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Performance Analysis and Limitations of Grid Connected DFIG Wind Turbine under Voltage Sag and 3-Phase Fault

[1]Shilpa Mishra, Sandeep Shukla[2], Shimi.S.L.[3]
[1]*Department of Electrical Engineering NITTTR, Chandigarh, India*
[2]*Department of Electrical Engineering RGIPT, Raebareli, India*
[3]*Department of Electrical Engineering NITTTR, Chandigarh, India*

Abstract:- Wind energy is a notably precious renewable resource, for the production of electrical energy. It offers electrical power without much environmental shortcomings. In this paper initially, the performance of DFIG with variable speed wind turbine under normal and faulty (40% sag) condition is studied using simulation developed in MATLAB/SIMULINK. Results illustrate the transient behaviour of the Double Fed Induction Generator when a sudden 3-phase fault occurs at the grid. After the clearance of the grid fault, the control schemes manage to restore the normal operation of turbines. the controller performance is demonstrated by simulation results during fault and at the clearance of the fault. A critical assessment of the transient behaviour of the double fed induction generator has been performed for grid side faults.

Index Terms:— Doubly-fed induction generator, wind turbine, wind energy, current control, voltage sag**.**

I. INTRODUCTION

Wind based electrical energy generation is becoming a very attractive means to meet the growing electricity demand globally, owing to its cost effectiveness and being environmentally clean and safe [1], [2]. DFIG offers several advantages when compared with fixed speed generators including speed control. Using rotor side converter control these goals already has been achieved.

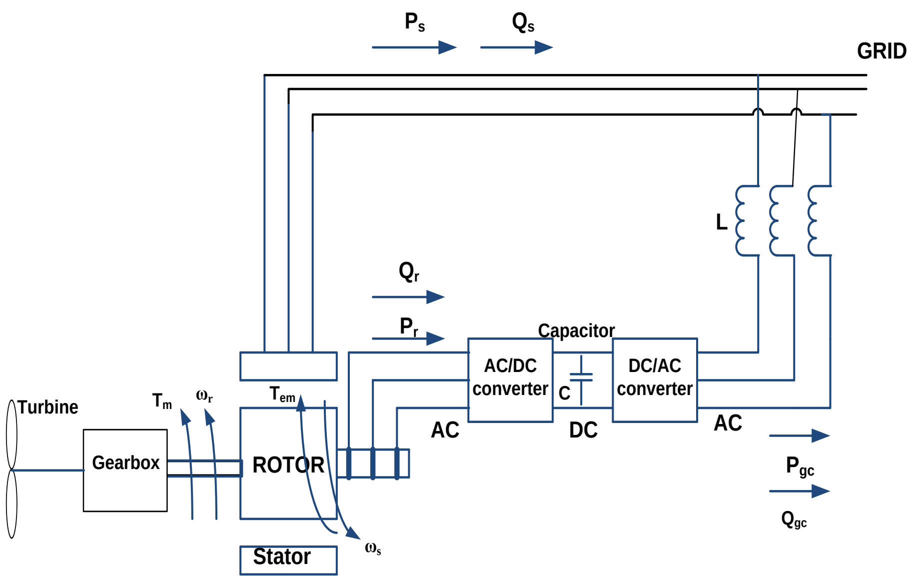

Fig.1 Variable Speed Wind Turbine with DFIG

Many concepts have been proposed for studying the behaviour of DFIG based wind turbine system connected to the grid. With the development of wind power; the interaction between wind turbine and grid will cause new problems about the safe and reliable operation of systems. One issue not paid enough attention is how to adjust the network protection schemes when the wind plant inserted to the system. As far as the protection is concerned, the basic challenge is the understanding the characteristics of wind generator short circuit current.

In this paper the performance study of a three level inverter-fed vector controlled wind turbine DFIG under normal and faulty condition has been simulated. Basic Operation and control strategy used for simulation and performance analysis is presented in section-II. Simulated system and important results are given in section III and IV

II. OPERATION AND CONTROL OF DFIG

A simplified block diagram of a wind energy conversion system using DFIG is illustrated in Fig.1. It consists of a wind turbine, a gearbox, doubly-fed induction generator, and a rotor side converter and a grid side converter. The DFIG stator winding is directly connected to the grid whereas its rotor windings are connected by a back-to-back three level voltage source converters [3-7]. By controlling the rotor and grid side converters, the DFIG characteristics can be adjusted so as to achieve maximum of effective power conversion or capturing power [12]. These Converters are usually controlled by utilizing vector control techniques [1], capability for a wind turbine and to control its power flow from DFIG to grid with less fluctuation. In normal operation the aim of the machine side converter is to control independently the active and reactive power, while the grid side converter is used to keep the dc-link capacitor voltage at a set value regardless of the magnitude and the direction of the rotor power and to guarantee a converter operation with unity power factor (zero reactive power) [14]. Many different d-q vector control algorithms have been proposed and used for controlling the DFIG machine and grid-side converters for obtaining certain dynamic and transient performance of DFIGs.

The control configuration of the considered system is usually divided into machine (rotor) and grid-side converter controls. The rotor-side converter controls the active and reactive power of the DFIG independently, and the grid-side converter is controlled in such a way as to maintain the dc-link capacitor voltage in a set value and to maintain the converter operation with a desired power factor i.e. unity power factor [8-11].

A. Machine-Side Converter Control (MSC)

The main task of the machine side converter is to control the machine i.e., active and reactive power of the DFIG. 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 [1].

B. Grid-Side Converter Control (GSC)

The objective of the grid-side converter is to keep the dc link voltage constant irrespective of the direction of the rotor power flow. In order to keep the dc link voltage constant, a bidirectional converter is required to implement in the rotor side circuit. It is also a two stage controller operating in a grid AC voltage reference frame.

III. OPERATION OF DFIG UNDER FAULT

The DFIG generator has a three-phase wound rotor, which was supplied by a pulse width modulation (PWM) converter. When a fault occurs, the transient process was not only determined by machine itself but also the outer exciting system. So the waveform of fault current has variety. Only use of theory analysis was hard to describe the characteristic of fault current. As far as the protection concerned, the fundamental study is to understand the characteristics of the wind generator short-circuit current.

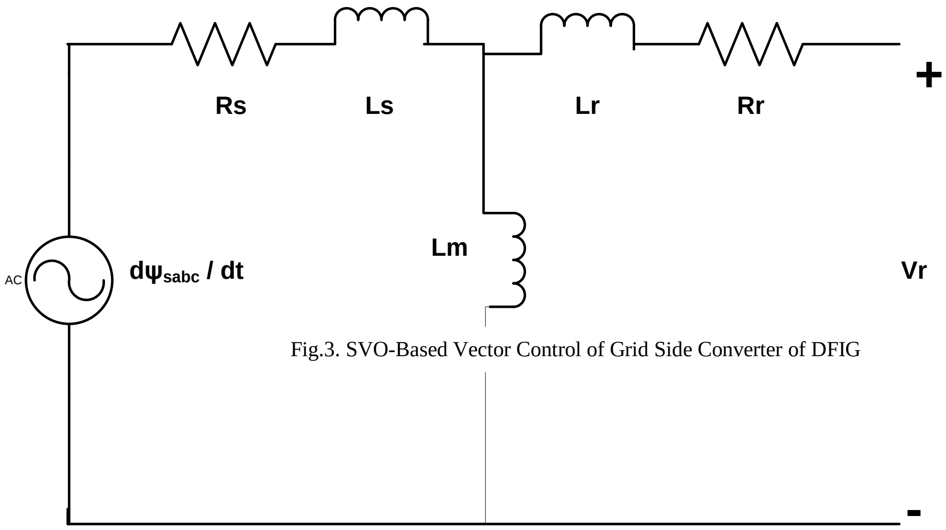

Fig.2 Rotor Side Equivalent Circuit

Thus the main objectives of the control system during network fault should be to limit the fluctuation of active and reactive power from DFIG to the grid and at the same time to limit the DC over voltage. The voltage drop depends, of course, on the location of the fault. The rotor current then increases to attempt to maintain the flux linkage within the rotor windings constant. DFIG under fault can be shown in fig. 3. However, for a DFIG the increase in the rotor current immediately after a fault will be determined by two factors. The first is the change in the stator flux and the second is the change in the rotor injected voltage.

In DFIG based system, the stator voltage and flux starts changing (reduces for dip) on the occurrence of a fault, the voltage at the DFIG generator terminal drops and it leads to a corresponding decrease of the stator and rotor flux in the generator. This results in a reduction of the electromagnetic torque and active power [25], depending on the severity of the fault. In the fault moment, as the stator voltage decreases significantly, high current transients appear in the stator and rotor windings [26], [27]. In order to compensate for the increasing rotor current, the rotor side converter increases the rotor voltage reference [26], which implies a "rush" of power from the rotor terminals through the converter. In an attempt to maintain rotor flux linkage, the rotor current increases.

The rotor side equivalent circuit of a DFIG under 3-phase short circuit fault is shown in Fig.2. Before the fault occurs, the voltage on the rotor side induced by stator-flux was Vs, the value is $j_s\omega_s\psi_{sabc}$, where s is the slip and ω_s is the synchronous angular speed. The exciting voltage is $V_r = sV_s$. When the fault occurs, the stator terminal voltage reduces to zero and the stator-flux stop to rotate, but the rotor was still rotating with the speed of $(1 - s)\ \omega_s$. Therefore, the induced voltage $d\psi_{sabc}/dt$ will became $j(1 - s)\psi_{sabc}$ [21]. In this situation, the exciting current cannot sustainable in fault period. In another situation, the converter which has big rating could provide the relatively large voltage to counteract the induced voltage, then the converter may connected to rotor and still offered the stable exciting current in the fault [20-22]. So the state of exciting current was mainly determined by the transient induced voltage, the converters rating, its control strategy, and the settings of crowbar protection [21]. Therefore, waveform and amplitude of rotor current may be significantly different for different fault levels.

Grid side converter is typically controlled using vector control strategy with the grid voltage orientation [28].

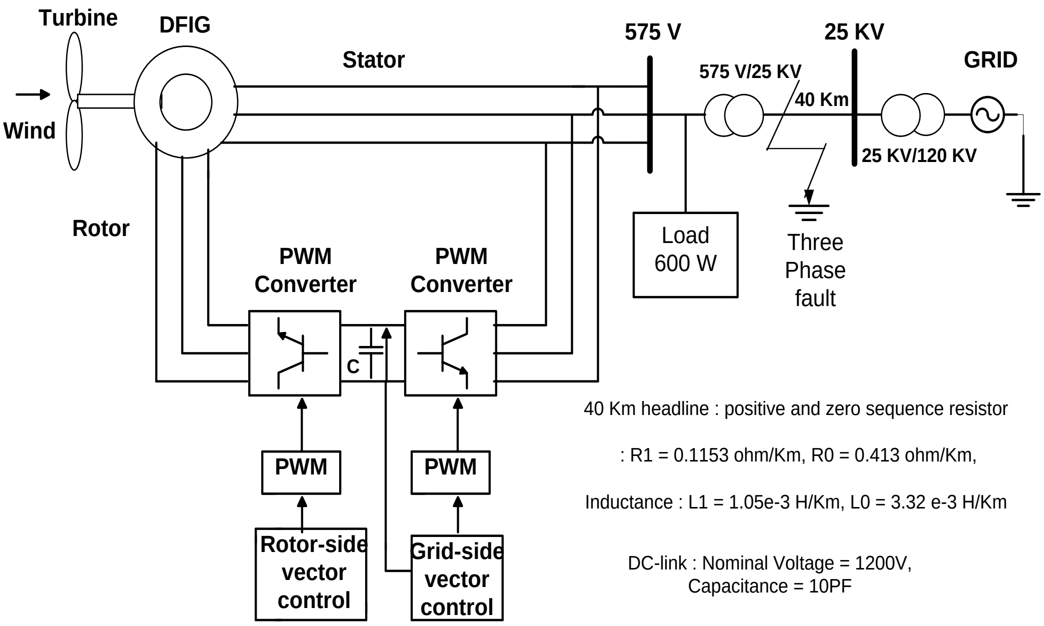

Fig. 3 Schematic of Simulated DFIG System under Grid Fault Condition

The component of axis voltage is zero and fixed with that of grid voltage space vector orientation. Hence, the active and reactive power of the grid-side converter [28] can be expressed as

$$P_g = V_{gd} I_{gd} \tag{15}$$

$$Q_g = -V_{gd} I_{gq} \tag{16}$$

Here, V_{gd} stands for the d- axis component of grid voltage I_{gq} and I_{gd} are the q-axis and d-axis components of grid current, respectively.

In DFIG, the power flow is bidirectional and is between rotor and grid side converters. If power losses in power electronic devices [30] are ignored, then for a constant dc-link voltage, the input power from the grid side should be equal to the input power of the rotor.

$$P_{gc}= V_{ga}I_{ga}+ V_{gb}I_{gb}+ V_{gc}I_{gc}= V_{gd}I_{gd} = V_{ra}I_{ra}+V_{rb}I_{rb}+ V_{rc}I_{rc}= P_{rc} \quad (17)$$

Where, V_{ga},V_{gb},V_{gc} are the three phase instantaneous grid voltages, I_{ga}, I_{gb}, I_{gc} are the instantaneous grid currents and P_{gc} is the instantaneous grid side converter input power. Whereas V_{ra}, V_{rb}, V_{rc} are the three phase instantaneous DFIG rotor voltages, I_{ra}, I_{rb}, I_{rc} are the instantaneous rotor currents, and P_{rc} is the instantaneous rotor input power.

When this bidirectional power is changed dynamically between the grid-side converter and the rotor-side converter [28-30], the instantaneous power of the dc-link capacitor may be given as,

$$P_c= V_{dc}I_c=CV_{dc}dV_{dc}/dt \quad (18)$$

Consequently, keeping in mind the condition of instantaneous power balance [29], the power, P_{gc} is equal to the sum of the instantaneous input rotor power P_{rc} and P_c, i.e.,

$$CV_{dc}\, dV_{dc}/dt= P_{gc}- P_{rc} = V_{gd}I_{gd}-(V_{ra}I_{ra}+ V_{rb}I_{rb}+ V_{rc}I_{rc}) \quad (19)$$

Assuming constant Vgd under normal condition, the variation in dc-link capacitor voltage is calculated by the d-axis component of grid current, I_{gd}, and the instantaneous power, P_{rc}.

If there is a sudden change in the grid voltage due to fault or any other abnormalities, the power balance is lost, which will cause the dc-link capacitor current and voltage to fluctuate as can be inferred from equation (11) -(15). In addition, the rotor current will also experience sudden changes, but as the dynamic response of outer dc-link voltage control loop is far slower compared to the response of inner current control loop, the grid side converter will not be able to transfer sufficient amount of instantaneous energy to the rotor-side converter. To counter the power imbalances caused due to fault, the dc-link capacitor will discharge some of its stored energy to feed the rotor-side converter and therefore, dc link voltage will decline. Since, the rotor-side converter runs on energy feedback status and the grid-side converter cannot feed more instantaneous power back to the grid therefore, the dc-link voltage will increase due to the excessive instantaneous energy as per equation (11)-(15) [29]. Thus, during the dynamic regulation of DFIG, dc-link voltage may fluctuate due to imbalanced power flow between the input and output instantaneous energy of the converter and hence, causing degraded operation of the DFIG unit.

IV. SIMULATION RESULTS AND DISCUSSION

This section presents the simulation results for a vector control DFIG system under normal and grid fault condition. The test system shown in Fig.5 has been developed using in MATLAB/SIMULINK to demonstrate the effect of fault on DFIG. Performance of this test system under normal and different fault conditions has been tested.

A. Wind Turbine DFIG at Normal Condition

Fig.4-9 shows the DFIG under the standard working state; the total active power is equal to 45-50% of nominal power. The power flow is approximately 70-80% through the stator and 20-30% through the rotor. The DFIG wind turbine produces around 4.9 MW active power, corresponding to the mechanical turbine output for a 12 m/s wind speed. The resultant turbine speed is 1.093 pu (1328 rpm) of generator speed (1200 rpm). By using the SVO rotor side vector control scheme, the reactive power is kept at 0 MVAR, to sustain the stator at unity power factor; so that more power can be extracted from the stator side and only 20-30 % power can be extracted from the rotor side, ensuing in 30-40 % diminution in the machine rating. Due to reduction in the machine rating, outlay of the overall system is reduced. The rating of the converter is simply 20-30 % of the total power, so losses in the converters are condensed since the power handled by converters is barely a tiny proportion of total power. By SVO grid side converter control, the dc link voltage is maintained unvarying at 1200 V. Under customary operating state of affairs the active power, reactive power and dc link voltage are steadfast.

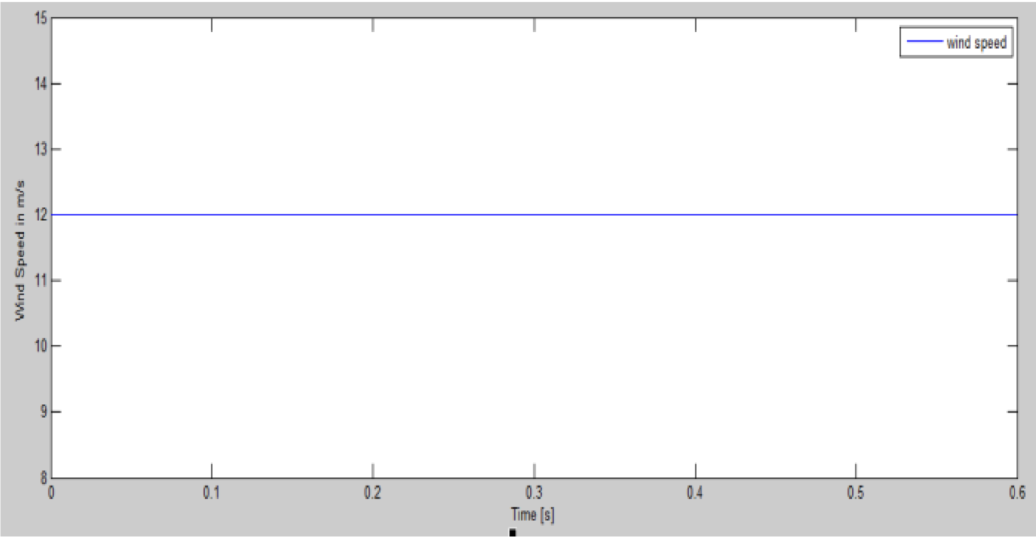

Fig. 4 Wind Speed in m/s

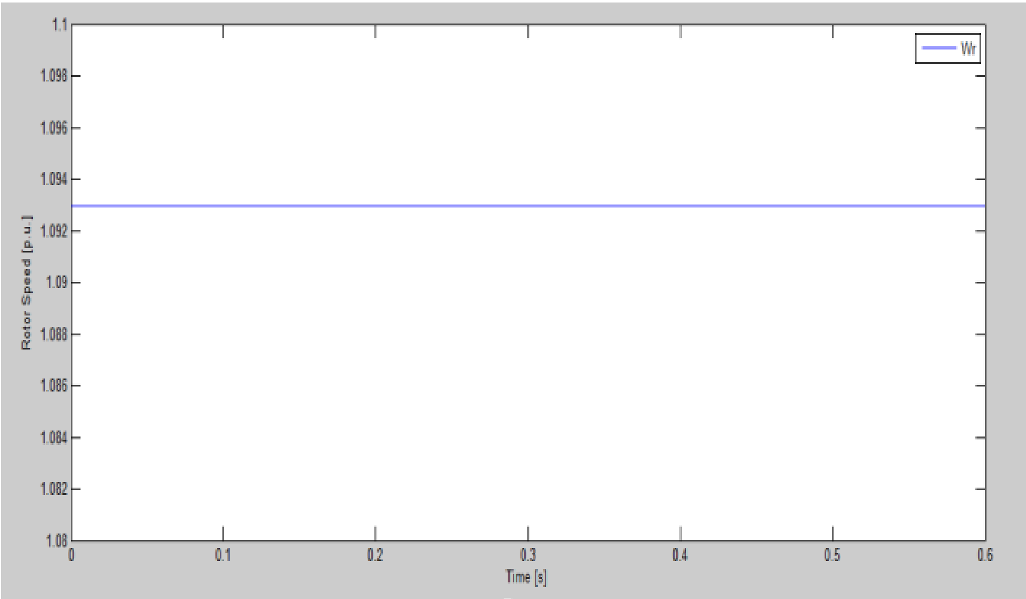

Fig.5. Rotor Speed under normal condition

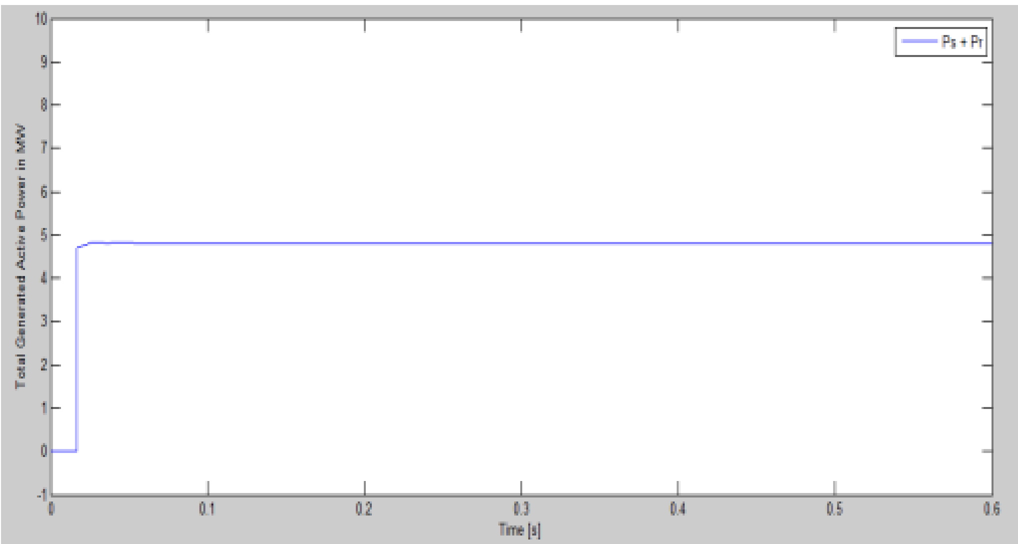

Fig.6. Total Active Power under normal condition

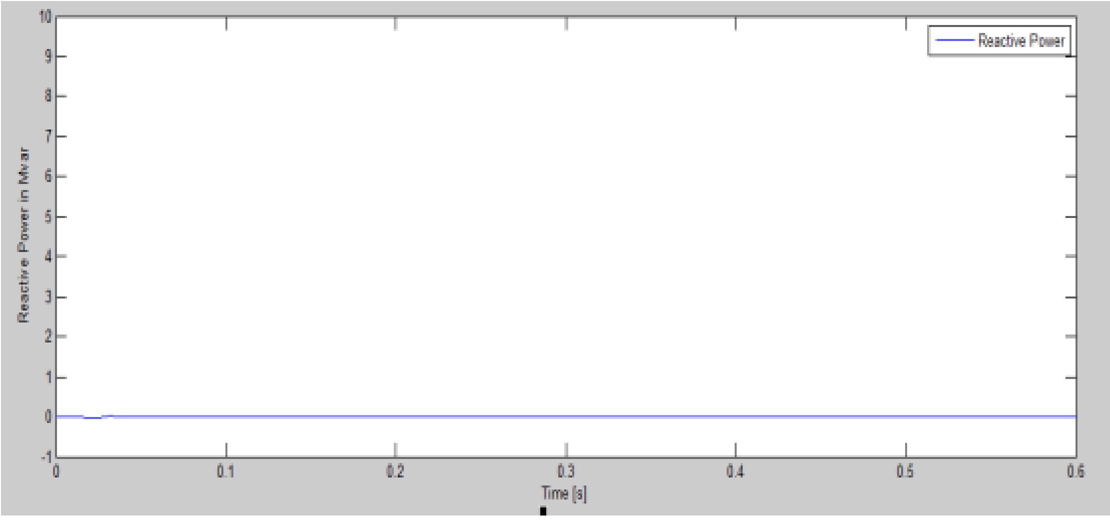

Fig.7. Reactive Power under Normal Condition

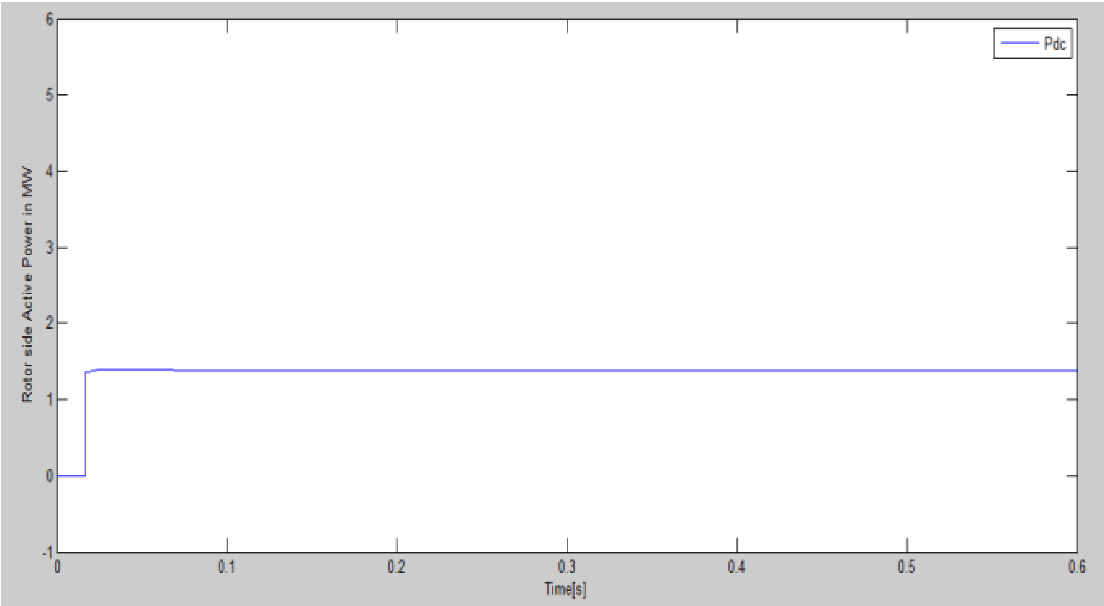

Fig.8. Rotor Active Power under Normal Condition

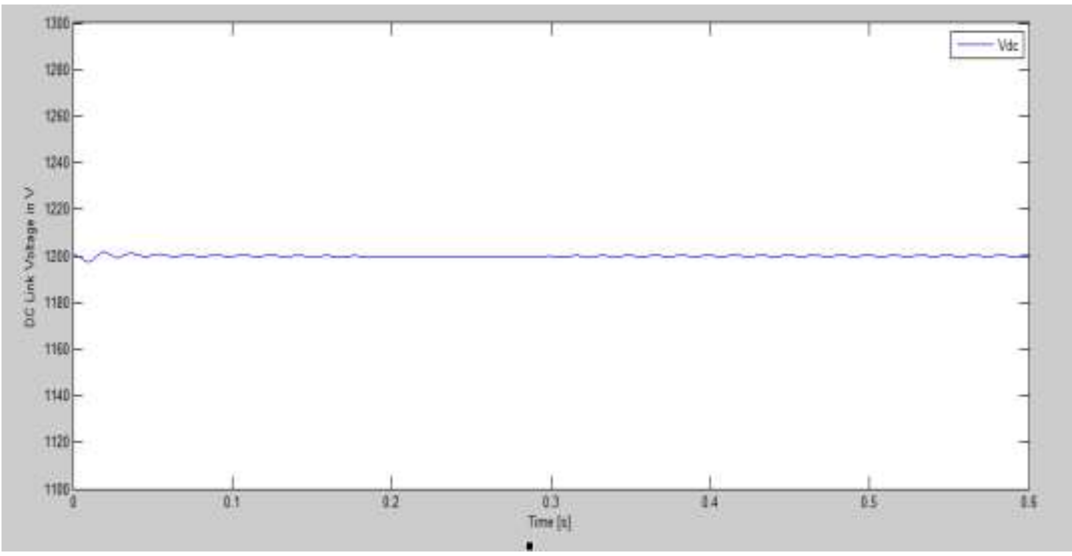

Fig.9. DC link Voltage under Normal Condition

B. Wind Turbine DFIG during Grid fault (Voltage dips to 40%)

When voltage drops down to around 40%, i.e. there is 40% sag, at 10 ms and after 130 ms the fault causing the voltage sag on the grid is cleared. The voltage starts to recover. For the duration of fault, active and reactive powers start fluctuating as rotor speeds up and down. Similarly, the dc link voltage fluctuates throughout sag.

From Fig.16, the maximum value of dc link voltage obtained is 1265 V whereas the rated set value is 1200 V. In this case the majority power flows through the rotor. This phenomenon might lead to the damage of the converters. Hence rotor protection is of paramount importance in case of majority fault condition. Since the dc link voltage varies in this case, there is considerable chance of damage to the capacitor

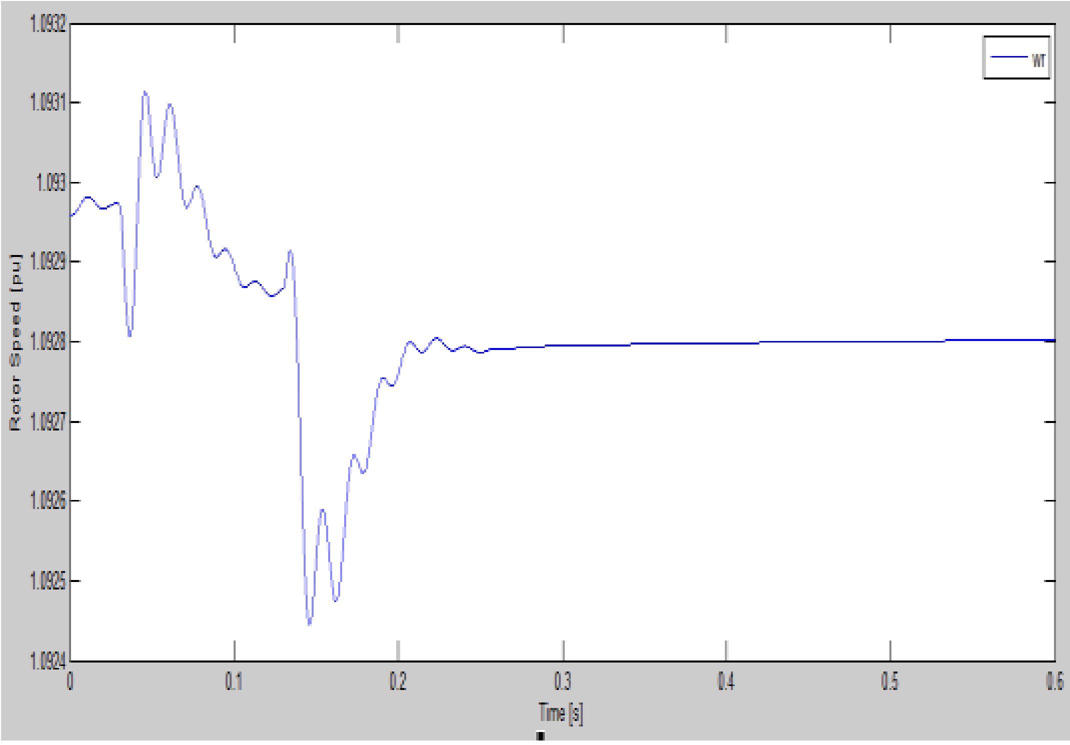

Fig.10. Rotor Speed under 40% Voltage Dip

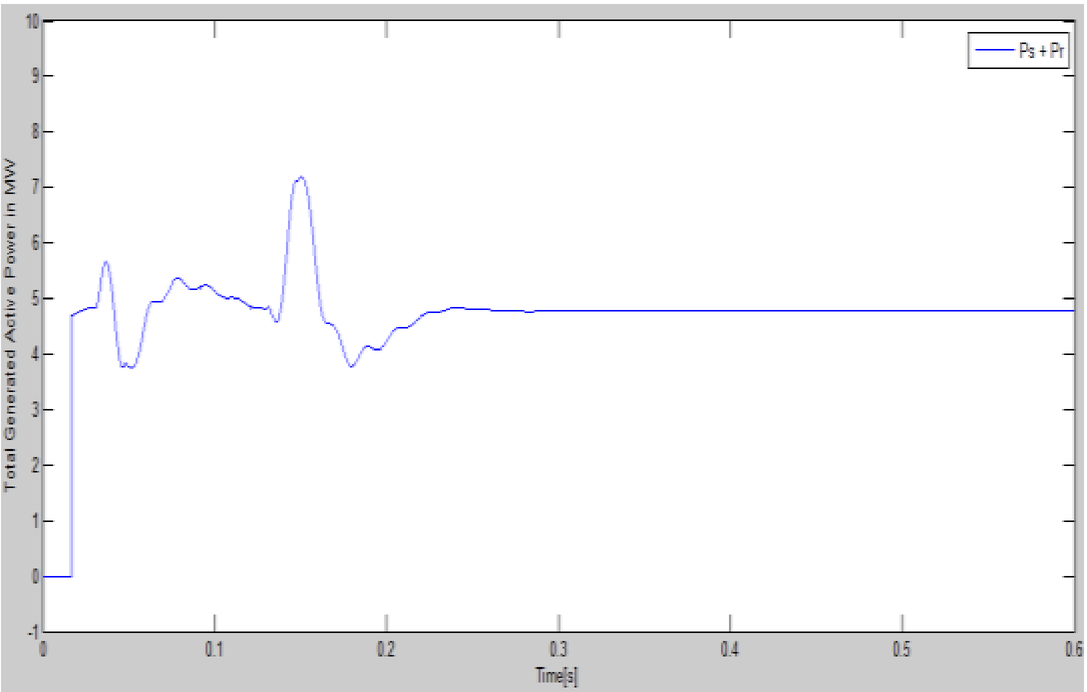

Fig.11. Total Active Power under 40% Voltage Dip

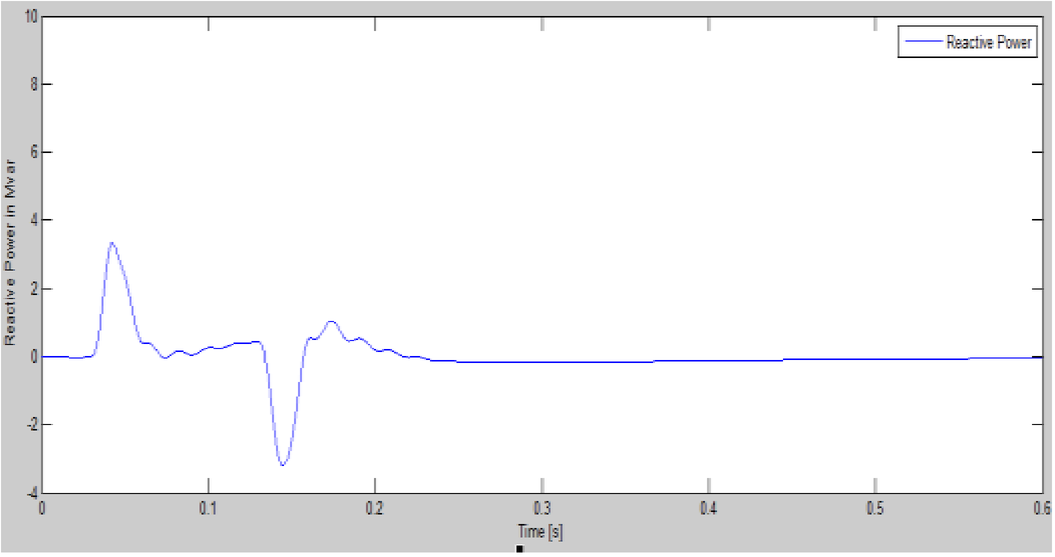

Fig.12. Reactive Power under 40% Voltage Dip

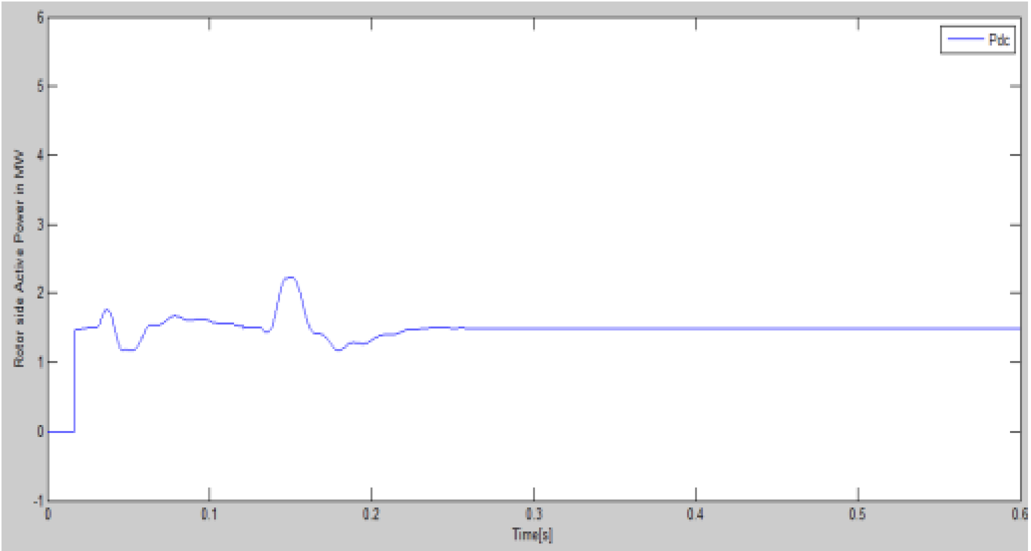

Fig.13. Rotor Active Power under 40% Voltage Dip

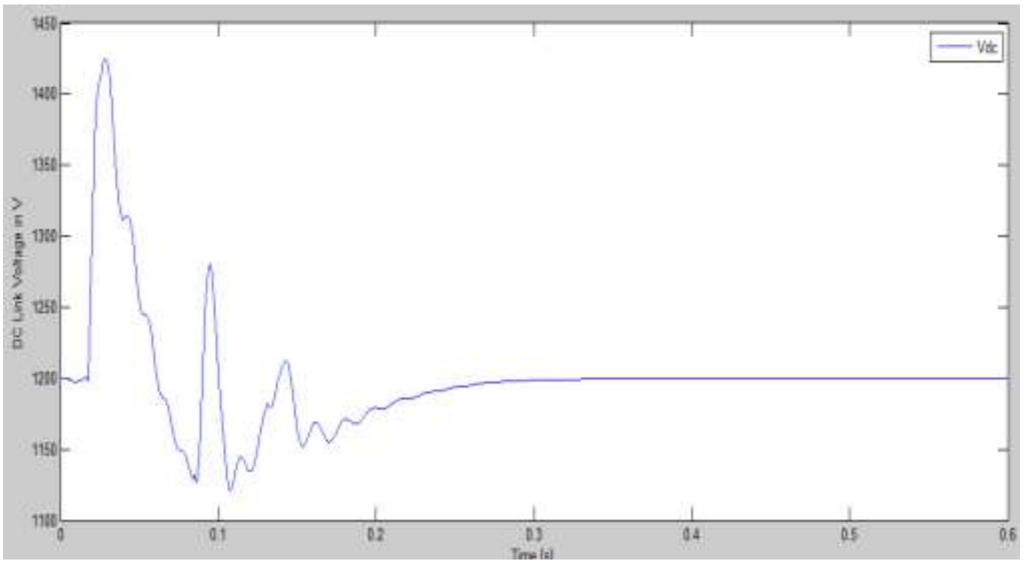

Fig.14. DC Link Voltage under 40% Voltage Dip

C. Wind Turbine DFIG with Three Phase Symmetrical Fault at 25 KV

When three phase symmetrical fault occurs at 10 ms at the wind farm busbar (25KV), and it is removed at 130ms, it causes the busbar (575 V) voltage drop down to 0.25pu (143.75 V). The fault location is at the high voltage side of the step-up transformer at the wind farm busbar. The drop in voltage at 575 V bus depends on the percentage impedance drop

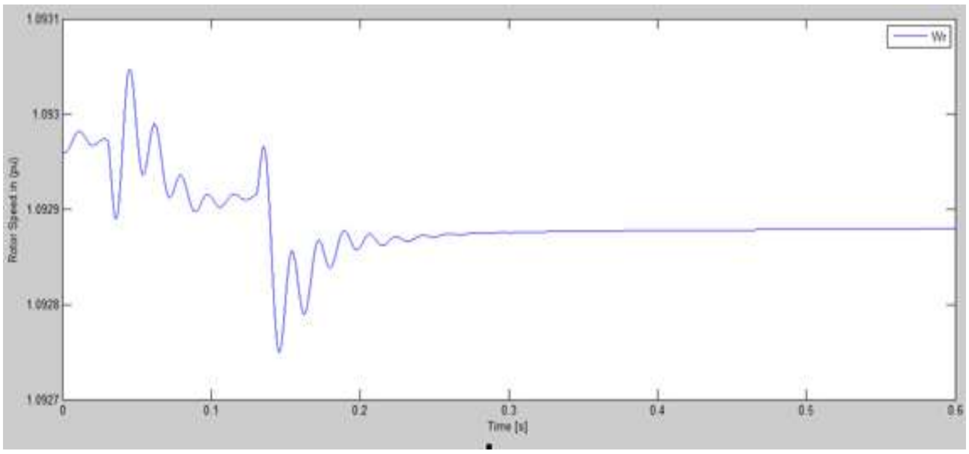

Fig.15. Rotor Speed under Three Phase Fault at 25 KV Bus

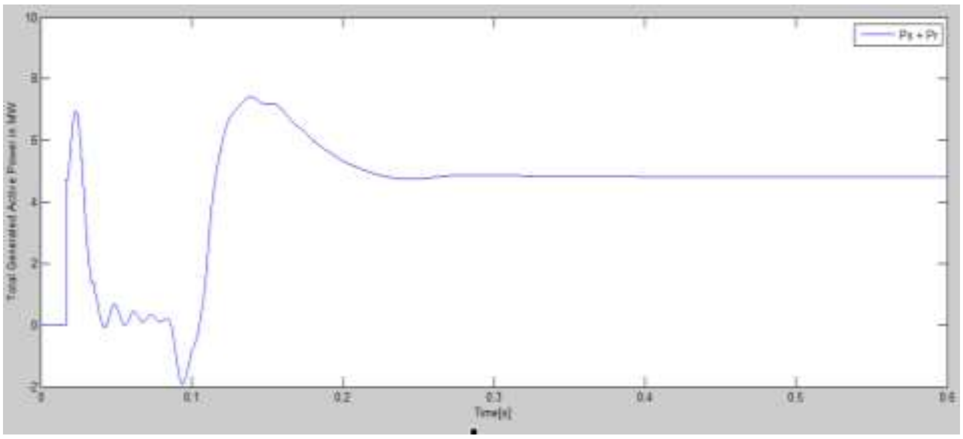

Fig.16. Total Active Power under Three Phase Fault at 25 KV Bus

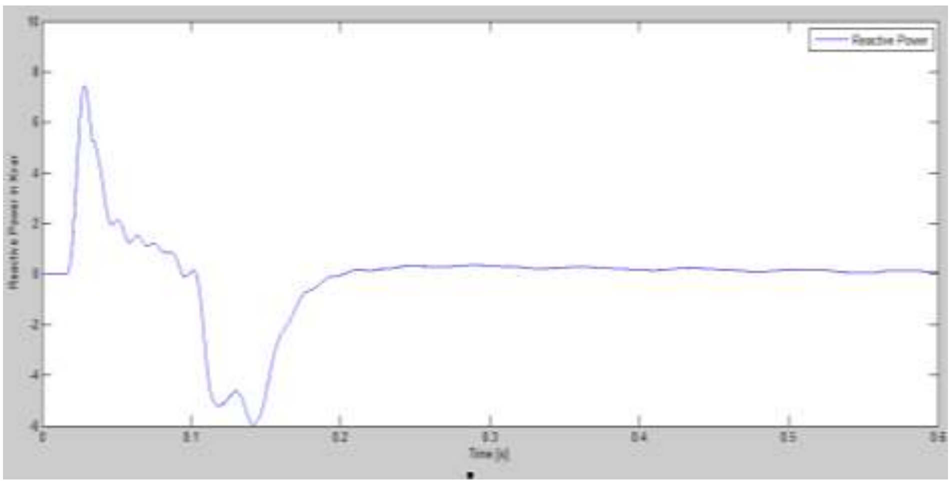

Fig.17 Total Reactive Power under Three Phase Fault at 25 KV Bus

When three phase fault occurs at 25 kV busbar, the voltage drop down approximately 25%, i.e. 75% sag at 10ms. During 3-phase fault, first of all active power reaches to 7 MW approximately, then fall down to zero and then goes negative. After 130 ms the fault causing the voltage sag on the 575V busbar is cleared as the duration of the fault is 120ms, and under the normal condition the wind turbine produces about 45% of the nominal power. Similarly, as the reactive power should maintain at 0 MVAR, i.e., stator is operated at unity power factor, so majority of the power (70-80%) flow from the stator side. But during fault turbine start to generate and absorb the reactive power and so, 70-80% power will flow through rotor so the converter may destroy because it has to handle the power beyond its power rating limit. The maximum value of DC link voltage during three phase fault with SVO controller has arrived at 1425V whereas the rated set value is 1200V; and the capacitor would be under excessive voltage stress and possible destroyed. The minimum value of the dc link voltage is 960V and it would drop down to the much lower value if the input voltage of the grid side converter declines more deeply.

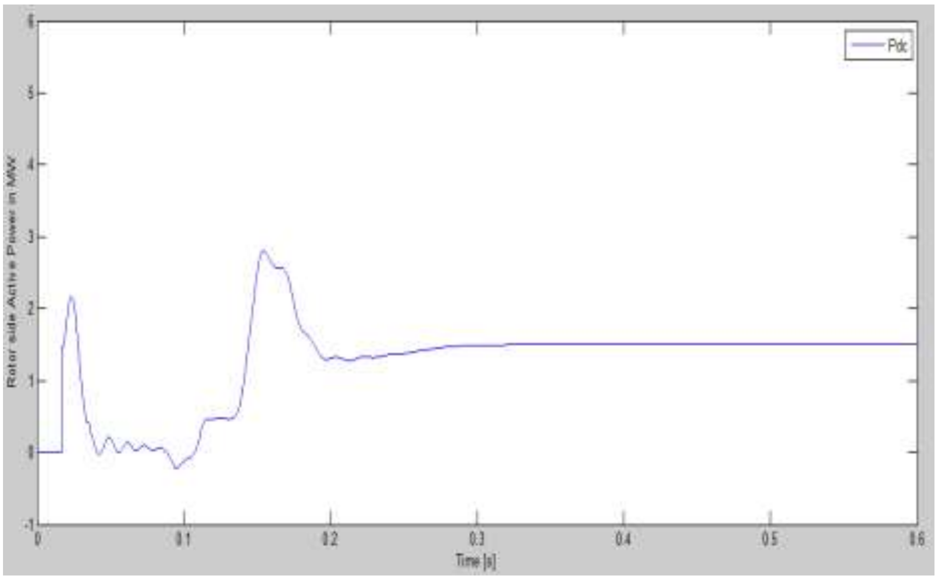

Fig.18 Rotor Active Power under Three Phase Fault at 25 KV Bus

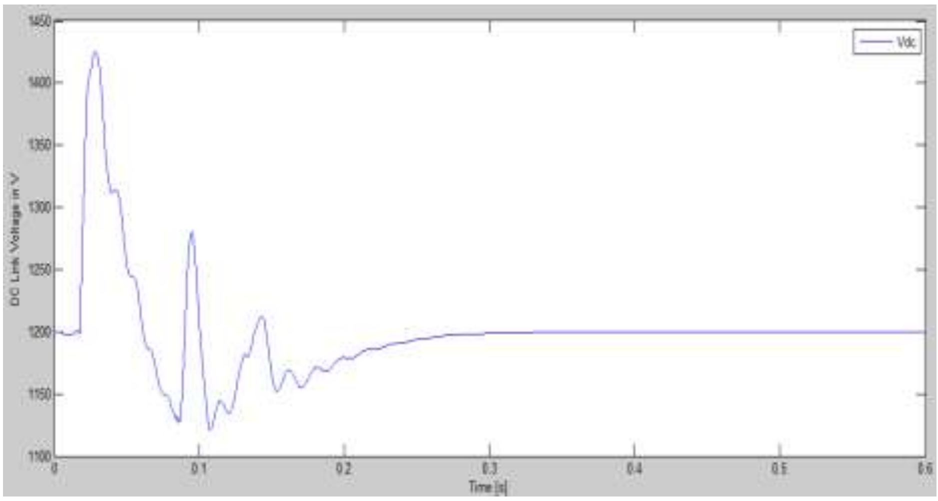

Fig 19 DC link Voltage under Three Phase Fault

V. CONCLUSION

DFIG performance is presented under steady-state, dynamic and faulty conditions. The magnetic saturation, electro-magnetic transients and other nonlinear factors are neglected. With vector control of rotor and grid side converters, connected to DFIG Wind Turbine one can control the flow of active and reactive power from DFIM to grid and maintain the dc link voltage constant under normal operating conditions at constant wind speed of 12 m/s. This controller and system performances have been studied under normal condition, 40% voltage sags and three phase short circuit fault condition at 25 KV. With 40% sag fluctuations are more and may become harmful for converters and capacitors. It is also observed from simulations that when three phase fault, there is a large fluctuation in the active and reactive power flow to the grid. During this transients power flowing through the rotor circuit becomes about 70-80% of total power flow, which may damage the converters connected to the rotor circuit of DFIG.

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