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 losing 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
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, \( \lambda \) and power coefficient, \( C_p \), can be expressed in terms of the eqns. (2) to (4) as shown below [18]-[20].

\[
P_{\text{ref}} = 0.5 \rho C_p(\lambda, \beta) \pi R^2 V_w^3 [W] \quad (1)
\]

\[
C_p(\lambda, \beta) = 0.5(\Gamma - 0.022\beta^2 - 5.6)e^{-0.17\Gamma} \quad (2)
\]

\[
\lambda = \frac{\omega_{\text{nom}} R}{V_w} \quad (3)
\]

\[
\Gamma = \frac{R}{\lambda \cdot 1609} \quad (4)
\]

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

\[
C_t = \frac{C_p(\lambda)}{\lambda} \quad (5)
\]

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

Where, \( P_{\text{ref}} \) is the extracted power from the wind, \( \rho \) is the air density\([\text{kg/m}^3]\), \( R \) is the blade radius \([\text{m}]\), \( V_w \) is wind speed \([\text{m/s}]\), blade pitch angle is \( \beta [\text{deg}] \), \( \omega_{\text{nom}} \) is the rotational speed \([\text{rad/s}]\), and \( T_M \) is the wind turbine output torque \([\text{Nm}]\). Figures 1 and 2 show the wind turbine characteristics [21] used in this study for both IG (FSWT) and DFIG (VSWT) respectively.

**Fig. 1.** \( C_p-\lambda \) 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 \( P_{\text{ref}} \) and the optimal rotor speed \( \omega_{\text{opt}} \) 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 \( P_{\text{ref}} \) signal.

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

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

\[
\omega_{\text{opt}} = 0.0775V_w \quad [\text{pu}] \quad (9)
\]
Comparative Study between Two Protection Schemes for DFIG-based Wind Generator Fault Ride Through

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

![Pitch controller for FSWT](image)

**Fig. 5.** Pitch controller for VSWT

![Pitch controller for VSWT](image)

### 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

![DFIG System with both schemes](image)

**Fig. 7.** Model system in protection scheme 1

![Model system in protection scheme 1](image)

**Fig. 8.** Frequency converter configuration in protection scheme 2

![Frequency converter configuration in protection scheme 2](image)

### Table 1. Generator Parameters

<table>
<thead>
<tr>
<th>Generator Type</th>
<th>IG</th>
<th>DFIG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>690V</td>
<td>690V</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>0.01pu</td>
<td>0.01pu</td>
</tr>
<tr>
<td>Stator leakage reactance</td>
<td>0.07pu</td>
<td>0.15pu</td>
</tr>
<tr>
<td>Magnetizing reactance</td>
<td>4.1pu</td>
<td>3.5pu</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>0.007pu</td>
<td>0.01pu</td>
</tr>
<tr>
<td>Rotor leakage reactance</td>
<td>0.07pu</td>
<td>0.15pu</td>
</tr>
<tr>
<td>Inertia constant</td>
<td>1.5sec</td>
<td>1.5sec</td>
</tr>
</tbody>
</table>
Table 2. Rating and Parameters of Excitation Circuit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC link voltage</td>
<td>1.5kV</td>
</tr>
<tr>
<td>DC link capacitor</td>
<td>50,000 μF</td>
</tr>
<tr>
<td>Device for power converter</td>
<td>IGBT</td>
</tr>
<tr>
<td>PWM carrier frequency</td>
<td>2kHz</td>
</tr>
<tr>
<td>Upper limit of DC voltage (E_{dc-max})</td>
<td>1.65kV (110%)</td>
</tr>
<tr>
<td>Lower limit of DC voltage (E_{dc-min})</td>
<td>0.75kV (50%)</td>
</tr>
<tr>
<td>Short circuit parameter of protective device for over voltage</td>
<td>0.2 ohm</td>
</tr>
</tbody>
</table>
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 $E_{dc-max}$ and thus, the chopper is turned on and the energy is dissipated by the internal resistance. The value of $E_{dc-max}$ 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, $V_{dq0}$ and $V_{abc}$ 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 $\theta_{PLL}$ and $\theta_s$ 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, $V_{dq0}$ and $V_{abc}$ 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.
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.
Comparative Study between Two Protection Schemes for DFIG-based Wind Generator Fault Ride Through

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.

Acknowledgements

This work was supported by Japan Gas Corporation Scholarship Foundation (JGC-S)/NIKKI SANEFOSHI and The Petroleum Institute, Abu Dhabi, U.A.E.

References


Kenneth E. Okedu is currently a Ph.D. student in the department of Electrical and Electronic Engineering, Kitami Institute of Technology, Hokkaido, Japan. He received his B.Sc. and M. Eng. degrees in Electrical and Electronic Engineering from the University of Port Harcourt, Nigeria in 2003 and 2006 respectively. His research interests include the stabilization of wind farm with doubly fed induction wind generator variable speed wind turbine, and power system stability analysis.

S. M. Muyeen received his B.Sc. Eng. degree from Rajshahi University of Engineering and Technology (RUET), Bangladesh, formerly known as Rajshahi Institute of Technology, in 2000, and M. Sc. Eng. and Dr. Eng. degrees from Kitami Institute of Technology, Japan, in 2005 and 2008 respectively, all in Electrical and Electronic Engineering. After completing his Ph.D. program he worked as a Postdoctoral Research Fellow under the versatile banner of Japan Society for the Promotion of Science (JSPS) from 2008-2010 at the Kitami Institute of Technology, Japan. Presently he is working as Assistant Professor in Electrical Engineering department at the Petroleum Institute, UAE. His research interests are power system stability and control, electrical machine, FACTS, energy storage system (ESS), renewable energy, and HVDC system.

Rion Takahashi received the B.Sc. Eng. and Dr. Eng. degrees from Kitami Institute of Technology, Japan, in 1998 and 2006 respectively, all in Electrical and Electronic Engineering. Now he is working as Associate Professor in Department of Electrical and Electronic Engineering, Kitami Institute of Technology. His major research interests include analysis of power system transient, FACTS and wind energy conversion system.

Junji Tamura received his B. Sc. Eng. degree from Muroran Institute of Technology, Japan, in 1979 and M.Sc. Eng. and Dr. Eng. degrees from Hokkaido University, Japan, in 1981 and 1984 respectively, all in Electrical Engineering. He became a lecturer in 1984, an Associate Professor in 1986, and a Professor in 1996 at the Kitami Institute of Technology, Japan. Currently he is a Vice President of the Kitami Institute of Technology.