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Enhanced Crowbar Protection for Fault Ride through Capability of Wind Generation Systems

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ABSTRACT

Due to increasing demand in power, the integration of renewable sources like wind generation into power system is gaining much importance nowadays. The heavy penetration of wind power into the power system leads to many integration issues mainly due to the intermittent nature of the wind and the desirability for variable speed operation of the generators. As the wind power generation depends on the wind speed, its integration into the grid has noticeable influence on the system stability and becomes an important issue especially when a fault occurs on the grid. The protective disconnection of a large amount of wind power during a fault will be an unacceptable consequence and threatens the power system stability. With the increasing use of wind turbines employing Doubly Fed Induction Generator (DFIG) technology, it becomes a necessity to investigate their behavior during grid faults and support them with fault ride through capability. This paper presents the modeling and simulation of a doubly fed induction generator according to grid code compatibility driven by a wind turbine connected to the grid. This paper analyses the voltage sag due to a three-phase fault in the wind connected grid. A control strategy including a crowbar circuit has been developed in MATLAB/SIMULINK to bypass the rotor over currents during grid fault to enhance the fault ride through capability and to maintain system stability. Simulation results show the effectiveness of the proposed control strategies in DFIG based grid connected wind turbine system.

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1. INTRODUCTION

With increased penetration of wind power into electrical grids, Doubly Fed Induction Generator (DFIG) based wind turbines are largely deployed due to their variable speed feature and hence influencing system dynamics [1]. This has created an interest in developing suitable models for DFIG to be integrated into power system studies [5-9]. The continuous trend of having high penetration of wind power, in recent years, has made it necessary to introduce new practices. For example, grid codes are being revised to ensure that wind turbines would contribute to the control of voltage and frequency and also to stay connected to the host network following a disturbance. Wind turbines use a DFIG consisting of a wound rotor induction generator and an AC/DC/AC converter. The stator winding is connected directly to the grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The AC/DC/AC converter is basically either a set of Insulated-Gate Bipolar Transistor (IGBT) based voltage source converters (VSCs) or a pulse width modulation (PWM) converter, which uses sinusoidal PWM technique to reduce the harmonics present in the wind turbine driven DFIG system. To control the speed of wind turbine gearboxes or electronic control can be used. The pitch control system can be effectively used to prevent the windmill from excess speed increase, so that the rotor speed stability of the wind generators can be enhanced. The schematic line diagram of a DFIG wind turbine connected to grid is shown in Figure 1.

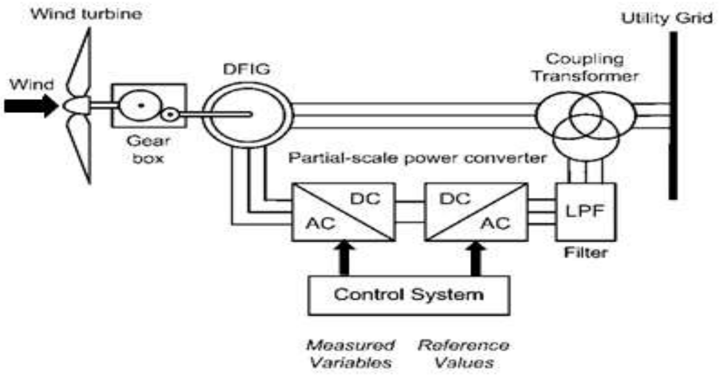


Figure 1. Schematic line diagram of a DFIG wind turbine connected to grid

DFIG allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed while minimizing mechanical stress on the turbine during gusts of wind. Another advantage of DFIG is the ability of power electronic converters to generate or absorb reactive power, thus eliminating the need for installing capacitor banks.

In [2-3] various issues & challenges of integrating renewable sources into the grid and the influence of wind turbine on the grid have been discussed. A.K.Pathak et.al [4] have given a critical review on voltage and reactive power management of wind farms to grid. The modeling and simulation of DFIG along with corresponding converter controls has been described in [5-9]. A control method for a DFIG machine inverter in order to regulate the active and reactive power exchanged between the machine and the grid consisting of used in wind energy conversion systems is proposed in [10]. In [11], grid codes that make wind energy compatible to grid integration are considered**.** In [12], low voltage ride through capability of DFIG based wind energy conversion system in the asymmetrical grid fault situation is analyzed and control scheme to support the power grid and mitigate the oscillations in the generator torque and dc link voltage is proposed. In [13-14] a solution is described to limit the high current in the rotor during grid faults in order to protect the converter through a crowbar circuit consisting of a set of bypass resistors connected to the rotor windings. Therefore, fault current characteristics of DFIG during slight voltage dips [15] are studied. In [16], an adaptive fault ride through strategy is proposed for systems with high penetration of wind and maximum power restrictions on the wind farms. In [17], Superconducting Fault Current Limiter, which has the competence to limit the fault current and protect the equipments from damage is proposed.

The paper is organized as follows: Section 2 presents the modelling of DFIG system. The control technique of DFIG system is given in section 3. The details about fault ride through capability are mentioned in section 4. The proposed protection scheme is presented in section 5. The results and discussions are summarized in section 6 and is concluded in section 7.

2. MODELING OF DFIG SYSTEM

The DFIG system is modeled as follows: A d-q reference frame is chosen to model the DFIG. The stator and rotor voltages of a DFIG are mentioned:

$$V_s = R_s I_s + \frac{d\psi_s}{dt} + j\,\omega_s\,\psi_s \quad (1)$$

$$V_r = R_r I_r + \frac{d\psi_r}{dt} + j\,\omega_{sl}\psi_r \quad (2)$$

Where, $\psi_s = L_{ls}\, I_s + L_m I_r$

$\psi_r = L_m\, I_s + L_{lr} I_r$

R_s and R_r are the stator and rotor resistances respectively. L_{ls}, L_{lr} and L_m are the stator, rotor and magnetizing inductances respectively. V_s and V_r are stator and rotor voltages, I_s and I_r are their currents. The stator and slip speed are ω_s and $\omega_{sl} = \omega_s - \omega_r$ and ω_r is the rotor angular speed. ψ_s and ψ_r are stator and rotor flux linkages.

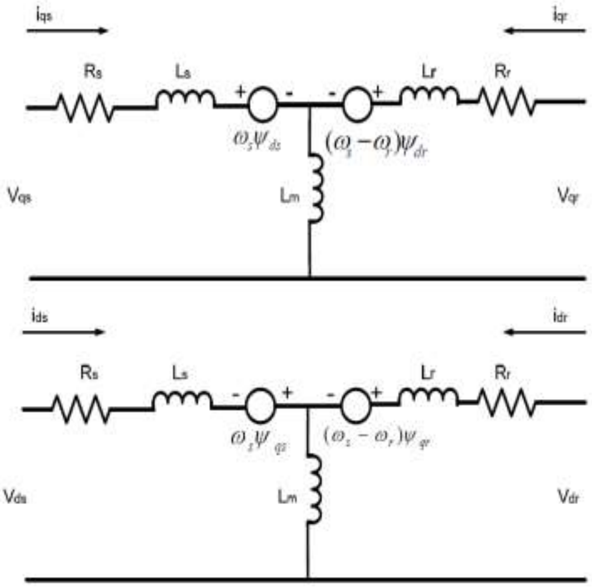


Figure 2. Equivalent circuit of DFIG in dq-reference frame

The electrical model of DFIG in synchronous reference frame (dq-frame) is given in Figure 2 and the equations, where quantities of rotor side are referred to stator side. Subscripts ‘s’ and ‘r’ refer to stator and rotor side respectively, while ‘d’ and ‘q’ refer to direct and quadrature axes respectively.

$$\begin{cases} V_{ds} = R_s i_{ds} + \frac{\psi_{ds}}{dt} - \omega_s \psi_{qs} & (3) \\ V_{qs} = R_s i_{qs} + \frac{\psi_{qs}}{dt} + \omega_s \psi_{ds} & (4) \\ V_{dr} = R_r i_{dr} + \frac{\psi_{ds}}{dt} - s\omega_s \psi_{qr} & (5) \\ V_{qr} = R_r i_{qr} + \frac{\psi_{qs}}{dt} + s\omega_s \psi_{dr} & (6) \end{cases}$$

$$\begin{cases} \psi_{ds} = (L_{ls} + L_m)\, i_{ds} + L_m i_{dr} & (7) \\ \psi_{qs} = (L_{ls} + L_m)\, i_{qs} + L_m i_{qr} & (8) \\ \psi_{dr} = (L_{lr} + L_m)\, i_{dr} + L_m i_{ds} & (9) \\ \psi_{qr} = (L_{lr} + L_m)\, i_{qr} + L_m i_{qs} & (10) \end{cases}$$

where $L_{ls} + L_m = L_s$ and $L_{lr} + L_m = L_r$
The electromagnetic torque is given by

$$T_e = 1.5\,(\psi_{qr} i_{dr} - \psi_{dr} i_{qr}) \tag{11}$$

And the equation of motion is given by

$$\frac{d\omega_m}{dt} = \frac{1}{2H_m}(T_m - T_e) \tag{12}$$

Where ω_m is the mechanical angular speed of the rotor, H_m is the mechanical inertia constant of generator, and T_m is the mechanical torque produced by the wind turbine.Active power flows through rotor and stator of the generator and combination of both constructs the total active power. The equation for reactive power might be different from the actual reactive power, which is fed into the grid as reactive power flowing from rotor side of the DFIG depends on the control strategy of its power electronic converters. Grid Side Converter (GSC) can provide some amount of reactive power depending on its capacity. Therefore, GSC impact must be taken into account in power flow calculation.

$$P = P_s + P_r = 1.5\,(V_{ds}\, i_{ds} + V_{qs} i_{qs} + V_{dr} i_{dr} + V_{qr} i_{qr}) \tag{13}$$

$$Q = Q_s + Q_r = 1.5\,(V_{qs}\, i_{ds} - V_{ds} i_{qs} + V_{qr} i_{dr} - V_{dr} i_{qr}) \tag{14}$$

Power converters cannot generate or consume active power, although they can produce or consume reactive power. Due to this fact, control strategy of power converters does not have any impact on the active power flow. Also, all the active power that flows into, from the rotor winding will be drawn or fed into the grid, respectively.

3. CONTROL MECHANISM OF DFIG SYSTEM

The control mechanism in the wind turbines plays an important role to control and extract the maximum energy from available wind while protecting the wind turbine components. The generator speed control is the most effective way to extract the maximum power from a low wind speed by using the power electronic converters.

3.1. Pitch Angle Control

Pitch angle adjustment is a very effective way to limit output power by changing aerodynamic force on the blade at high wind speeds. The pitch control system can be effectively used to prevent the wind system from excess speed increase, so that the rotor speed stability of the wind generator can be enhanced. Rotor speed stability refers to the ability of an induction (asynchronous) machine to remain connected to the electric power system and running at a mechanical speed close to the speed corresponding to the actual system frequency after being subjected to a disturbance. The pitch angle is calculated by an open loop control of regulated turbine speed as shown in Figure 3.

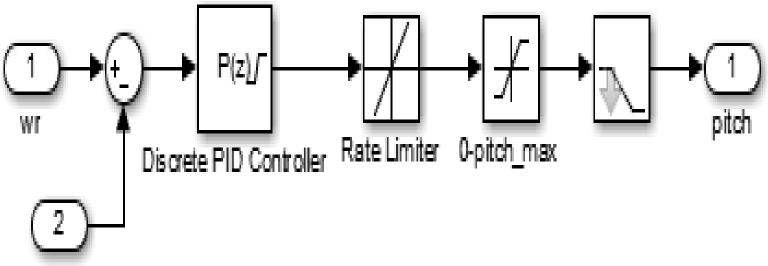


Figure 3. Pitch angle controller

3.2. Stator Side Converter Control

The Grid side converter is used to regulate the voltage of the DC bus capacitor. For the stator side controller the d-axis of the rotating reference frame used for d-q transformation is aligned with the positive sequence of grid voltage. Figure 4 shows the control system of the Stator Side Converter which is used to regulate the DC link voltage between both converters.

The control of the stator side converter is performed using the dq reference frame. The actual voltage V_{dc} at the DC link is compared with its reference value V_{dc_ref} and the error between both signals is passed through a PI controller which determines the reference signal for the dq-axis current I_{dq_ref}. This latter signal is subtracted with its current value I_{dqs} and the error is sent to another PI controller to obtain the reference voltage for the dq-axis current. This is then transformed to abc reference.

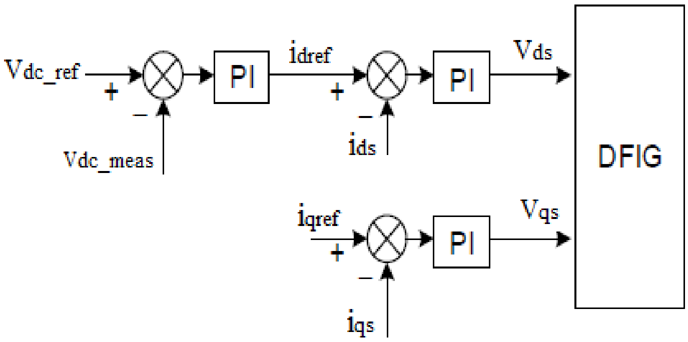


Figure 4. Stator side converter control

3.3. Rotor Side Converter Control

The rotor-side converter controller is used to control independently the stator voltage (or reactive power) and output active power of the wind turbine. The generic control loop [9] is illustrated in Figure 5. Since the converter operates in a stator-flux dq-reference frame, the rotor current is decomposed into an active power (d-axis) and a reactive power (q-axis) component. When the wind speed changes, the active and reactive (or voltage) power of the generator will also change. As shown in Figure 5, actual active power of the generator is compared with reference point value, which is determined by the wind speed. The difference between these two values will go to a Proportional Integral (PI) controller, which is used to generate the required value of d-axis rotor current. Likewise, a PI controller of the reactive power side is used to generate the required d-axis rotor current. The two outputs of both PI controllers are transformed from the d-q frame into the abc frame to obtain the required value of rotor currents. The triggering pulses would control the IGBT switches in the rotor-side converter and that will enhance the stability of entire system by sustaining the frequency and voltage within permissible tolerances.

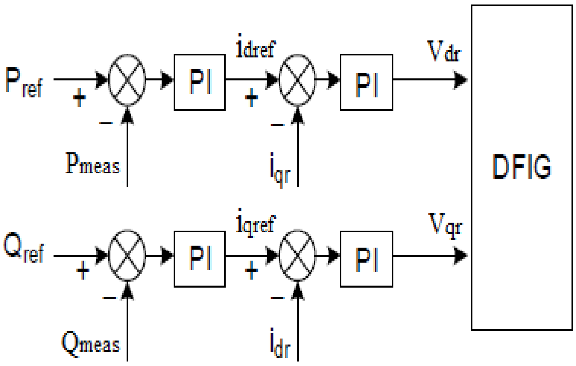


Figure 5. Rotor side converter control

4. LOW VOLTAGE RIDE THROUGH (LVRT) CAPABILITY OF DFIG:

Whenever there is a grid voltage dip caused by a fault in the grid, it results in the stator voltage dip and induces a large current in the rotor side leading to over- current in the rotor and over voltage across the dc link capacitor. The over- current and over voltage will destroy the converters and the DFIG. Protecting rotor side converter (RSC) during grid faults becomes a vital issue, which can be solved by shorting the rotor circuit of the induction generator through turning on a crowbar. Traditional operational guidelines and relevant standards for wind power generation systems require the wind power generator to be off automatically when a fault or an abnormal operation occurs in the grid. But with the development of wind power technologies, grid-connected wind systems have considerable influence on grid stability, so grid-connected wind power generators should posses fault ride through capability [4] which means that when the voltage of the generator's grid-connected point sags, the generator must be keep the grid in connected state till the voltage recovers to the normal state, so as to ride through the low voltage area. This is called Low Voltage Ride Through (LVRT) or Fault Ride Through (FRT).

Typical FRT capability [10] requirement, expected from large wind farms is as shown in Figure 6. The time duration for which the wind system is required to stay connected for different levels of voltage depressions according to Indian grid code requirements is specified in Table 1. This is to ensure that the wind system is capable and ready to supply power to the grid immediately after clearing the fault to maintain system stability. V_f represents 15% of nominal system voltage and V_{pf} represents minimum voltage for normal operation of the wind turbine.

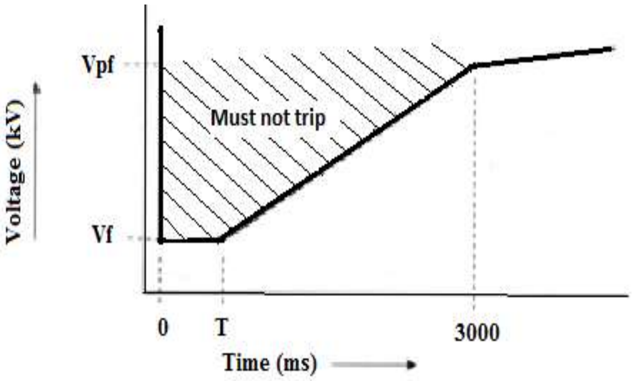


Figure 6. Typical FRT capability requirement

Table 1. Fault clearing time and voltage limits
(According to Indian Grid Code Requirements, Centre for Wind Energy Technology, Chennai)

Nominal system Voltage (kV)	Fault clearing time (ms)	V_{pf} (kV)	V_f(kV)
400	100	360	60
220	160	200	33
132	160	120	19.8
110	160	96.25	16.5
66	300	60	9.9

5. PROPOSED PROTECTION SYSTEM

A protection system called active crowbar as shown in Figure 7 is one of the methods that is used to enhance DFIG operation during the grid voltage dips. The active crowbar comprises fully controllable element such as IGBT and thereby limits the rotor voltage. According to the grid code requirements, wind turbines must remain connected to the grid during grid faults. The crowbar circuit prevents the disconnection of DFIG system during faults. It is inserted in the rotor circuit during a fault for a short period of time. The crowbar protects the rotor side converter from tripping due to over-currents in the rotor circuit or overvoltage in the DC link. During grid faults, it disconnects the rotor side converter in order to protect it.

The IGBT is turned on when the dc link voltage reaches its maximum value (for example, 20% above rated voltage) or the rotor current reaches its limit value (typically 2 p.u.). Simultaneously, the rotor of the DFIG is disconnected from the rotor side converter and connected to crowbar. When the crowbar is activated the rotor side converter pulses are disabled and the machine behaves like a squirrel cage induction machine directly coupled to the grid. Shorting the rotor with this crowbar provides a bypass for the large currents by fast elimination of rotor transients, so that the terminal voltage is enhanced. Thus the stability of the system is improved. Using this technology, the DFIG can stay connected to the grid, thus riding through the low voltage area and resume operation as soon as possible. Crowbar activation may occur not only at the instant of a voltage dip but also in a situation where voltage recovery is abrupt after fault clearance.

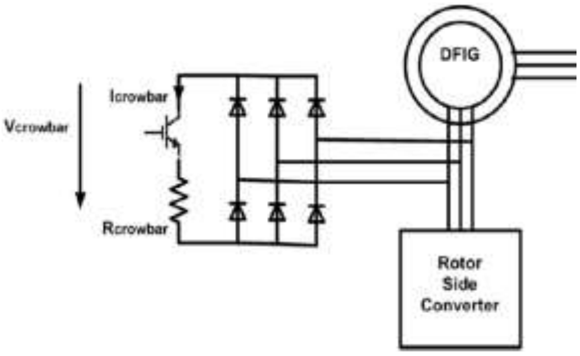


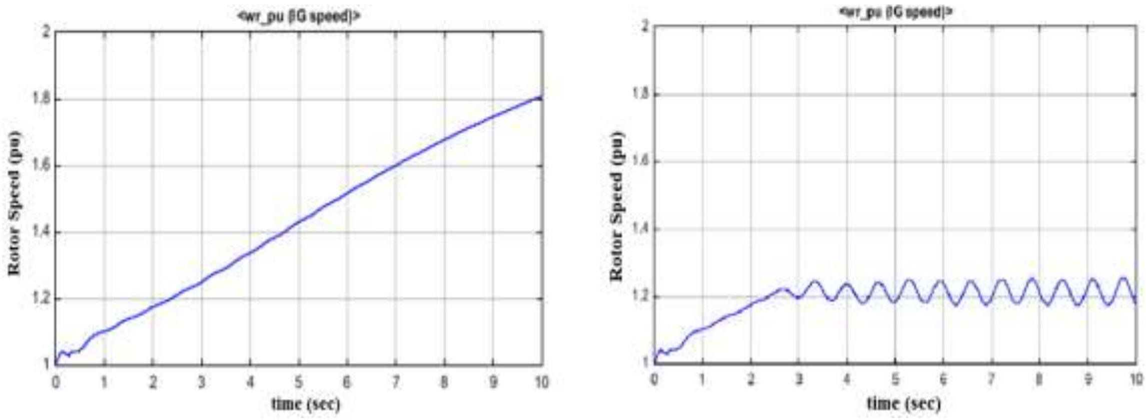
Figure 7. Connection of crowbar in the rotor circuit

6. RESULTS AND DISCUSSION

A detailed simulation model of the DFIG system is developed in MATLAB/SIMULINK R2014b software with a processing speed of 1.9 GHz. A list of parameters considered for the DFIG based wind turbine system is also presented in the appendix. A three phase to ground fault is simulated between 0.01 and 0.1 sec. The total simulation time is chosen as 0.5 sec.

6.1. Effect of Pitch Angle Controller

The pitch angle control is realized by a PI controller. Pitch angle controller prevents the rotor from excess increase in speed so that the rotor speed stability of the wind generators can be enhanced. In Figure 8(a) and 8(b), the simulation results show the rotor speed during grid faults without and with pitch angle controller. It can be seen that without pitch angle controller, the rotor speed increases to high values but with pitch angle controller, the rotor speed gets stabilized.



(a) (b)

Figure 8. Rotor speed during grid fault (a) without pitch angle controller, (b) with pitch angle controller

6.2. Voltage Dip Behavior of DFIG without Crowbar Protection

A voltage dip (or voltage sag) is a sudden reduction (between 10% and 90%) of the voltage at a point in the electrical system, which lasts for half a cycle to 1 min. Here, a three-phase fault lasting for 0.09sec is simulated at the point where the DFIG is connected to the grid. The grid is taken as a voltage source of 415V and the transmission line is represented as a lumped line with a resistance and an inductance of 0.00022 pu and 0.000058 pu which is shown in Figure 9. The machine parameters as well as the controller parameters can be found in the Appendix. The resulting stator voltage dip is shown in Figure 10. It can be seen that the voltage reduces after the occurrence of the fault. This voltage dip causes high currents in the rotor circuit. In Figure 11, the d-axis and q-axis component of the rotor current are shown. It can be seen that the rotor currents oscillate to about three times the rated current. These high currents will destroy the converter, if nothing is done to protect it. The active power output is shown in Figure 12. It can be seen that

DFIG draws more amount of reactive power during the fault. From Figure 13, it can be seen that the DC link voltage during the fault raises to high values.

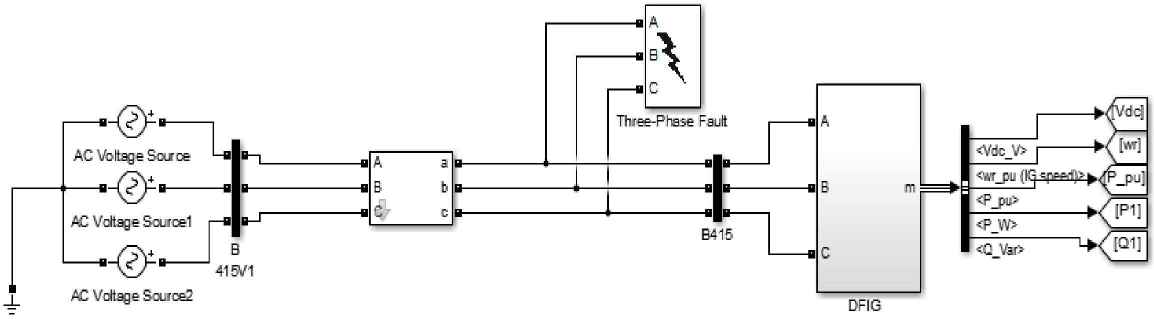


Figure 9. Simulink model of DFIG system connected to grid

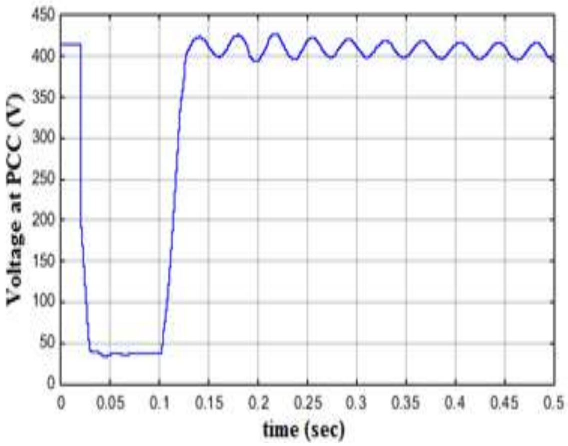


Figure 10. Voltage Dip at PCC without crowbar protection

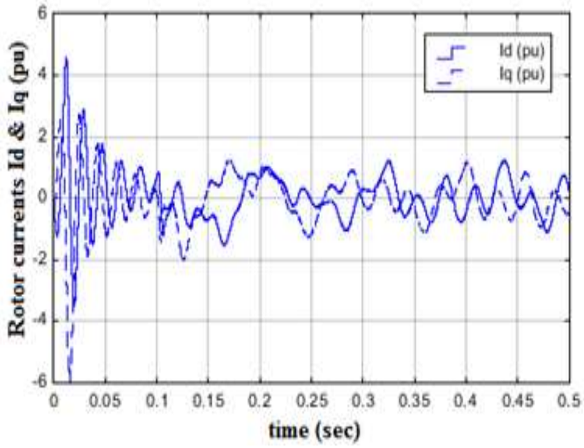


Figure 11. Rotor currents i_d & i_q without protection

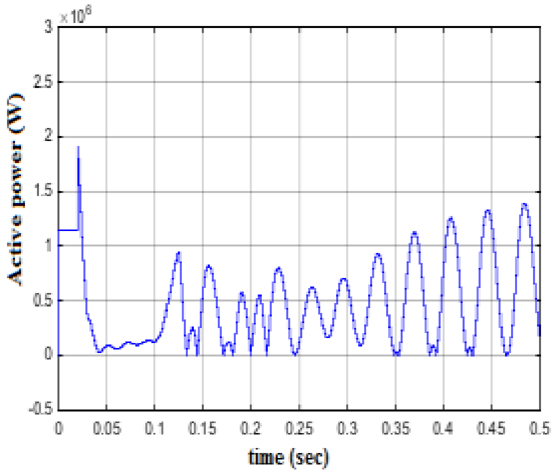


Figure 12. Active power without crowbar protection

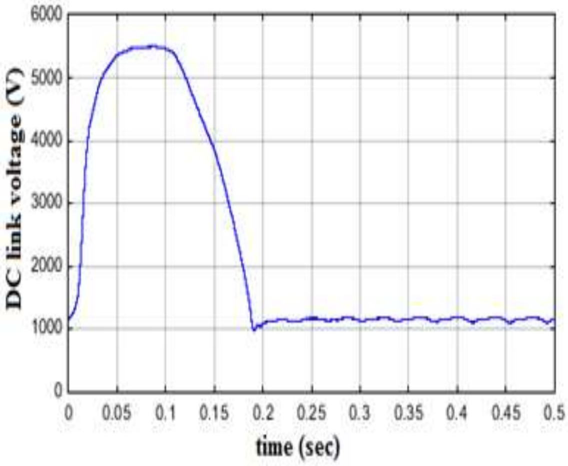


Figure 13. DC link voltage without crowbar protection

6.3. Voltage Dip Behavior of DFIG with Crowbar Protection

The basic idea of the protection technique is to limit the high current in the rotor and enhance the voltage after the fault. The behavior of the DFIG during a voltage dip of 0.09 sec is shown in Figure 14. It can be seen that the voltage after the fault is enhanced to the same voltage before the fault. Also the rotor currents oscillations are reduced with protection as shown in Figure 15. These currents do not flow through the converter but through the bypass in the rotor circuit via a crowbar circuit that is connected to the rotor windings. This should be done without disconnecting the converter from the rotor or from the grid. Because the generator and converter stay connected, the synchronism of operation remains established during and after the fault. The active power output is shown in Figure 16. The DC link voltage remains at a constant value of 1150V with protection which is shown in Figure 17.

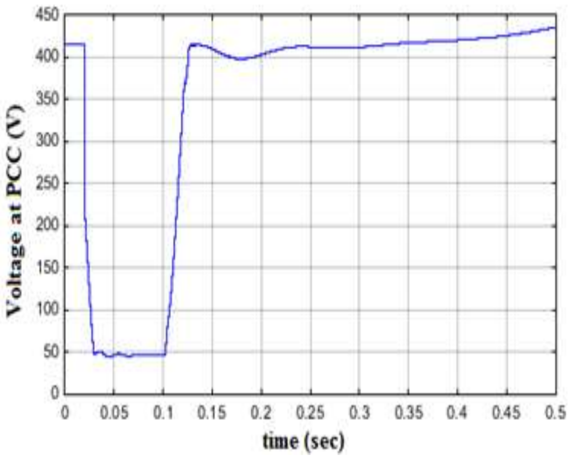


Figure 14. Voltage at PCC with crowbar protection

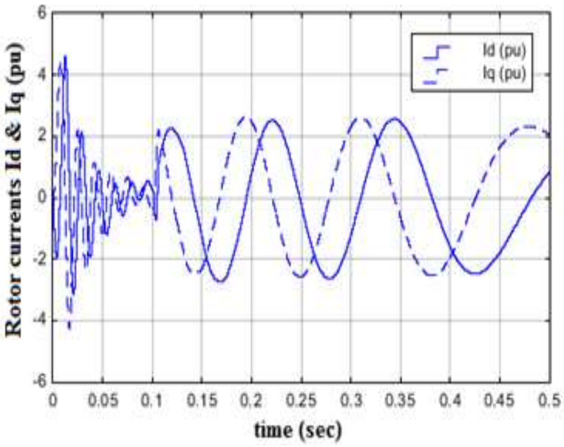


Figure 15. Rotor currents i_d & i_q with crowbar protection

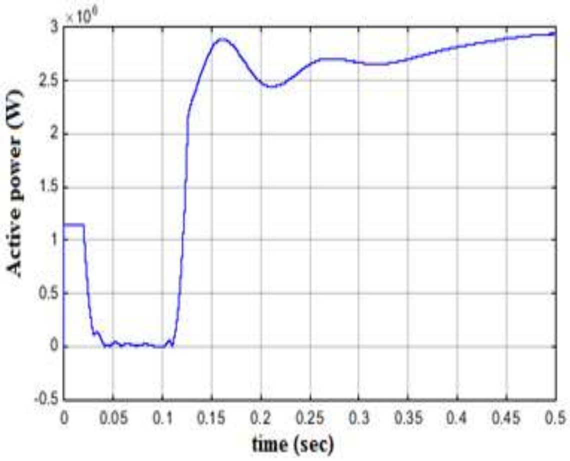


Figure 16. Active power with crowbar protection

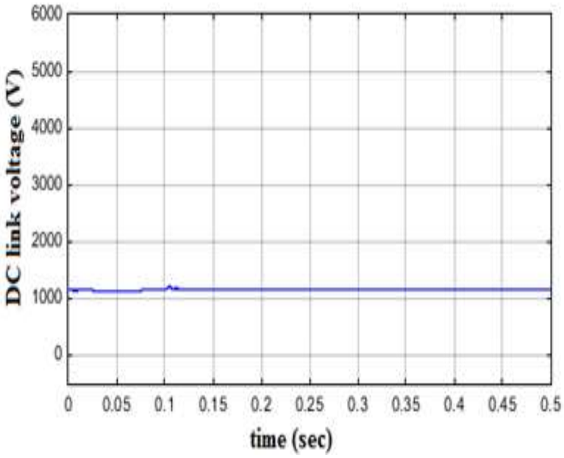


Figure 17. DC link voltage with crowbar protection

7. CONCLUSION

The modeling and simulation of a doubly fed induction generator (DFIG) driven by wind turbine is implemented with different control strategies. The GSC, RSC and pitch angle controllers are modelled using PI controllers. The paper primarily analyzed the effect of a three-phase fault in the grid connected DFIG system. It is shown that pitch angle controller can be effectively used to protect the turbine from excess speed increase so that rotor speed stability is maintained. To protect the DFIG system during grid faults, crowbar protection is installed in the rotor windings of the DFIG system. The crowbar protection attenuates severe faults, maintaining the dc link voltage and dissipating the excess currents of the rotor. Hence the crowbar protection enhanced the fault ride through capability of the wind turbine by mitigating the voltage sag created on the grid side. The simulation results verified the performance of the control scheme.

REFERENCES

[1] T. Ackermann. Wind power in power systems, John Wiley & Sons Ltd., England, 2005.

[2] P. Veena, V. Indragandhi, R. Jeyabharath, V. Subramaniyaswamy. Review of grid integration schemes for renewable power generation system, *Renewable and Sustainable Energy Reviews*. 2014; 34: 628–641.

[3] Dr. Mamatha Sandhu, Dr. Tilak Thakur. Issues, Challenges, Causes, Impacts and Utilization of Renewable Energy Sources - Grid Integration. *Int. Journal of Engineering Research and Applications,* 2014; 4(3): 636-643.

[4] A.K. Pathak, M.P. Sharma, Mahesh Bundele. A critical review of voltage and reactive power management of wind farms. *Renewable & Sustainable Energy Reviews*. 2015; 51: 460–471.

[5] Hee-Sang Ko, Gi-Gab Yoon, Nam-Ho Kyung, Won-Pyo Hong. Modeling and control of DFIG-based variable-speed wind-turbine. *Electric Power Systems Research.* 2008; 78: 1841–1849.

[6] Nicholas W. Miller, William W. Price, Juan J. Sanchez-Gasca. Dynamic Modeling of GE 1.5 and 3.6 Wind Turbine-Generators. *GE-Power Systems Energy Consulting.* GE WTG Modeling-v3-0.doc, 10/27/03.

[7] Phlearn Jansuya, Yuttana Kumsuwan. Design of MATLAB/Simulink Modeling of Fixed-Pitch Angle Wind Turbine Simulator. *Energy Procedia*. 2013; 34: 362 – 370.

[8] Rakesh Sharma, KuldeepSahay, Sateyndra Singh. Modeling and Simulation of Fixed and Variable Speed of DFIG Wind System. *IJRDET*. 2014; 362 – 370.

[9] C. Hamon. Doubly-fed Induction Generator Modeling and Control in DigSilent Power Factory, Master Thesis, KTH School of Electrical Engineering. 2010.

[10] F. Poitiers, T. Bouaouiche, M. Machmoum. Advanced control of a doubly-fed induction generator for wind energy conversion. *Electric Power Systems* Research. 2009; 79: 1085–1096.

[11] Berk Rona, Onder Guler. Power system integration of wind farms and analysis of grid code requirements. *Renewable and Sustainable Energy Reviews*. 2015; 49: 100–107.

[12] Hua Geng, Cong Liu, Geng Yang. LVRT Capability of DFIG-Based WECS under Asymmetrical Grid Fault Condition. *IEEE transactions on Industrial electronics*. 2012; 60(6): 2495-2509.

[13] Shilpa Mishra, J.N Iyer. Crowbar Protection of Micro-Grid with DFIG Wind Turbine. *International Journal of Scientific Engineering and Research*. 2014; 2(1).

[14] Johan Morrenand Sjoerd W. H. de Haan. Ride through of Wind Turbines with Doubly-Fed Induction Generator During a Voltage Dip. *IEEE Transactions on Energy Conversion*. 2005; 20(2).

[15] Xiangping Kong , Zhe Zhang , Xianggen Yin, Zhenxing Li. Study on Fault Current of DFIG during Slight Fault Condition. *TELKOMNIKA*. 2013; 11(4): 2221-2230.

[16] Songyan Wanga, Ning Chen, Daren Yu, Aoife Foley, Lingzhi Zhu, Kang Li, Jilai Yu. Flexible fault ride through strategy for wind farm clusters in power systems with high wind power penetration. *Energy Conversion and* Management. 2015; 93: 239–248.

[17] Anju M, R. Rajasekaran. Power System Stability Enhancement and Improvement of LVRT Capability of a DFIG Based Wind Power System by Using SMES and SFCL. *International Journal of Electrical and Computer Engineering*. 2013; 3(5): 618-628.

Appendix

Parameters	Value
Nominal power	1.5 MW
Stator side Nominal Voltage	415 V
Rotor side Nominal voltage	1975 V
Stator Resistance	0.023 pu
Stator Inductance	0.18 pu
Rotor Resistance	0.016 pu
Rotor Inductance	0.16 pu
Magnetizing Inductance	2.9 pu
Nominal frequency	50 Hz
Nominal wind speed	15 m/s
Wind turbine Inertia Constant	4.32
Shaft spring Constant	1.11
Shaft Mutual damping	1.5
Turbine initial speed	1.2
Initial output torque	0.83
Grid side converter maximum current	0.8 pu
Grid side coupling inductor (L,R)	0.3, 0.003
Nominal DC bus voltage	1150 V
DC bus Capacitor	10000e-6 F
Crowbar Resistance	40*0.016 pu

BIOGRAPHIES OF AUTHORS

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