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Fault Ride-Through Analysis of Doubly Excited Induction Generator During Voltage Dip

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Abstract

This paper presents an overview of the effect of voltage dip on the doubly fed induction generator (DFIG) connected to utility grid. The main concern in the paper is to the control of the DFIG wind turbine and of its power converter with the ability to protect itself without disconnection during grid fault conditions. After setting up the basic machine, converters and grid-filter equations, parameters of controllers are derived. Regulator parameters are also discussed. The investigated DFIG system is simulated using MATLAB/Simulink to implement the derived model and its dynamic response to normal and faulty condition. The dynamic model of DFIG wind turbine includes models for both mechanical components as well as for all electrical components and controllers. The viewpoint of the paper is to carry out different simulations and hence to provide insight and understanding of the grid fault impact on both DFIG wind turbines and on the power system itself.

***Index Terms—Wind Turbine, DFIG, Converters, LVRT, RSC, GSC, WECS*.**

1. Introduction

Power generation from the fossil fuel has many adverse effects on the environment. Being non-polluting in nature and with the advancement in the arena of power electronics, the non-conventional energy resources, especially wind energy has become most promising alternative for fossil fuel in power generation. Wind generation now meets a significant percentage of electrical demand worldwide. In the first half of 2012, the world added about 16.5GW of wind generation, a 7.04% increase to total more than 254GW. This is enough to cover about 3% of the world's electricity demand.[1]

In WECS with full power handling capabilities, the power converter is in series with the synchronous or induction generator, in order to transform the variable amplitude/frequency voltages into constant amplitude/frequency voltages. In a partial power handling WECS or DFIG, the converter processes maximum twenty five to thirty per cent of the total generated power (e.g. slip power) which possess an advantage in terms of the reduced converter cost and increased efficiency of the system. [2]

In doubly fed induction generator (DFIG), back to back converters is used to decoupled control of active and reactive power to utility grid. The function of rotor side converter (RSC) is to control the active and reactive power of generator by means of controlling the rotor current components. [3][4]The grid side converter (GSC) is to convert variable-frequency, variable-voltage power from a generator into constant-frequency constant-voltage power, and to regulate the output power of the WPGS. Traditionally a gearbox is used to couple a low speed wind turbine rotor with a high speed generator in a WPGS. . Based on the principles of field oriented control (FOC) for electrical machine drives, the converter switching states were selected from an optimal switching based on the instantaneous errors between the angular position of the estimated converter terminal voltage vector and the reference and estimated values of active and reactive power.

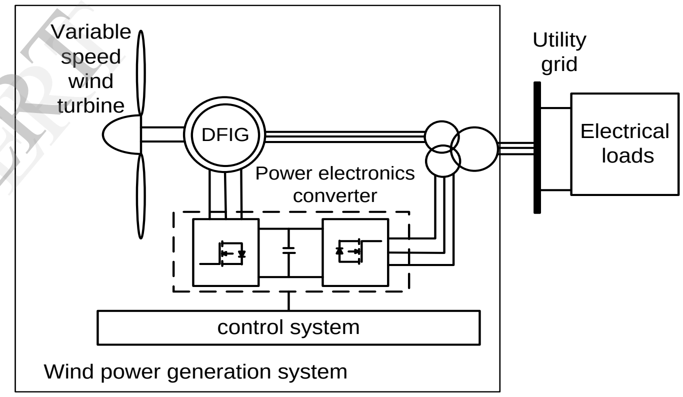


Figure 1. Typical wind power generation system connected to a utility grid.

Voltage sag is a serious problem for DFIG because of low rating of RSC converter, approximately 30% of generator rating. The cause of voltage sag is sudden load changes, starting of heavy loads; drop a lightning bolt near transmission line etc. For reliable and safe grid operation, resulted in the power system operators revising nowadays the grid codes in many countries. [5][6]

Basically, for wind power these grid codes require an operational behaviour with several control tasks similar to those of conventional power plants. One of these control tasks is the fault ride-through capability of the wind turbines, which addresses primarily the design of the wind turbine controller and protection in such a way that the wind turbine is able to remain connected to the network during grid faults (e.g., short circuit fault). [7][8] There is serious concern about the influence of the wind power on the power system stability, especially during grid faults. It is therefore necessary to carry out investigations of the dynamic interaction between power system and large wind farms, with suitable models and accurate transient simulations. [9][10]

This paper proposes a FOC control strategy for a DFIG based wind energy generation system. The control method is based on the assumption of stator voltage vector on d-axis and the magnetic saturation where electro-magnetic transients and other nonlinear factors are neglected. During faulty condition, the magnitude variation of transmission line voltage is affects the output parameters of wind power generation system (WPGS). These results on a 2MW DFIG generation system are presented to illustrate the performance of the proposed control strategy during the variations of input parameters.

2. Indian wind grid codes (IWGC)

Grid connection codes define the requirements for the connection of generation and loads to an electrical network which ensure efficient, safe and economic operation of the transmission and/or distribution systems. [8][10] With the growth of wind power; the interaction between WECS and gird will cause new problems about the safe and reliable operation of systems.

2.1 Voltage at the grid connection point

The wind turbines are required to operate within typical grid voltage variations. For safe and reliable operation of grid, the approximately range of variation of voltage is in between +10% to -10%.

2.2 Frequency of operation for wind farms

For the operating range of frequencies between 47.5 Hz to 51.1 Hz, the WTGs shall operate according to the frequency response curve given by authority.

2.3 Active power and power factor

The grid connected wind farm shall be capable of applying the active power between the limits of 0.95 power factor lagging to 0.95 power factor leading at the grid connection point.0

2.4 Reactive power and voltage control

The wind farm shall have provision for VAr compensation /support such that they do not draw reactive power from the grid.

2.5 Low voltage ride through capability

During fault ride through, the WTGs in the wind farm shall have the capability to meet the following requirement [11]:

a) Shall minimize the reactive power drawl from the grid.

b) The wind turbine generators shall provide active power in proportion to retained grid voltage as soon as the fault is cleared.

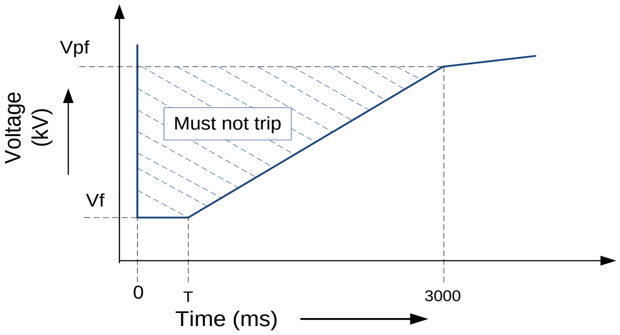


Figure 2. Fault ride through characteristics

Where,
Vf = 15% of nominal system voltage
Vpf = Minimum voltage mentioned in table
The fault clearing time for various system nominal voltage levels is given in Table 1.

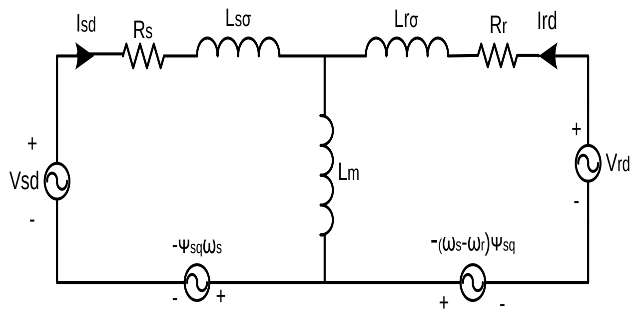
Table 1. Fault clearing time and voltage limits

Nominal system voltage (kV)	Fault clearing time, T(ms)	Vpf (kV)	Vf (kV)
400	100	360	60.0
200	160	200	33.0
132	160	120	19.8
110	160	96.25	16.5
66	300	60	9.9

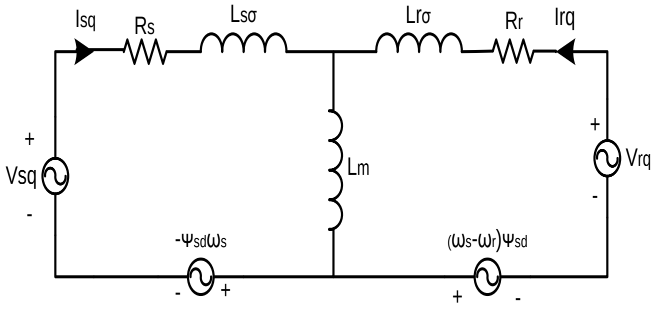
With increasing penetration, wind farms will have major impact in India power system. So, the behaviour of wind farms should tend to be same as conventional power plants. Staying connected during system fault is that step towards that direction.

3. Mathematical modelling of DFIG

The mathematical model of the DFIG is represented using the synchronously rotating reference frame (dq-frame) as shown in Figure 3.



(a) *d*-axis equivalent circuit



(b) q-axis equivalent circuit
Figure 3. Equivalent circuit of DFIG in the synchronous reference frame

$$V_{ds} = R_s I_{ds} - \omega_e \psi_{qs} + \frac{d}{dt}\psi_{ds} \quad (1)$$

$$V_{qs} = R_s I_{qs} - \omega_e \psi_{ds} + \frac{d}{dt}\psi_{qs} \quad (2)$$

$$V_{dr} = R_r I_{dr} - (\omega_e - \omega_r)\psi_{qr} + \frac{d}{dt}\psi_{dr} \quad (3)$$

$$V_{qr} = R_r I_{qr} + (\omega_e - \omega_r)\psi_{dr} + \frac{d}{dt}\psi_{qr} \quad (4)$$

where V_{ds}, V_{qs}, V_{dr}, V_{qr} are the d and q-axis stator and rotor voltages, respectively. I_{ds}, I_{qs}, I_{dr}, I_{qr} are the d and q-axis stator and rotor currents, respectively. ψ_{ds}, ψ_{qs}, ψ_{dr}, ψ_{qr} are the d and q-axis stator and rotor fluxes, respectively. ω_e is the angular velocity of the synchronously rotating reference frame. ω_r is rotor angular velocity, R_s and R_r are the stator and rotor resistances, respectively. The flux linkage equations are given as:

$$\psi_{ds} = L_s I_{ds} + L_m I_{dr} \quad (5)$$

$$\psi_{qs} = L_s I_{qs} + L_m I_{qr} \quad (6)$$

$$\psi_{dr} = L_r I_{dr} + L_m I_{ds} \quad (7)$$

$$\psi_{qr} = L_r I_{qr} + L_m I_{qs} \quad (8)$$

Where, L_s, L_r and L_m are the stator, rotor, and mutual inductances, respectively, with $L_s = L_{ls} + L_m$ and $L_r = L_{lr} + L_m$: L_{ls} being the self-inductance of stator and L_{lr} being the self-inductance of rotor. The reactive and active power of the stator and rotor are expressed in d and q reference frame as follows:

$$P_s = 1.5(V_{sd} I_{sd} + V_{sq} I_{sq}) \quad (9)$$

$$Q_s = 1.5(V_{sq} I_{sd} - V_{sd} I_{sq}) \quad (10)$$

$$P_r = 1.5(V_{rd} I_{rd} + V_{rq} I_{rq}) \quad (11)$$

$$Q_r = 1.5(V_{rq} I_{rd} - V_{rd} I_{rq}) \quad (12)$$

4. Control of rotor side converter (RSC)

The active and reactive powers which are delivered from the DFIG to the grid are controlled by means of controlling the rotor currents of the DFIG. The operation of rotor side controller is shown in Figure 4. [12][13]

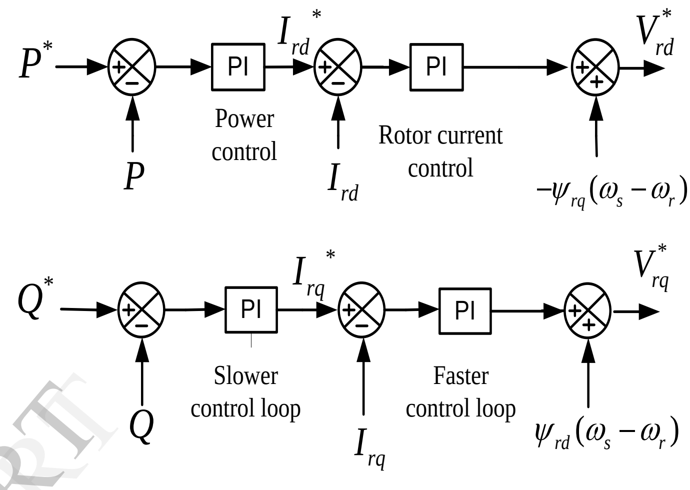


Figure 4. DFIG Rotor side converter control structure

In Stator Voltage Orientation (SVO), neglecting the stator resistive voltage drop, the active and reactive powers of the stator and rotor are expressed as,

$$P_s = 1.5\frac{L_m}{L_s} V_{sd} I_{rd} \quad (13)$$

$$Q_s = 1.5\frac{V_s}{L_s}\left(\frac{V_s}{\omega_s} + \frac{L_m}{L_s} I_{rq}\right) \quad (14)$$

$$P_r = 1.5(V_{rd} I_{rd} + V_{rq} I_{rq}) \quad (15)$$

$$Q_r = 1.5(V_{rq} I_{rd} - V_{rd} I_{rq}) \quad (16)$$

From the above equations, it is obvious that power fed to the grid can be controlled by controlling the rotor current's components. [14][15] The rotor current components can be controlled by the vector control techniques.

5. Control of grid side converter (GSC)

The purpose of the grid-side converter is to keep the constant DC link voltage irrespective of the direction of the rotor power flow. In order to maintain the DC link voltage constant, a bidirectional converter is required to implement in the circuit connected rotor side. [15][16] This converter work as a rectifier below the synchronous speed and above synchronous speed this converter works as an inverter to supply all generated power to the grid at a constant DC link voltage.

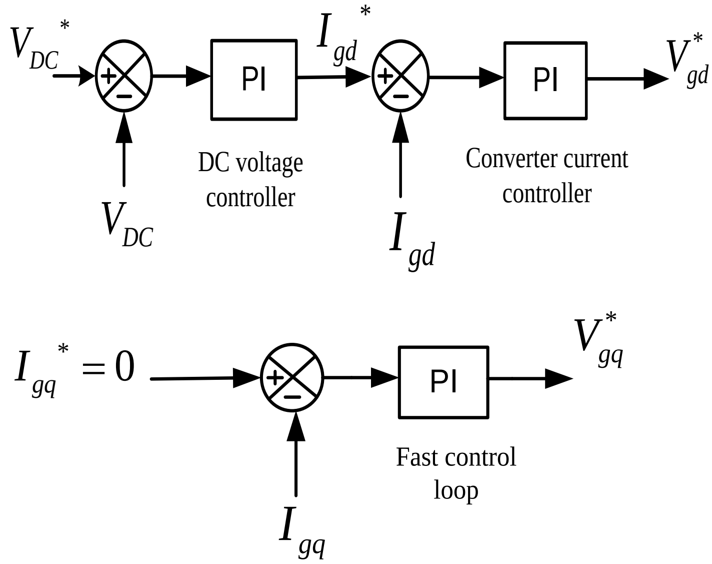


Figure 5. DFIG Grid side converter control structure

Sinusoidal pulse width modulation technique is used to generate the switching pulses for back to back converters. Also the main function of GSC is to compensate the reactive power with respect to their reference value.[17]

6. Simulation Results with Discussion

The proposed model is used to simulate under the three phase symmetrical fault condition. When three phase fault occurs at 132KV Bus, the voltage sag at 690V will depend on the percentage impedance drop of DFIG.

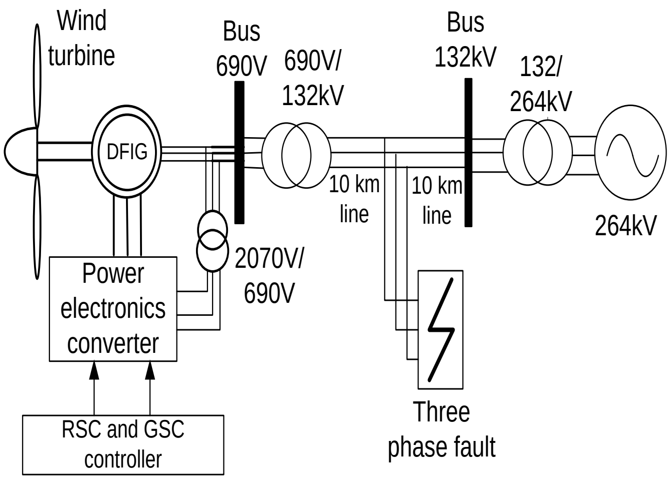


Figure 6 Proposed DFIG model connected to faulty grid

Using the software package MATLAB/Simulink is used to simulate the WPGS under normal and faulty condition as shown in Figure 6. The DFIG is rated at 2 MW, and its parameters are given in the Appendix.

Case I – Simulated DFIG during normal condition

In this case, the dynamic behavior of the variable speed wind turbine (VSWT) is analyzed under normal condition. This study of the results proves that the control strategy developed in this technique is well performed. The nominal converter dc link voltage was set at 1380 V, and the switching frequencies for both converters were 50MHz. The main objective of the grid side converter is to control the dc link voltage, and it has been controlled using a similar method as for the dc voltage controller in a voltage source converter (VSC) transmission system.

During the simulation, the grid side converter was triggered first to regulate the converter dc-link voltage. The DFIG stator was then energized with the rotor rotating at a fixed speed and the rotor side converter was disabled. When RSC is enabled, it has controlled the active and reactive power of generator using SVO strategy.

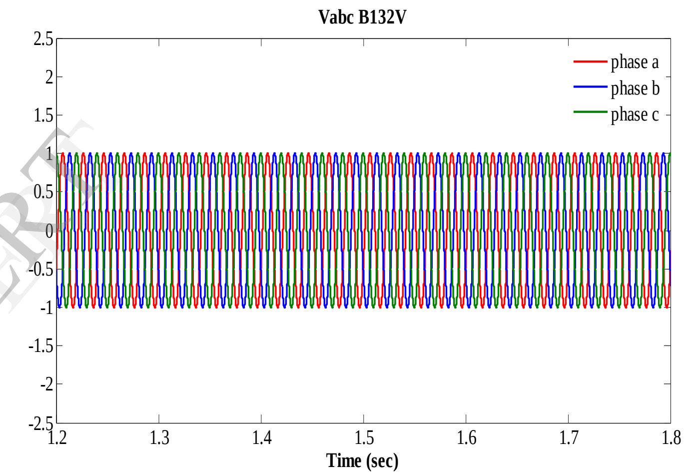


Figure 7. Three phase voltage at bus 132 kV in per unit

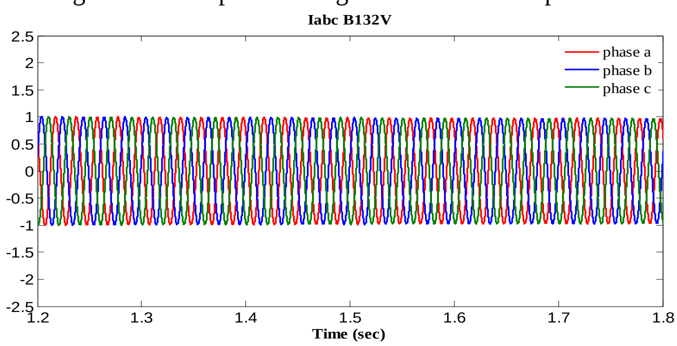


Figure 8. Three phase current at bus 132 kV in per unit

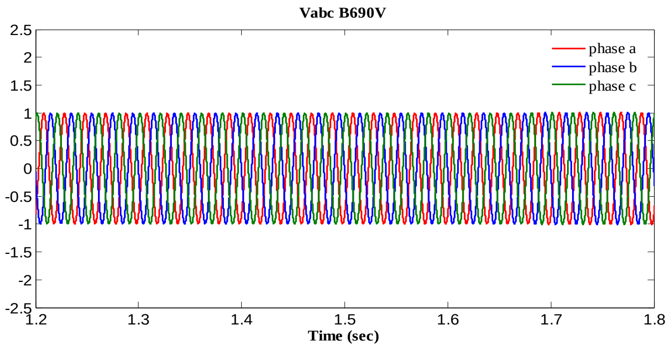


Figure 9. Three phase voltage in per unit at bus 690 V

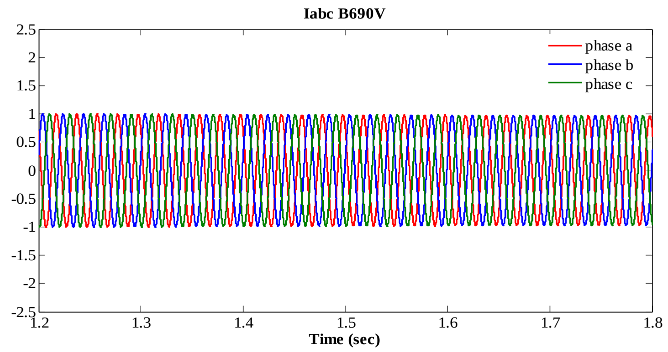


Figure 10. Three phase current in per unit at bus 690V

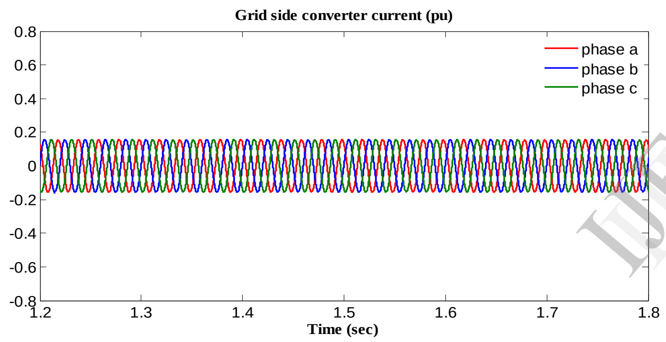


Figure 11. Three phase grid side converter current in per unit fed to grid

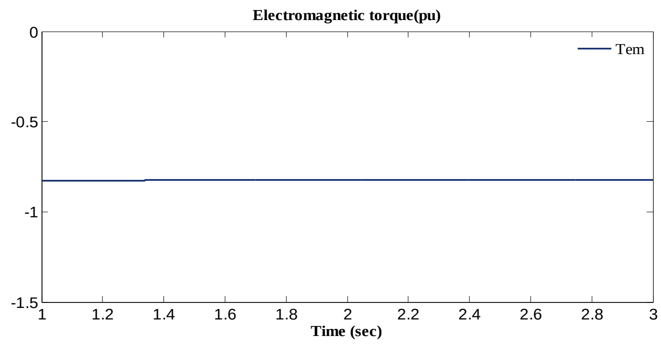


Figure 12. Electromagnetic torque during normal condition in per unit

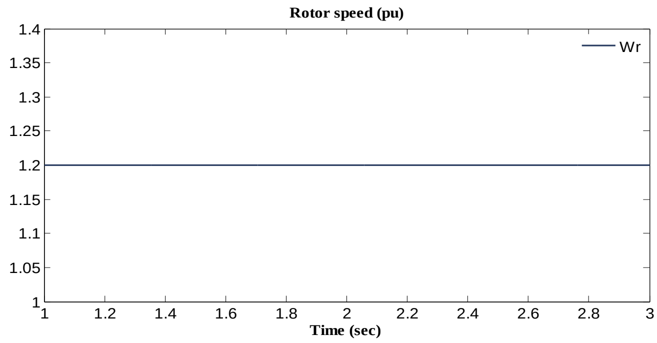


Figure 13. Rotor speed in per unit

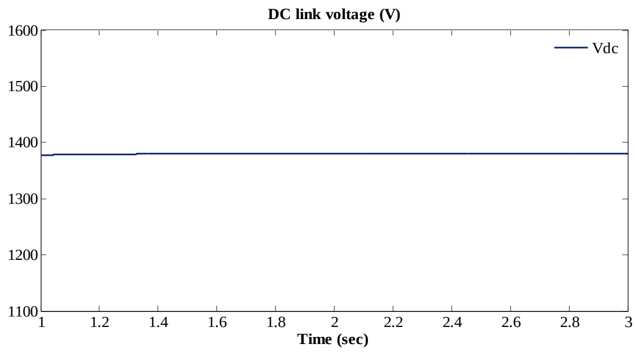


Figure 14. DC-link voltage during normal condition in volt

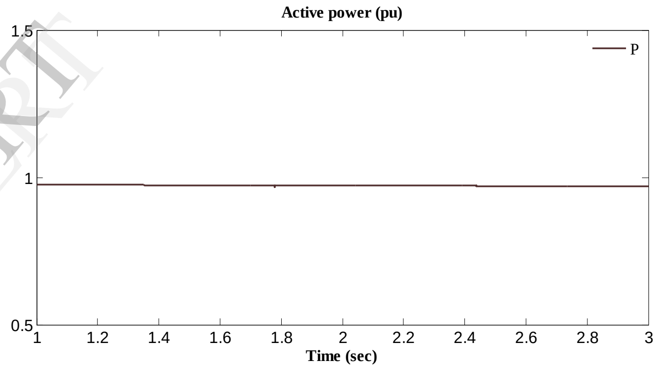


Figure 15. Total active power during normal condition in per unit

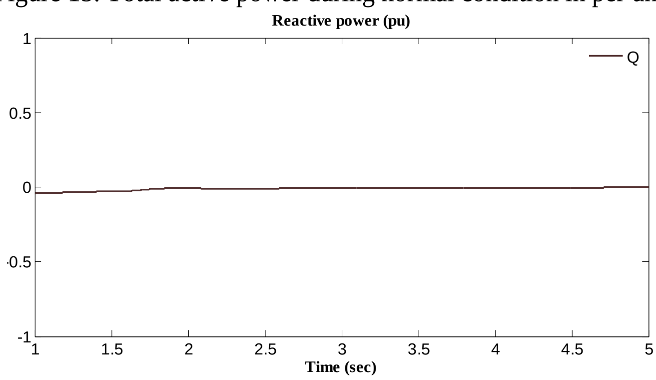


Figure 16. Total reactive power during normal condition in per unit

A DFIG system connected to a grid using 132kV transmission line with 20km length. The three phase voltage and current of transmission line is shown in Figure 7 and Figure 8. Also the three phase voltage and current waveform (Figure 9 and Figure 10) at bus 690V is shows that, WPGS is worked properly in normal condition. In Figure 5, it can be seen that the DC voltage control loop is compensating the error between reference and actual value accordingly (Figure 14). Figure 15 and Figure 16 shows the active and reactive power generated by DFIG, and hence proves that the wind power generation system works as a unity power factor.

Case II – Simulated DFIG during three phase symmetrical fault condition

A three phase fault block is connected in centre of the transmission line with 30 ohm fault resistance. It generates the 60% dip on three phase voltage waveform at 132kV bus (Figure 17).

It can be seen that the effect of voltage dip on transmission line affects the three phase current at 132 kV bus and the voltage at 690V bus (Figure 18 and Figure 19).

The reference value for GSC is made to change suddenly; as a result, it has been tracked by the actual parameters of generator. Hence, the GSC started injecting reactive power soon after a fault is initiated in the network (Figure 26).

The DC link transient is also slightly increased, due to the reactive power prioritization of the GSC as shown in Figure 24.

The fault duration inserted in transmission line is 0.3 sec as shown in results, which is removed in 1 sec. According to IWGC, the proposed model is able to withstand during faulty duration. Hence the proposed control strategy works properly in both normal and three phase fault condition.

During faulty condition, the sudden increment of rotor current Figure 21 affects the back to back converters of lower rating, hence some protection system is needed to handle this situation.

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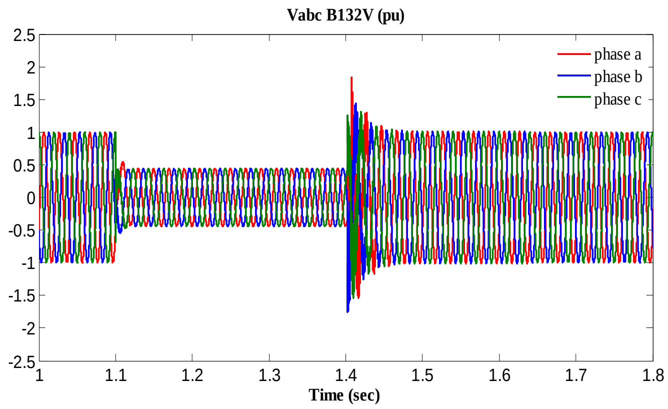

Figure 17. Three phase voltage at bus 132 kV during faulty condition

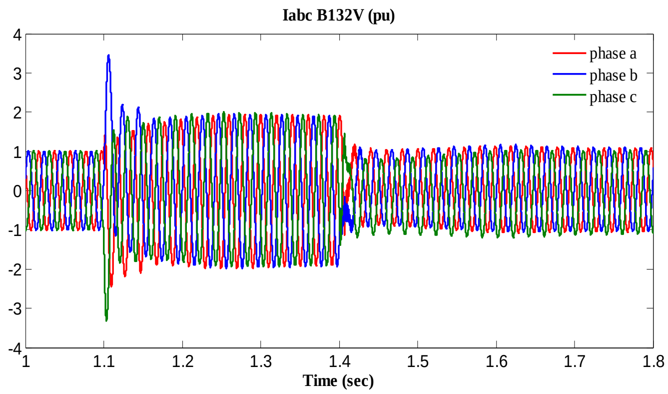

Figure 18. Three phase current at bus 132kV during faulty condition

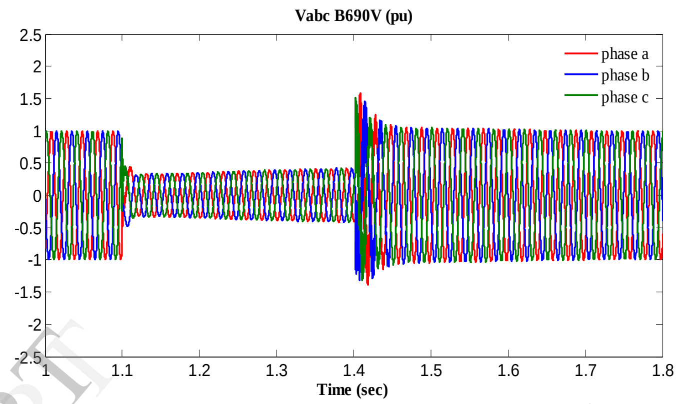

Figure 19. Three phase voltage at bus 690V during faulty condition

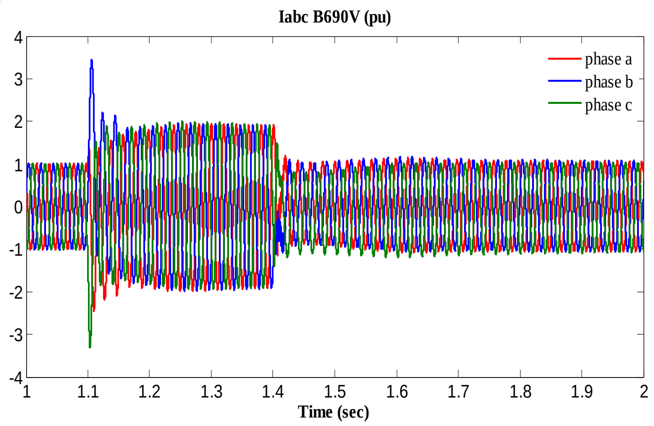

Figure 20. Three phase current at bus 690V during faulty condition

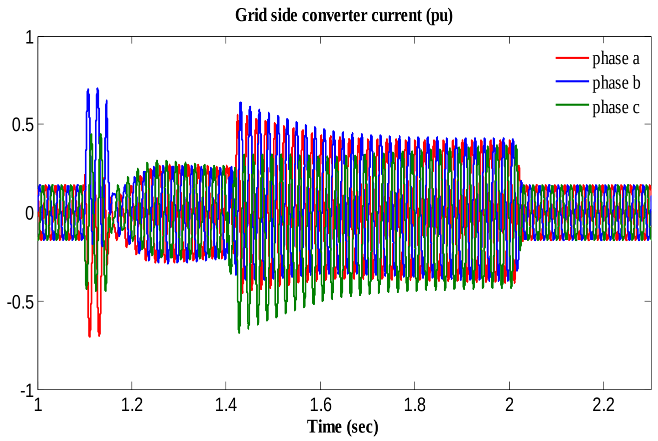

Figure 21. Three phase grid converter current during faulty condition

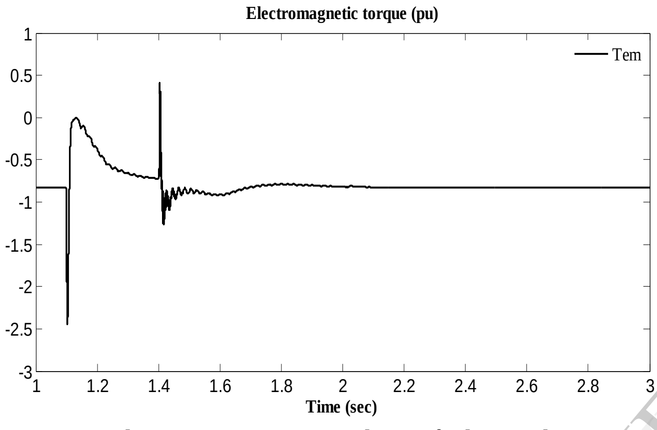

Figure 22. Electromagnetic torque during faulty condition

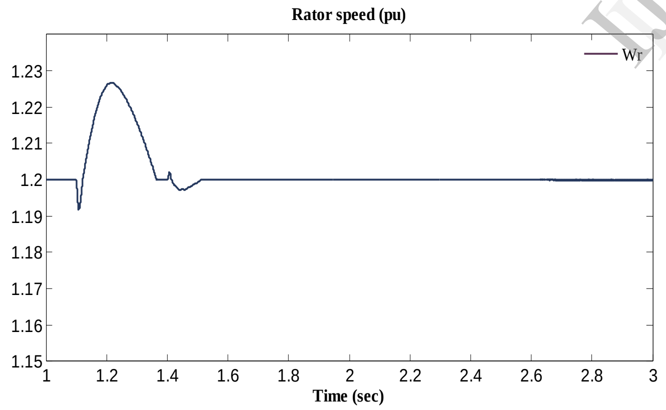

Figure 23. Rotor speed during faulty condition

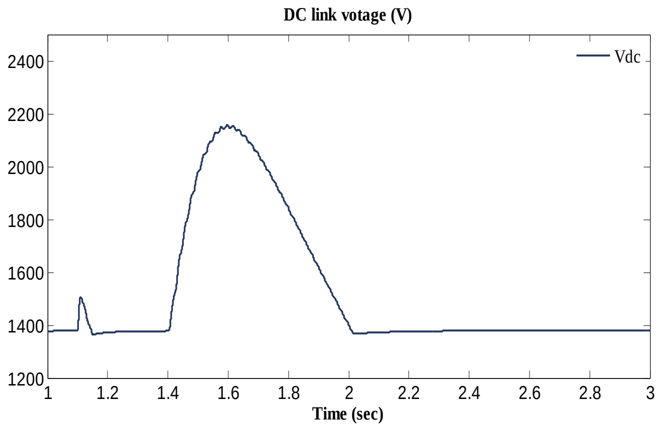

Figure 24. DC link voltage during faulty condition

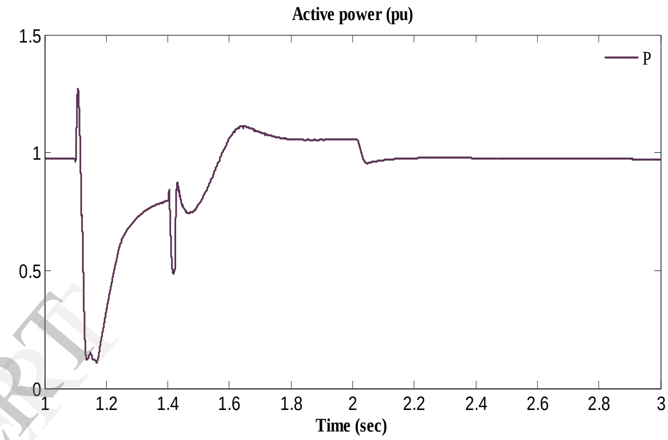

Figure 25. Total active power during faulty condition

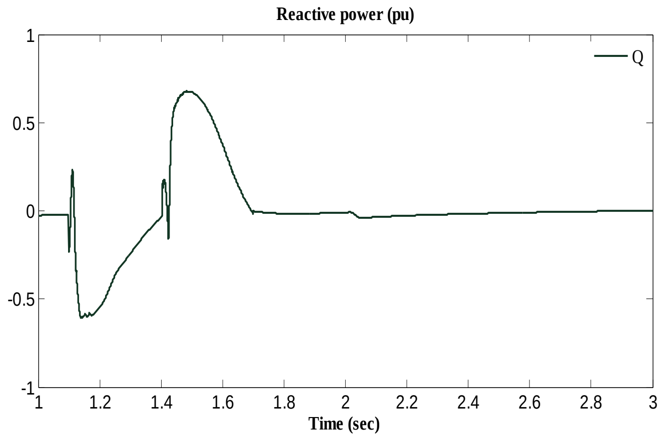

Figure 26. Total reactive power during faulty condition

7. Conclusion

The response of DFIG wind turbine under normal and its dynamic response to voltage sag have been shown. The MATLAB/SIMULINK software package is used to simulate the proposed WPGS system. The results of normal condition are presented, and prove the decoupled control of active and reactive power of generator using field oriented control concept. The SVO based RSC and GSC controller is performed well, and provides the unity power factor. It has been observed that under normal condition, 20-30% power is flowing through the rotor circuit of DFIG.

In view of the voltage dip on transmission line, the developed DFIG model can be applied to investigate the dynamic behavior of generator voltage and currents and the variation in the total active/reactive powers as well as electromagnetic torque. After 1sec, the three phase fault causing the voltage dip on the 690V bus bar is cleared then the wind turbine is operated under the normal condition and produces the nominal active power and the reactive power which is maintained to be zero. It concludes that SVO strategy increases the low voltage ride through capability of machine and is acceptable for IWGC without tripping. This has also been discussed that under normal condition the converter power rating will be around twenty five percent to rated power and ensures the unity power factor operation of DFIG.

APPENDIX A

TABLE 2.PARAMETERS OF WIND TURBINE

Nominal Mechanical Output Power	1.8MW
Cut-in wind speed	6m/s
Base wind speed	12m/s
Cut-out wind speed	18m/s
Base rotational wind speed	1.2pu
Maximum power at base wind speed	1pu

TABLE 3. PARAMETERS OF THE DFIG SIMULATED

Rated Power	2MW
Stator Line-Line Voltage	690Vrms
No. of Pole pair	3
Operating frequency	50
Stator resistance, (R_s)	0.0108pu
Stator leakage inductance,($L_{s\sigma}$)	0.102pu
Rotor resistance, (R_r)	0.0121pu
Rotor leakage inductance, ($L_{r\sigma}$)	0.11pu
Mutual inductance, (L_m)	3.362pu
Inertia constant , (H(s))	0.5
Friction factor, (F)	0.01pu

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