Analysis of DFIG based Wind Energy System with Grid Integration under normal and abnormal conditions

Prashant Debre, Akshay Kadu, M.R.Ramteke, D.R.Tutakane

[1]*(Electrical Engg,Rajiv Gandhi College of Engineering & Research/RTM Nagpur University, India)*
[2]*(Electrical Engg,Rajiv Gandhi College of Engineering & Research/RTM Nagpur University, India)*
[3]*(Electrical Engg,Visvesvaraya National Institute of Technology, Nagpur/Deemed to be University, India)*
[4]*(Electrical Engg, Shri Ramdeobaba College of Engineering and Management/RTM Nagpur University, India)*

Abstract: *This paper describes the detailed modeling and control of a doubly fed Induction Generator (DFIG) interconnected with grid under normal and abnormal condition. The stator and rotor side converters are realized using H-bridge voltage source converter (VSC) with their appropriate control. It is found that DFIG effectively injects power into the grid, simultaneously maintaining grid requirement for synchronization with limited reactive power capability. An extensive digital simulation has been carried out using MATLAB environment in order to study the behavior of DFIG under normal and abnormal condition. The satisfactory system performance proves the suitability of control for DFIG with grid integration.*

Keywords: *Doubly fed Induction Generator, Grid, Voltage Source Converters, Wind energy.*

I. Introduction

The worldwide energy crisis and increasing pollution due to conventional power generation methodology, there is need to adopt for clean energy generation through the natural resources such as solar, wind; biogas etc. Wind power in the clean energy generation is having its own importance amongst all the renewable energy sources. But the integration of wind energy with the grid becomes a new challenge due to the irregular nature of wind With the recent progress in modern power electronics, the concept of a variable-speed wind turbine (VSWT) equipped with a doubly fed induction generator (DFIG) is fetching more attention because of its improved dynamic performance during grid disturbances as compared to traditional wind turbine generators. Initially wind turbines employ with squirrel-cage induction generators (SGIG) without speed and power controller. During past decade, concept of variable speed is adopted with decoupled active and reactive controller for efficient energy generation and integration with utility grid [1-2].

DFIG is wound rotor induction machine which is simple in construction and cheaper than the synchronous machine. The DFIG converter consists of a rotor-side converter (RSC) and a grid-side converter (GSC) connected back-to-back by a dc-link capacitor. The required rating of this converter is typically 25-30 % of total system power which reduces converter cost, less harmonics injection to the connected grid and improved overall efficiency of the wind turbine system [3-4].These inbuilt converter controllers have ability to control reactive power and decouple control of active and reactive power by independently controlling the rotor current and inject wind power at constant voltage and frequency to the utility grid. However during fault condition, due to limited reactive power capability and fault ride through capability of DFIG, it is necessary to assess its dynamical behavior, steady state performance, and impacts on the interconnected power network with regard to its reactive power capability and voltage control.

According to the grid codes, DFIG based wind energy systems are now-a- days considered as a conventional power generation plant. The main elements in the grid codes include fault ride-through requirements, active/reactive power control, frequency/voltage regulation, and system protection [5].To enable a large-scale application of the wind energy without compromising the power-system stability, the turbines should stay connected and contribute to the grid in case of a disturbance such as a voltage dip. As per IEEE grid codes, during the grid disturbances, DFIG may disconnect from grid if fault is not cleared within 150ms.There are two major issues during fault condition, to be controlled i.e. over current in rotor and stator circuits and DC-link overvoltage. This leads to have excessive energy which cannot be transmitted into the grid during fault condition. Conventionally crowbar resistance is connected across rotor terminals which dissipate the excessive energy.

In this paper detailed analysis of turbine and 1.5 MW DFIG is carried out and interfaced with the grid via transmission lineModeling of rotor side and grid side converters is synthesizes and gains are calculated using butterworth polynomial for optimal control. The system performance is evaluated under normal and abnormal condition using MATLAB/SIMULINK.

II. Modeling Of Dfigand Its Turbine

The detailed configuration of a DFIG along with wind turbine and converter system is shown in Fig. 1.The wound rotor induction generator is feeding from both stator and rotor side to the grid. Stator windings are directly connected to grid whereas rotor winding is feeding power through AC/DC/AC converter to utility grid. In order to inject electrical power to grid at constant voltage and frequency over wide range of wind speeds, converter needs to control power flow both in magnitude and direction. Therefore two four quadrant IGBT based PWM converters namely rotor side converter (RSC) and grid side converter (GSC) connected back to back by dc link capacitor is used[8].
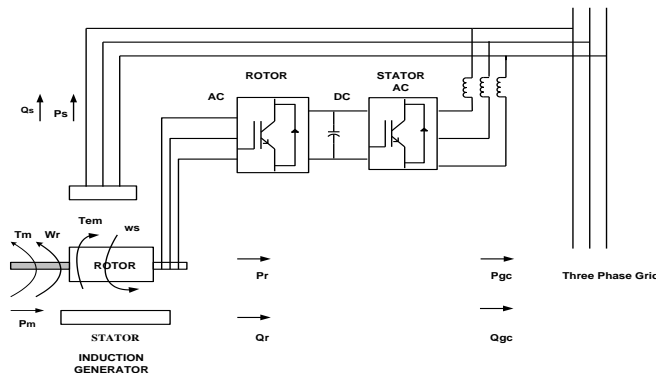
2.1 Generator

Fig. 1. Schematic diagram of the DFIG WT system

The standard configuration of grid connected wind energy conversion system is shown in the Fig. 1. The turbine transmits mechanical power to the electric power generating system as equations (1) and (2)

$$P_m = \mathrm{T}_m \omega_r \tag{1}$$

$$P_s = \mathrm{T}_{em} \omega_s \tag{2}$$

At steady speed for lossless generator;

$$\mathrm{T}_m = \mathrm{T}_{em} \ \& \ P_m = P_s + P_r$$

Therefore, $P_r = P_m - P_s = -sP_s$

Where, $s = \dfrac{1}{\omega_s}(\omega_r - \omega_s)$

This shows that rotor electrical output power is fraction of stator power, only when slip of machine is negative. The sign of Pr is a function of the slip sign. Pr is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed).Importantly for super synchronous speed operation, Pr is transmitted to DC link capacitor and tends to raise the DC voltage with negative phase sequence whereas for sub synchronous speed operation, Pr is taken out from the DC link capacitor and tends to decrease the DC bus voltage with positive phase sequence.

Hence the grid side converter is used to generate or absorb the grid electrical power P_{gc} in order to keep the DC voltage constant. In steady state for a lossless AC/DC/AC converter P_{gc} is equal to P_r and the speed of the wind turbine is determined by the power P_r absorbed or generated by the rotor side converter. The rotor side converter is used to control the wind turbine output power and the voltage (reactive power) measured at the grid terminals. The grid side converter is used to regulate the voltage of the DC bus capacitor. The voltage equations of stator and rotor circuits of induction generator can be given in d-q reference frame as;

$$v_{ds} = R_S i_{ds} - \omega_s \psi_{qs} + \frac{1}{\omega_b}\frac{d\psi_{ds}}{dt} \tag{3}$$

$$v_{qs} = R_s i_{qs} + \omega_s \psi_{ds} + \frac{1}{\omega_b}\frac{d\psi_{ds}}{dt} \tag{4}$$

$$v_{dr} = R_r i_{dr} - (\omega_s - \omega_r)\psi_{qr} + \frac{1}{\omega_b}\frac{d\psi_{dr}}{dt} \tag{5}$$

$$v_{qr} = R_r i_{qr} + (\omega_s - \omega_r) \psi_{dr} + \frac{1}{\omega_b} \frac{d\psi_{qr}}{dt} \tag{6}$$

Where $i_s = i_{ds} + ji_{qs}$ and $i_r = i_{dr} + ji_{qr}$ are the stator and rotor current vectors; $V_s = V_{ds} + jV_{qs}$ and $V_r = V_{dr} + jV_{qr}$ are stator and rotor voltage vectors respectively; $\omega_b, \omega_s, \omega_r$ are the base, stator and rotor angular frequencies.

2.2 Drive Train

Wind turbine modeling basically consists of shaft and drive train modeling. The aerodynamically model and control system model concludes wind turbine model. To study dynamic stability of DFIG wind turbine two mass models is consider because turbine shaft is not as stiff as that of conventional synchronous generators [9]. The equivalent two mass models are simple and sufficient with reasonable accuracy for dynamic studies. The mathematical equations which represent the two mass model of drive train by neglecting turbine and generator self-damping are expressed as

$$\frac{d\omega_r}{dt} = \frac{1}{2H_g}(T_{sh} - T_e - B\omega_r) \tag{7}$$

$$\frac{d\omega_t}{dt} = \frac{1}{2H_t}(T_m - T_{sh}) \tag{8}$$

$$\frac{d\theta_t}{dt} = \omega_b(\omega_t - \omega_r) \tag{9}$$

Where ω_t and ω_r is the wind turbine and generator rotor speed respectively. H_g and H_t are generator and turbine inertia constants. θ_t is the shaft twist angle in radian and B is the friction coefficient of generator. The mechanical torque exerted on shaft of turbine is a result of lift (L) and drag (D) forces on the blades attached to the rotor shaft. The electromagnetic torque T_e, shaft torque T_{sh} and the mechanical torque T_m are expressed as;

$$T_e = Lm(i_{qs}i_{dr} - i_{ds}i_{qr}) \tag{10}$$

$$T_{sh} = K_{sh}\theta_t + D_{sh}\omega_b(\omega_t - \omega_r) \tag{11}$$

$$T_m = \frac{\rho\pi R^2 C_p(\lambda,\beta)v_w^3}{\omega_t} \tag{12}$$

Where, R is turbine radius in meter, from these forces maximum mechanical power which can be extracted from wind as per Bet'z formula is given by;

$$P_m = 0.5\rho AV^3 C_P(\lambda,\beta) \tag{13}$$

Where, P_m is power extracted from wind in watts; V_w is wind velocity in m/s; ρ is air density in kg/m^3; A is the area covered by wind turbine rotor in m^2. λ is tip speed ratio and β is blade pitch angle. C_p is performance coefficient and is highly nonlinear power function of λ and β given by;

$$C_P = 0.22(\frac{116}{\lambda_i} - 0.4\beta - 5)e^{\frac{-12.5}{\lambda_i}} \tag{14}$$

where, $\lambda_i = \dfrac{1}{\dfrac{1}{(\lambda + 0.08\beta)} - (\dfrac{0.035}{\beta^3 + 1})} \tag{15}$

and $\qquad \lambda = \omega_t R / V_w$

for variable speed wind turbines, the rotational speed of turbine is adjusted over a wide range of wind speeds so that tip speed ratio is maintained at its optimal value thereby C_p reaches its maxima and consequently mechanical power output from wind turbine. At higher wind speeds mechanical power is kept at its rated value by pitching the turbine blades. The above equations are evaluated for different values of $\lambda = 1$ to 20 and $\beta = 0^0$ to 15^0, and characteristics is shown in Fig. 2. It is found that the optimal C_p is 0.4382 for corresponding $\lambda = 6.32$ and $\beta = 0^0$[7].
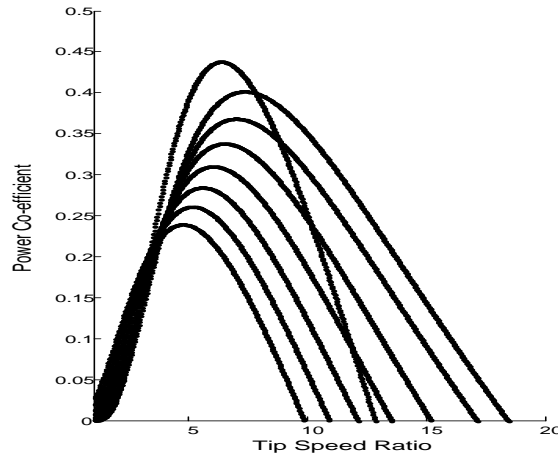
Fig.2. Simulated Wind Turbine characteristics for optimal Power

2.3 Pitch Angle Control
Pitch angle controller is activated for high wind speed to avoid fatal over speeding. Since, pitch angle directly relates to the performance of power extraction from wind, therefore, pitch angle of blade is controlled to optimize power extraction of WT as well as to prevent over rated power production during high speed [6].Due to large size of rotor blades, pitch angle is expressed as nonlinear function of control voltage signal and real pitch angle.
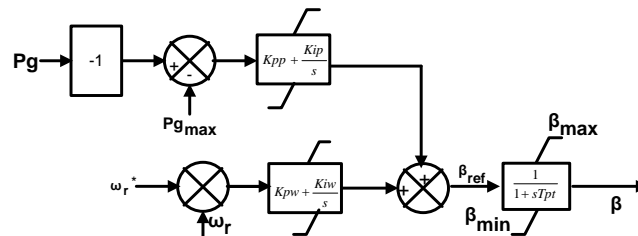
Fig. 3. Schematic diagram of the Pitch Control System

The control strategy using(16) is shown in Fig. 3,

$$\frac{d\beta}{dt} = \frac{1}{T_\beta}(\beta_{ref} - \beta)$$ (16)

Where lower part is rotor speed regulator and the upper part isaerodynamic power limiter. The entire controller is realized by means of PI controller. When generator speed exceeds rated speed at high speed, the pitch control activates and angle is tuned such that turbine power limited to its rated value.

III. Analysis Of Controller And Optimal Gain Calculation
3.1 Grid Side Converter(GSC)
Vector control for GSC during normal operation is shown in the Fig.4. It is used to control DC link capacitor voltage(V_{dc})and reactive power flow between GSC and grid by controlling current (I_d, I_q) in synchronous reference frame.DC Voltage dynamics in DC link capacitor is expressed by;

$$C_p V_{dc} = i_{dc} = \frac{3}{4}\left(M_{dr}I_{dr} + M_{qr}I_{qr}\right) + \frac{3}{4}\left(M_{df}I_{df} + M_{qf}I_{qf}\right)$$ (17)

Where C is DC link capacitance, M_{dr}andM_{qr}areq and d axis modulation index for RSC and $M_{df}$and $M_{qf}$are q and d axis modulation index for GSC. Also,

$$C_p V_{dc} = K_{dc}(v_{dc}^* - v_{dc})$$ (18)

Where K_{dc} is PI controller gain for dc voltage controlswhich given by;

$$K_{dc} = K_{pdc} + \frac{K_{idc}}{p}$$

Therefore, $C_p V_{dc} = \left(K_{pdc} + \frac{K_{idc}}{p} \right) V_{dc}* - (K_{pdc} + \frac{K_{idc}}{p})V_{dc} \frac{V_{dc}}{V_{dc}*} = \dfrac{\frac{1}{C_{dc}}\left(pK_{pdc} + K_{idc} \right)}{p^2 + p\frac{K_{pdc}}{C_{dc}} + \frac{K_{idc}}{C_{dc}}}$ (19)

Comparing (19) with Butterworth second order polynomial as given below,

$$P^2 + \sqrt{2}\omega_{0dc}P + \omega_{0dc}{}^2$$

Where ω_{0dc} is bandwidth frequency of DC voltage controller,

$$K_{pdc} = \sqrt{2}\omega_{0dc} * C_{dc}$$

3.2 Rotor Side Converter (RSC)
      Under normal operation, the control scheme of RSC is shown in fig.5 which consists of two cascaded vector control with inner control loop which regulates d-axis and q-axis rotor currents. The outerloop regulates the stator active power i.e.DFIG rotor speed and reactive power i.e. DFIG terminal voltage.
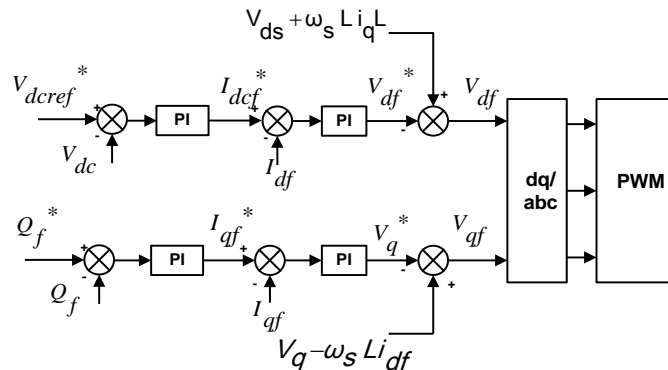

Fig. 4. Control scheme of GSC side controller.

The typical proportional integral (PI) controllers gains for RSC current control is given by:

$$Kp = \sqrt{2}\omega_0 \sigma L_r - r_r$$

$$Ki = \sigma L_r \omega_0 2$$

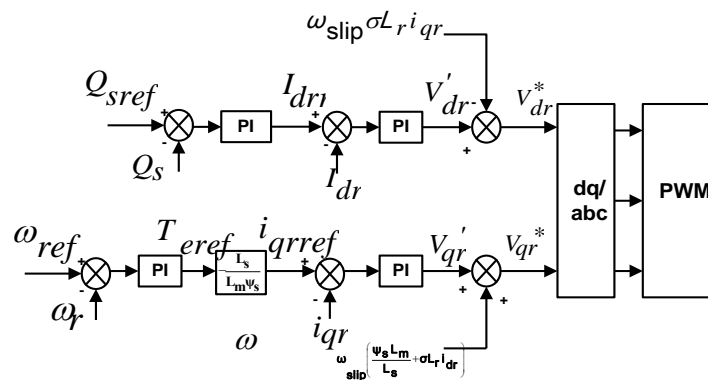Where, ω_{0dc} is bandwidth frequency of speed controller.

Fig.5. Control scheme of RSC

IV.   Dfig System Under Study In Matlab

The system used for simulation study is shown in Fig.6, in which complete DFIG WT has been developed for 50Hz, 1.5 MW and is interfaced with the grid via transmission line. Inorder to study the behavior of system under normal and abnormal condition, fault is created in line at 1.3 sec and cleared at 1.4 sec.The impact of fault on active power andreactive power flow, rotor speed and dc link voltage isobserved and also measures the voltage sag at different buses with and without fault.
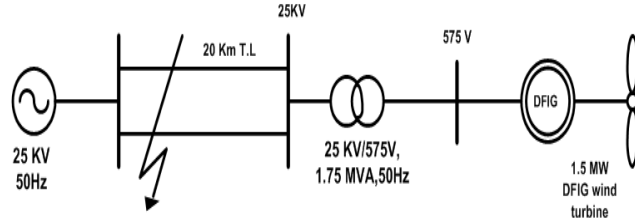
Fig.6 Single line diagram of system under study

V.   Analysis And Results

5.1 Under Normal Operating Conditions

The system is simulated under normal operating conditions and results are summarized below. It is evident from Fig. 7(a) The voltage and currents are found to be balanced and sinusoidal indicating satisfactory synchronization of DFIG with grid. Fig.7 (b) shows that the active power delivered by DFIG to the grid is seen to be 1.4 MW including losses. However, DFIG is having limited capability of reactive power generation. It is observed that the voltage magnitude is maintained at its rated value i.e 1 pu.

Further, it is depicted from Fig. 7(c) that, along with the power flow control, theDFIG control maintains the dc-link voltage at its reference value of 1150 V, which represents the robustness of the control. It is also seen that the rotor speed is pulsating at its rated value of 1.2 pu.
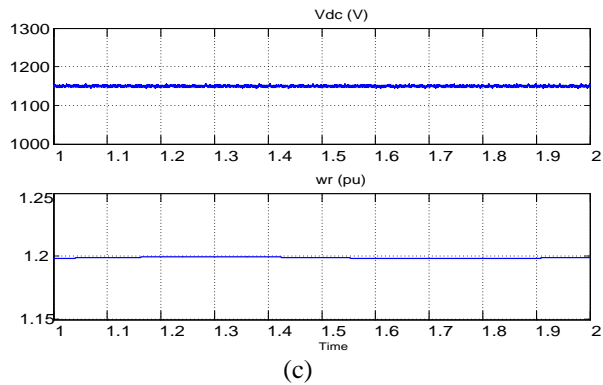
(c)

(c)
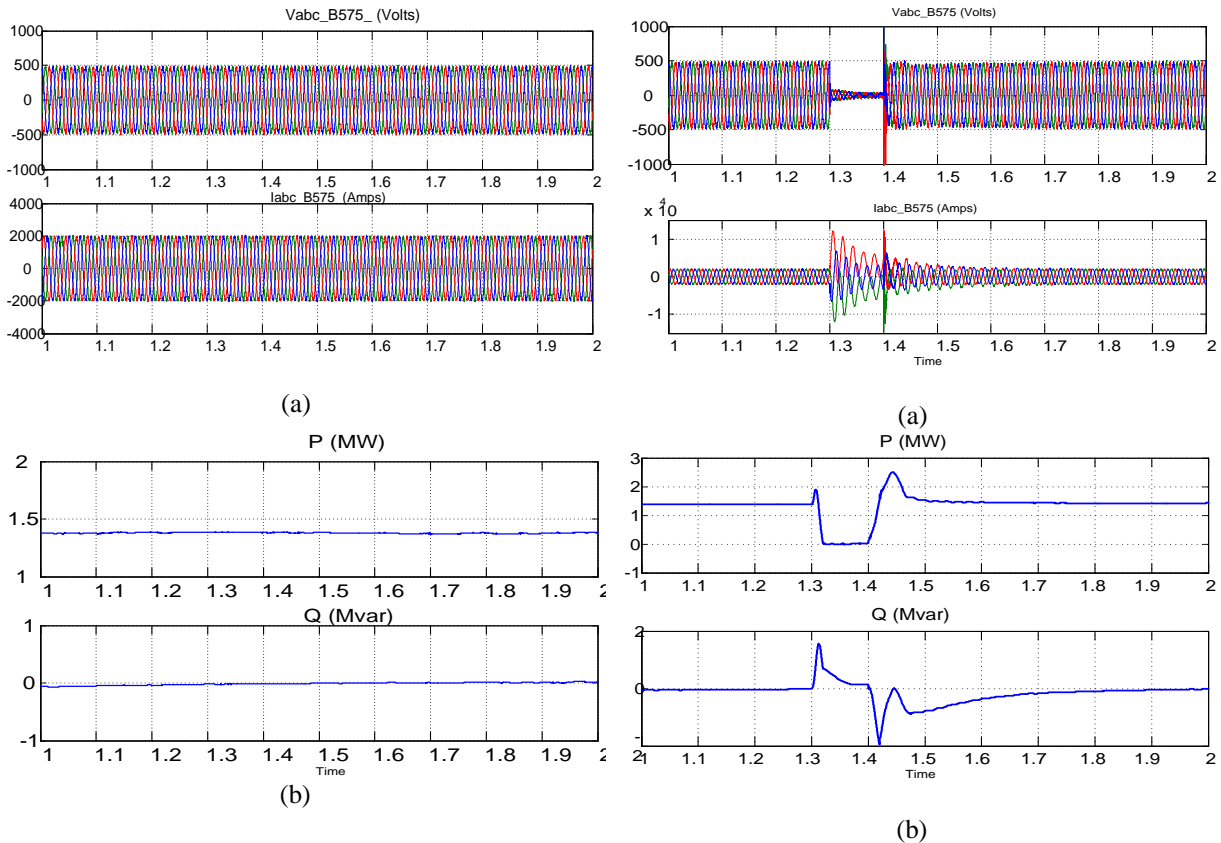
Fig. 7.Simulated steady state response of the studied DFIG WT system at wind speed of 12m/s for normal operating conditions (a) Magnitude of current and voltage supplied by DFIG at PCC 575v bus, (b) Active ,Reactive power, (c) DC link voltage and Rotor speed.
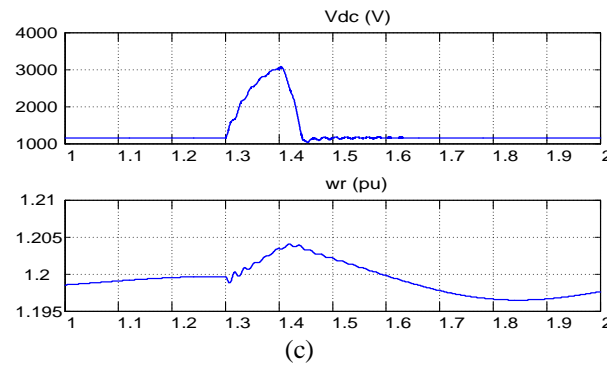
Fig. 8.Simulated transient response of the studied DFIG WT system at wind speed of 12m/s with line fault created at 1.3 sec and cleared at 1.4 sec (a) Magnitude of current and voltage supplied by DFIG at PCC 575v bus, (b) Active ,Reactive power, (c) DC link voltage and Rotor speed.

5.2. Under Abnormal Operating Conditions:

The system is simulated under abnormal operating conditions by creating a fault at 1.3 sec and cleared at 1.4 sec, and the results are summarized below. It is evident from Fig. 8(a,b) that the active power and voltage magnitude delivered by DFIG to the grid falls rapidly during fault period, whereas reactive power shoot-up to +1.8 Mvar at occurrence of fault and -1.8 Mvar at the instant of fault clearance. During these conditions the voltage and currents are found to be unbalanced.

Further, it is depicted from Fig. 8(c) those, the dc-link voltage boost-up approximately thrice the rated value during fault period. It is also seen that the rotor speed is increases from rated value.

VI. Conclusion

Variable wind speed turbine system equipped with doubly fed induction generator, interconnected with grid is implemented. It is observed that DFIG is capable of maintaining grid requirement under normal operating condition, however during fault period the dc link capacitor voltage increases due to over acceleration of rotor. To protect power electronic devices from this over voltage there is need to provide a strategy which regulates dc link voltage within permissible limit.

APPENDIX

The parameters of the studied DFIG WT system are as follows:

Wind turbine: cut- in wind speed 4m/s;rated wind speed 12m/s; Inertia constantH_t =3s; Damping Coefficient D_{sh} =0.01pu ;Shaft stiffness coefficient K_{sh} =0.5pu

DFIG: rated power 1.5 MW;rated voltage 575v; Number of Poles P=4; Stator resistance R_s= 0.00706pu; Rotor resistance R_r= 0.005 pu; Stator leakage inductance L_{ls}= 0.171pu; Rotor leakage inductance L_{lr} = 0.156 pu; Mutual inductance L_m= 2.9pu; Inertia Constant H_g= 5.04 s; Friction coefficient$B$= 0.01pu

Converters: Resistance of Grid side inductor R_L= 0.003 pu; inductance of Grid side inductor L_L= 0.3 pu; Nominal DC link voltage =1150v; DC link capacitor = 0.01F

References

[1]. BinWu, Yongqiang Lang, NavidZargari,SamirKouro,Power Conversion And Control Of Wind Energy Systems,A John Wiley & Sons, Inc.2011.

[2]. Thomas Ackermann, Royal Institute of Technology, Wind Power in Power Systems, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO198SQ,England, 2005.

[3]. Wei Qiao, Ganesh Kumar Venayagamoorthy and Ronald G. Harley, Real-Time Implementation of a STATCOM on a Wind Farm Equipped With doubly Fed Induction Generators,IEEE Transactions on Industry Applications, Vol. 45, No. 1, January/February 2009.

[4]. R.Pena ,J.C.Clare and G.M.Asher, "Doubly Fed induction Generator using back to back PWM converters and its application to variable speed wind energy generation" , IEE Proc-Electr. Power Appl.,vol 143,No 3,pp 231-241,3,May 1996.

[5]. LihuiYang,ZhaoXu,Zhao Yang Dong, "Advanced control strategy of DFIG wind turbines for Power System Fault Ride Through", IEEE Transaction on power systems , vol. 27 No 2, 2,May 2012.

[6]. AggrawalA,Saini,Lalit Mohan and Bhim Singh, "control strategy for DFIG based Grid connected wind Energy conversion System", International Journal of Grid Distribution Computing,Vol.7,no.3,pp 49-60,2014

[7]. I.Margaris A. Tsouchnikas and N.Hatziargyriou, "Simulation of Doubly Fed induction Generator wind turbines" European Wind Energy Conference, Milan 2007.

[8]. Nicholas W.Miller,William W Price and Juan J.Sanchez-Gasca, "Dynamic Modeling of GE 1.5 and 3.6 MW wind Turbine-Generators", Version 3,GE Power Systems Energy Consulting, Oct 2003.

[9]. WieQiao,WeiZhou,Jose M. Aller& Ronald G Harley, "Wind Speed estimation based sensor less output maximization control for wind turbines driving a DFIG", IEEE Transaction on Power Electronics ,Vol 23,No 3,May 2008.