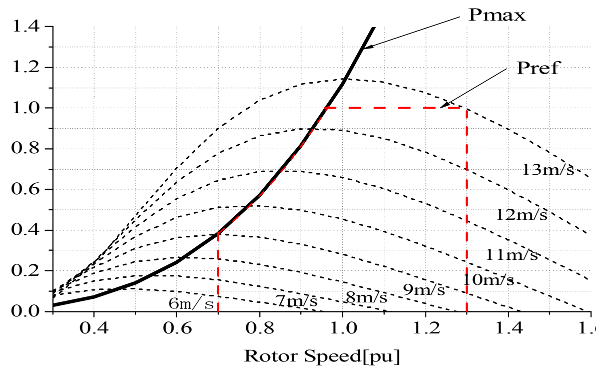

Fig. 2. Turbine characteristic with maximum power point tracking (for VSWT)

Equations (7) to (9) are used to determine the active power output reference P_{ref} and the optimal rotor speed ω_{ropt} as a function of wind speed for maximum power point tracking (MPPT) control. The operating range for rotor of DFIG is chosen between 0.7pu (minimum) to 1.3pu (maximum). Figure 3 shows the control block for generating P_{ref} signal.

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

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

$$\omega_{ropt} = 0.0775V_w \quad \text{[pu]} \tag{9}$$

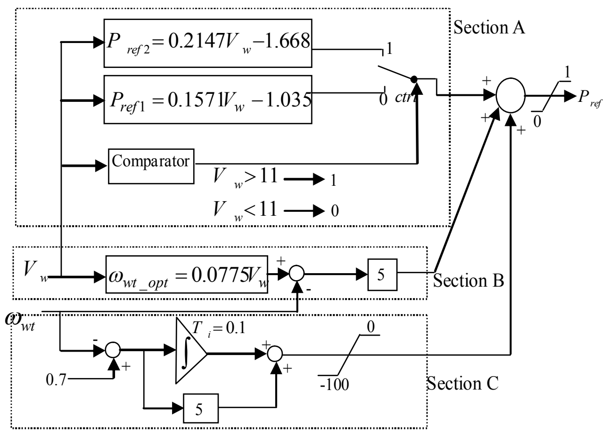

Fig. 3. MPPT Control block

Figures 4 and 5 respectively show the pitch angle controller for the FSWT and the VSWT used in this work.

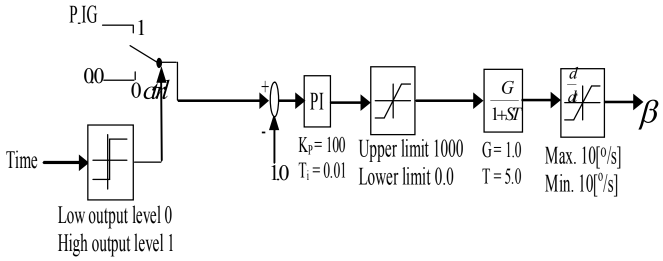

Fig. 4. Pitch controller for FSWT

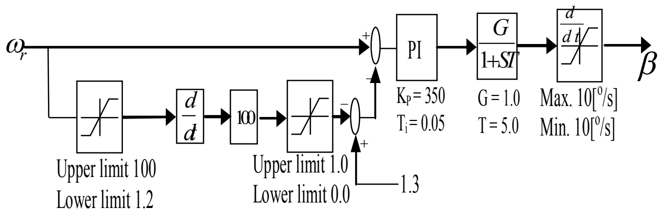

Fig. 5. Pitch controller for VSWT

3. Model System and DFIG Control

The schematic diagram of a DFIG with both protection schemes considered in this study is shown in Fig. 6. The model system with the crowbar switch (scheme 1) is shown in Fig. 7. In scheme 2, the crowbar is not connected, but a protective device is connected between the converter and inverter as shown in Fig. 8. Both schemes are analyzed under same operating conditions based on the parameters given in [18], which are shown in Tables 1 and 2 respectively.

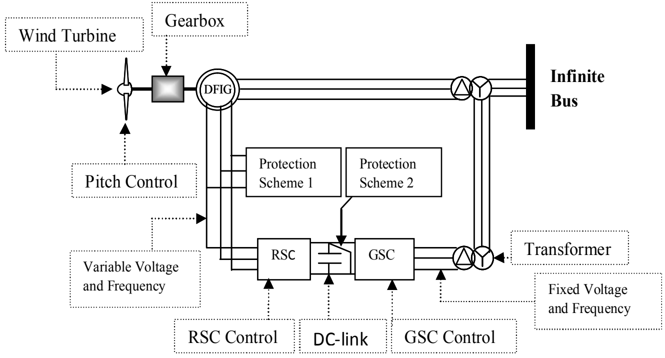

Fig. 6. DFIG System with both schemes

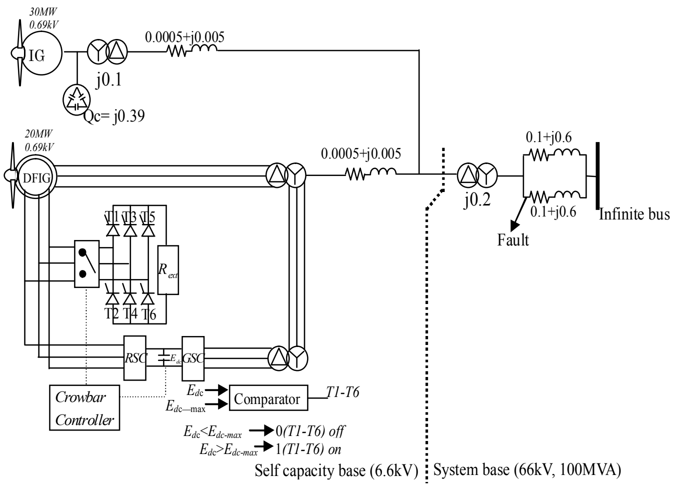

Fig. 7. Model system in protection scheme 1

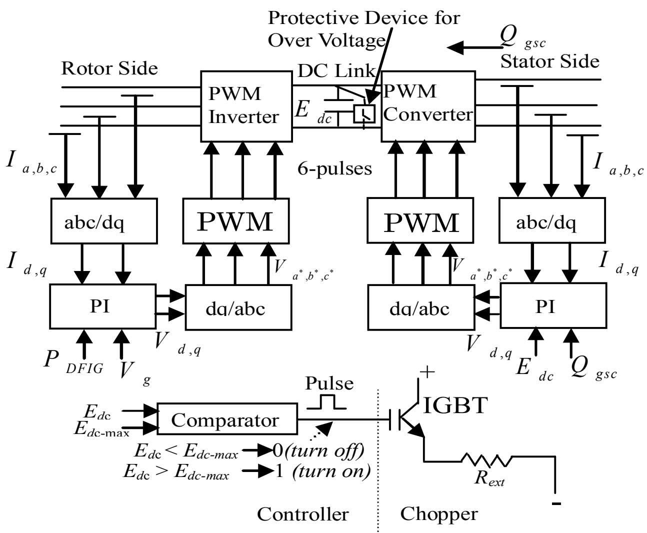

Fig. 8. Frequency converter configuration in protection scheme 2

Table 1. Generator Parameters

Generator Type	IG	DFIG
Rated voltage	690V	690V
Stator resistance	0.01pu	0.01pu
Stator leakage reactance	0.07pu	0.15pu
Magnetizing reactance	4.1pu	3.5pu
Rotor resistance	0.007pu	0.01pu
Rotor leakage reactance	0.07pu	0.15pu
Inertia constant	1.5sec	1.5sec

Table 2. Rating and Parameters of Excitation Circuit

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

3.1 Overview of the Effect of Grid Fault on DFIG System

The use of the partial-scale frequency converter in the generator's rotor makes DFIG attractive as a wind generator from an economical point of view. However, on the other hand, this converter arrangement requires advanced protection system, as it is very sensitive to disturbances on the grid [22], [23]. If there is no protection system, the DFIG can suffer from large transient currents in the stator during a grid fault since its stator circuit is directly connected to the grid. Because of the magnetic coupling between the stator and the rotor, the stator transient is transmitted to the rotor, resulting in both large rotor currents and voltages during the grid faults. Furthermore, the surge following the fault includes a rush of power from the rotor terminals towards the converter. Since the stator-to-rotor voltage ratio of the DFIG is designed according to the desired variable speed range, in case of grid faults it might not be possible to achieve the desired rotor voltage in order to control the large rotor currents. This means that the frequency converter reaches fast its limits and as a consequence it looses the independent control during the grid fault. As the grid voltage drops in the fault moment, the grid side inverter is not able to transfer the power to the grid that obtains from the rotor side converter and therefore, the excess energy in the DC-link capacitor rises the DC-bus voltage rapidly.

It is therefore necessary to protect the frequency converter against overcurrents, the rotor of the generator against overvoltages and the DC-link against overvoltages. The protection system monitors usually several signals such as rotor current and the DC-link voltage. When at least one of the control input signals exceeds its respective relay setting, the protection is activated.

3.2 Protection Scheme 1

A simple protection approach to the problem of voltage dips of the DFIG under grid fault is to place a crowbar circuit connected to the rotor as shown in Fig. 7. The crowbar short-circuits the rotor when E_{dc} exceeds $E_{dc\text{-}max}$ and the frequency converter connected to the rotor is protected. The crowbar protection is an insertion of external resistance to the rotor via the slip rings. The value of the crowbar resistance is dependent on the generator condition [24].

Crowbar circuits can be antiparallel thyristor crowbar, diode bridge crowbar or other unusual configurations. The thyristor bridge crowbar used in scheme 1 of this study, is usually preferred to the antiparellel thyristor and the rest of other configurations because it uses less thyrsitors and it is controlled more easily [25], [26]. Either when the voltage at the DC bus reaches its maximum value or when the rotor current exceeds its limit, the crowbar is activated, the rotor side converter is disconnected from the rotor, and the rotor windings are short-circuited by the crowbar. In this study, the control of the switching of the crowbar is activated when the DC voltage E_{dc} exceeds $E_{dc\text{-}max}$ shown in Table 2. When the crowbar is triggered, the rotor side converter is disabled and bypassed, and therefore, the independent controllability of active and reactive power is lost. Generator magnetization in this case is supplied from the stator instead of being supplied from the rotor circuit. Since the grid side converter is not directly connected to the rotor windings, when large transient currents appear, this converter is not blocked for protection. Therefore, the DFIG behaves as a conventional squirrel cage induction generator (SCIG) with an increased rotor resistance. By inserting the external resistance, i.e., crowbar resistance into the rotor circuit during grid faults, the pull-out torque of the SCIG is moved into the range of higher speeds [22]. The dynamic stability of the SCIG is thus dramatically improved by increasing the external resistance [24]. When the crowbar is removed, the rotor side converter is enabled again to control independently the active and reactive power.

3.3 Protection Scheme 2

A chopper or braking resistor (dumped load) could be added on the DC-link (Fig. 8) with a similar function to that of the rotor side crowbar, reducing the DC-link voltage. The chopper facilitates a voltage-raising action from the converter terminals during the fault ride through (FRT), and thereby enabling a faster regain of the control of the DC-link voltage [27].

The control in protection scheme 2 is based on that used in [18], where a protective device is connected between the converters as shown in Fig. 8. A 2-level, 6-pulse full-bridge power converter based on IGBT is used, in this study. A power converter which is operated by pulse width modulation (PWM) technique is almost a standard to drive an electric machine. When a disturbance occurs in the grid, the DC voltage becomes very high that goes beyond the rated value which may cause damage to the semiconductor devices. The protective device in this scheme is a simple chopper circuit. The pulse signal to trigger the IGBT is activated when E_{dc} exceeds $E_{dc\text{-}max}$, and thus, the chopper is turned on and the energy is dissipated by the internal resistance. The value of $E_{dc\text{-}max}$ and the short circuit parameter of protective device for overvoltages are same as that used in protection scheme 1, as shown in Table 2.

3.4 DFIG Control

The rotor of the DFIG is equipped with three phase windings, which are supplied via the rotor side slip rings by a voltage source converter (VSC) of variable frequency and magnitude. The converter enables decoupled active and reactive power control of the generator [28]-[32]. The control of the DFIG wind turbine consists of three parts:

- Speed control by controlling the electrical power provided to the converter as well as by the pitch angle.
- Rotor side converter (RSC) control directed at the control of active and reactive power on the stator side.
- Grid side converter (GSC) control that keeps the DC-link voltage constant and provides the additional opportunity to supply reactive power into the grid.

The RSC and GSC controls are usually implemented together in the same converter control software, whereas the speed control is realized as a separate unit (Fig. 5). The power converters are usually controlled utilizing vector control techniques [18], [33], and [34]. The DFIG control described below contains the electrical control of the power converters, which is essential for the DFIG behavior both in normal operation and during fault conditions.

The Rotor side converter and the Grid side converter control blocks for the DFIG are shown in Figs. 9 and 10 respectively. In Fig. 9, the rotor side converter controls the terminal (grid) voltage to 1.0pu. 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 as shown in the converter configuration circuit (scheme 2).

The circuit configuration of the rotor side, DC-link, and the grid side converter is given in Fig. 8. Fig. 10 shows the control block for the GSC control, where PLL provides the angle θ_{PLL} and θ_s is the effective angle for the abc-to-dq0 (and dq0-to-abc) transformation. 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.

As shown in Figs. 9 and 10 respectively, both the RSC and GSC are controlled by a two-stage controller. The first stage consists of very fast current controllers regulating the rotor currents to their reference values which are specified by a slower power controller in the second stage.

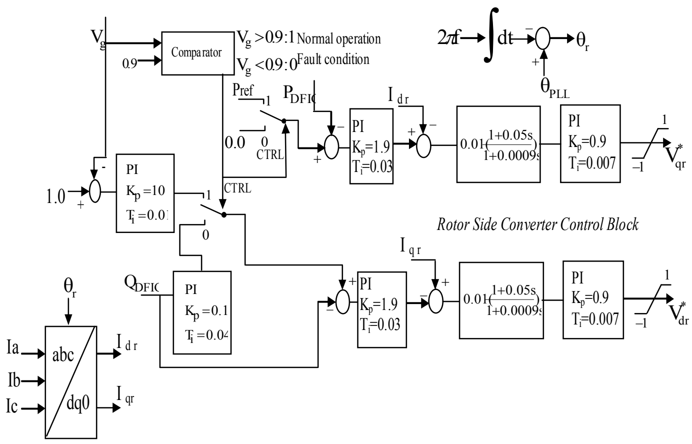

Fig. 9. Control block for rotor side converter of DFIG

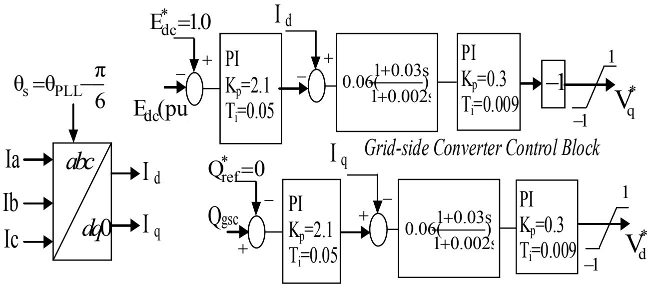

Fig. 10. Control block for grid side converter of DFIG

4. Simulation Results

Simulation analyses for a short circuit (three-line-to-ground, 3LG) fault shown in Fig. 7 are performed for three cases, that is, no protection, scheme 1, and scheme 2. In the fault analyses, the DFIG and the IG are generating their rated power under a constant wind velocity of 15m/sec. The simulation was run for 3sec in PSCAD/EMTDC [35], and the fault is considered to occur at 0.1sec. The circuit breakers on the faulted line are opened and reclosed at 0.2 sec and 1.0 sec, respectively. The simulation time step used for the study is 0.00001sec.

The simulation results with no protection scheme considered are also presented for showing the effects of a short-circuit fault on the converter circuit when no counter measures are adopted. As can be seen from Fig. 11 and Fig. 12, the grid fault can lead to considerable DC-link over-voltages and rotor circuit over-currents putting the entire system under stress. It can be concluded from the simulation results for the case without protection: Very high DC-link voltage appears as shown in Fig. 11, which would reach almost 2 times of the nominal value, and is far away from the normal capacitor specification.

Based on the above conclusion for the case with no protection, it can be realized that the use of protection scheme cannot be disregarded for the DFIG-based wind generator, because if there is no protection circuit, grid short circuit fault can result in deterioration of the frequency converter. On the other hand, fast separation of the generator system from the grid is not a favorable option since utilities expect its voltage support during and after the fault as per recent wind farm grid codes. Besides, the active power in-feed should not be interrupted for a longer period of time.

As can be seen from Fig. 11, though the very large voltage appears in the DC-link circuit in the case with no protection, the voltage can be maintained within the acceptable level in schemes 1 and 2. However, scheme 2 is superior to scheme 1 as shown in the same figure. The reactive power consumption in the GSC of the DFIG (Fig. 14) in both schemes is almost same. As can be seen from Fig. 12, rotor currents become very high in both schemes 1 and 2, and the transient peak of the current is higher in scheme 1. However, the switching strategy in scheme 2 is simpler than that of scheme 1 because of less number of switches are involved in the circuit. Fig. 13 shows the current in the protective circuit for both schemes. It can be observed that the peaks of the current are higher in scheme 1 than in scheme 2. Figs. 15 and 16 show the apparent power of the grid side converter and the rotor speed of the DFIG respectively for both schemes. It should be noted that IG is found to be stable for both schemes 1 and 2, when the DFIG is connected to the IG, as shown in Figs. 17 and 18 respectively, for the IG rotor speed and terminal voltage.

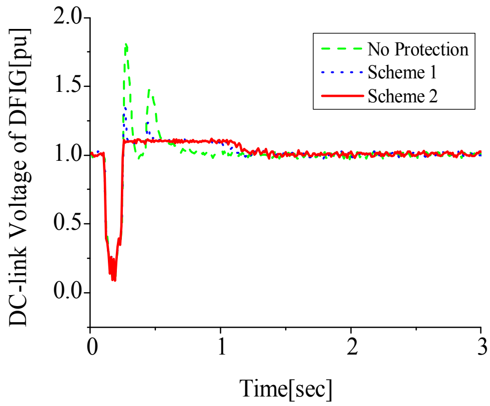

Fig. 11. DC-link voltage of DFIG

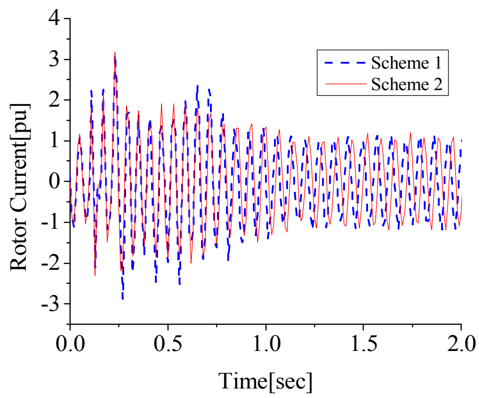

Fig. 12. Rotor current of DFIG

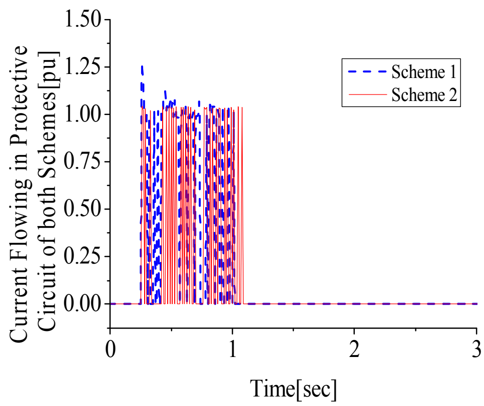

Fig. 13. Current of protective circuit in both schemes

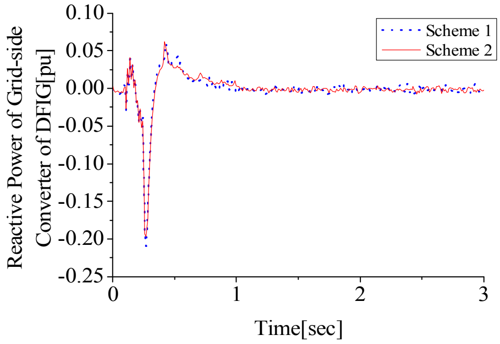

Fig. 14. Reactive power of GSC of DFIG

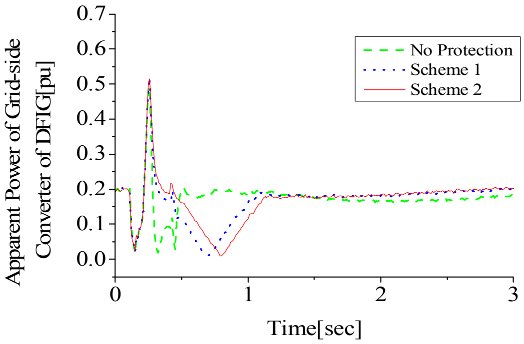

Fig. 15. Apparent power of GSC of DFIG

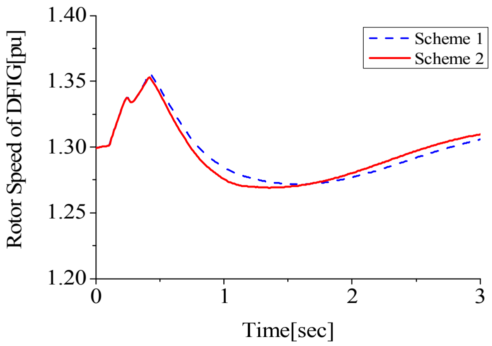

Fig. 16. Rotor speed of DFIG

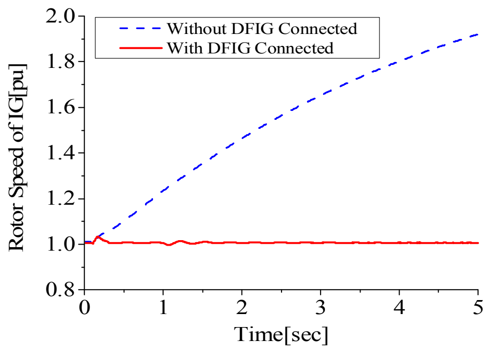

Fig. 17. Rotor speed of IG

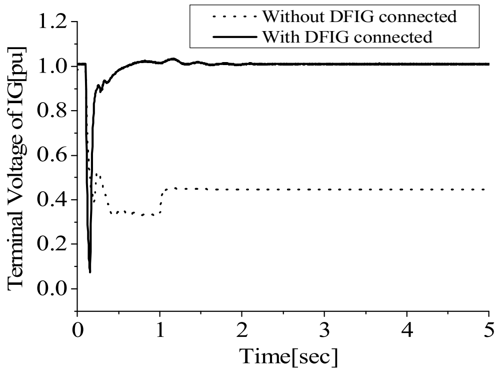

Fig. 18. Terminal voltage of IG

5. Conclusion

The protection of DFIG-based wind generator during grid fault has been investigated considering two protection schemes by using the DFIG to stabilize induction generator (IG). A grid fault affects both the mechanical and electrical components of the wind turbine. Therefore, it is imperative to protect the generator to avoid damage of its power converters during a grid fault. Though the two protection schemes investigated in this study are both effective in protecting the DFIG, it can be concluded that the scheme 2 is superior a little than scheme 1 considering the issues of low component cost and better performance.

In order to validate the schemes experimentally, a real time test bench composed of dSPACE/AD5435 based control scheme using MATLAB/Simulink and real time workshop is preferred. Gate signals will be supplied to the frequency converter from DSP system. It is investigated that Danfoss inverter is suitable for this work as the interfacing card. The results of the experimental validation of both schemes would be reported in the near future.

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References

[1] M. Tsili and S. Papathanassiou, "A Review of Grid Code Technical Requirements for Wind Farms," *Renewable Power Generation, IET*, vol. 3, no. 3, pp. 308-332, Sept. 2009.
[2] C. Wessels, and F. W. Fuchs, "Fault Ride Through of DFIG Wind Turbines During Symmetrical Voltage Dip with

Crowbar or Stator Current Feedback Solution," *Energy Conversion Congress and Exposition (ECCE)*, pp. 2771-2777, 2010.

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

[4] Tim Poor, American Superconductor, "Using FACTS Technology to Address Grid Interconnection Issues for Wind Farms," *Electric Energy Publications Inc*., 2010.

[5] B. Pokharel, and W. Gao, "Mitigation of Disturbances in DFIG-based Wind Farm Connected to Weak Distribution System Using STATCOM," *North American Power Symposium (NAPS)*, pp. 1-7, 2010.

[6] A. A El-Sattar, *et-al*, "Dynamic Response of Doubly Fed Induction Generator Variable Speed Wind Turbine Under Fault," *Electric Power System Research*, vol. 78, pp. 1240-1246, 2008.

[7] S. Santos, and H. T. Le, "Fundamental Time-Domain Wind Turbine Models for Wind Power Studies," *Renewable Energy*, vol. 32, pp. 2436-2452, 2007.

[8] B. H. Chowdhury, and S. Chellapilia, "Doubly-Fed Induction Generator Control for Variable Speed Wind Power Generation," *Electric Power System Research*, vol. 76, pp.786-800, 2006.

[9] 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.

[10] T. 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.

[11] 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, 2008.

[12] F. Blaabjerg, F. Iov, and K. Ries, "Fuse Protection of IGBT Modules against Explosions," *PCIM Conference*, China, 2002.

[13] T. Takahashi, "IGBT Protection in AC or BLDC Motor Drives," *Technical Paper, International Rectifier*, 90245, CA, USA, Feb. 28, 2000.

[14] H. Xie, "Voltage Source Converters with Energy Storage Capability," PhD Thesis, *Royal Institute of Technology, School of Electrical Engineering, Division of Electrical Machines and Power Electronic*, Stockholm, 2006.

[15] M. Haberberger, and F. W. Fuchs, "Novel Protection Strategy for Current Interruptions in IGBT Current Source Inverters," *Proceedings EPE-PEMC*, Norway, 2004.

[16] J. Lopez, P. Sanchis, X. Roboam, and L. Marroyo, "Dynamic Behavior of the Doubly Fed Induction Generator During Three-phase Voltage Dips," *IEEE Transaction on Energy Conversion*, vol. 22, no. 3, pp. 709-717, Sept. 2007.

[17] J. Lopez, E. Gubia, P. Sanchis, X. Roboam, and L. Marroyo, "Wind Turbines Based on Doubly Fed Induction Generator Under Asymmetrical Voltage Dips," *IEEE Transaction on Power Systems*, vol. 21., no. 4, pp. 1782-1789, Nov. 2006.

[18] 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.

[19] Tomoki Asao, Rion Takahashi, Toshiaki Murata, Junji Tamura, et al, "Smoothing Control of Wind Power Generator Output by Superconducting Magnetic Energy Storage System," *Proceeding of International Conference on Electrical Machines and Systems* 2007, Oct. 8-11, Seoul, Korea.

[20] W. Qiao, G. K. Venayagamoorthy, and R. G. Harley, "Real-Time Implementation of a STATCOM on a Wind Farm Equipped with Doubly Fed Induction Generators," *IEEE Trans. On Industrial Application*, Vol. 45, no. 1, 2009.

[21] 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.

[22] A. D. Hasan, and G. Michalke, "Fault Ride-Through Capability of DFIG Wind Turbines," *Renewable Energy*, vol. 32, pp.1594-1610, 2007.

[23] A. Petersson, "Analysis, Modeling and Control of Doubly-Fed Induction Generators for Wind Turbines," PhD Thesis, *Division of Electric Power Engineering, Department of Energy and Environment, Chalmers University of Technology*, Sweden, 2005.

[24] V. Akhmatov, "Analysis of Dynamic Behavior of Electric Power Systems with Large Amount of Wind Power," *PhD Thesis*, 2003, Orsted DTU.

[25] J. Niiranen, "Voltage Ride Through of a Doubly-Fed Generator Equipped with an Active Crowbar," *Nordic Wind Power Conference*, March 1-2, 2004.

[26] J. Niiranen, "Simulation of Doubly Fed Induction Generator Wind Turbine with an Active Crowbar," *EPE-PEMC,* Riga, Latvia, 2004.

[27] M. B. C. Salles, K. Hameyer, J. R. Cardoso, A. P. Grilo, and C. Rahmann, "Crowbar system in doubly fed induction wind generators," *Energies Article Journal*, ISSN 1996-1073, vol. 3, pp. 738-753, 2010.

[28] S. Peresada, A. Tilli, and A. Tonielli, "Power Control of a Doubly Fed Induction Machine via Output Feedback," *Control Engineering Practice*, vol. 12, pp. 41-57, 2004.

[29] S. Mler, M. Deieke, and R. De Doneker, "Adjustable Speed Generators for Wind Turbines Based on Doubly Fed Induction Machines and 4-Quadrant IGBT Converters Linked to the Rotor," *Records of the IEEE IAS Conference*, Rome, CD, 2000. R. Datta, and V. T. Ranganathan, "Decoupled Control of Active and Reactive Power for a Grid-Connected Doubly Fed Wound Rotor Induction Machine Without

[30] Position Sensor," *Conference Record of the 1999 IEEE Industry Applications Conference, Thirty-Fourth IAS Annual Meeting* (Cat. No. 99CH36370), pp. 2623-2628.

[31] A. Geniusz and Z. Krzeminski, "Control System Based on the Modified Multi-scalar Model for the Double Fed Machine," *Records of the PCIM Conference*, Nyberg, 2005.

[32] Z. Krzeminski, "Sensorless Multiscalar Control of Double Fed Machine for Wind Power Generators," Osaka, 2002.

[33] S. Heir, *Grid Integration of Wind Energy Conversion Systems*, ISBN: 0-471-97143, 1998.

[34] T. Sun, Z. Chen and F. Blaabjerg, "Voltage Recovery of Grid-Connected Wind Turbines after a Short-Circuit Fault," *Proceedings of 29th Conference of IEEE Industrial Electronics Society*, Roanoke, Virginia, 2003.

[35] "*PSCAD/EMTDC Manual*," Manitoba HVDC Research Center, 1994.

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