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Performance of Grid Connected DFIG Wind Turbine with PI and Fuzzy Controllers along with Crowbar Control for Enhancing Fault Ride through Capability

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ABSTRACT

Among the renewable energy sources, wind energy is one of the important resources which has a huge potential of providing electric supply in large amounts. But, as the penetration of wind energy increases, the integration of wind energy to the grid becomes a major issue. This is mainly because of the varying nature of wind speed and the need for variable operation of the connected wind turbines. Doubly Fed Induction Generators (DFIGs) are best suitable for variable speed applications which regulate output power with the help of power electronic interface. The influence of wind turbines on the grid stability becomes a noticeable issue, especially when there is a fault on the grid. The disconnection of such a large amount of wind generation during fault affects the stability of the system. Hence, a control system to ride through the fault i.e low voltage is necessary so that the wind turbine remains connected to the grid even during fault condition. This paper proposes a crowbar control mechanism which bypasses the excess rotor currents produced during the fault, thus improving the fault ride through capability of the wind turbines. For this, the grid side and rotor side controllers are designed using Proportional-Integral (PI) controllers. To enhance the controllability, fuzzy controllers can be used as an alternative to PI controllers. This paper also presents a comparative study of PI and fuzzy controller in enhancing the Low Voltage Ride Through (LVRT) capability of the wind turbines. The simulation is done on a grid connected DFIG wind turbine rated at 1.5MW using MATLAB/ SIMULINK and the obtained results validate the proposed control strategies of crowbar protection and fuzzy controller.

Key Words: Doubly Fed Induction Generator (DFIG), Fault Ride Through (FRT), FRT Grid Code, Pitch angle controller, Crowbar protection, PI Controller, Fuzzy Controller

1. INTRODUCTION

With increased penetration of wind power into electrical grid, DFIG wind turbines are gaining importance among other techniques due to their variable speed operation and reduced converter power [1]. They have the ability to regulate output power in a fast and accurate manner with the help of power electronic interface. This has led many authors to develop suitable models for DFIG to integrate 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 doubly fed induction generator (DFIG) consisting of a wound rotor induction generator and an AC/DC/AC converter. The AC/DC/AC converter acts as a frequency regulator between the fixed frequency stator and variable frequency rotor. It basically consists of either a set of insulated-gate bipolar transistor (IGBT) based voltage source converters (VSCs) or a pulse width modulation (PWM) converter. To control the speed of wind turbine gearboxes or electronic control can be used. The rotor speed stability of the wind generators can be enhanced effectively with the use of pitch control system

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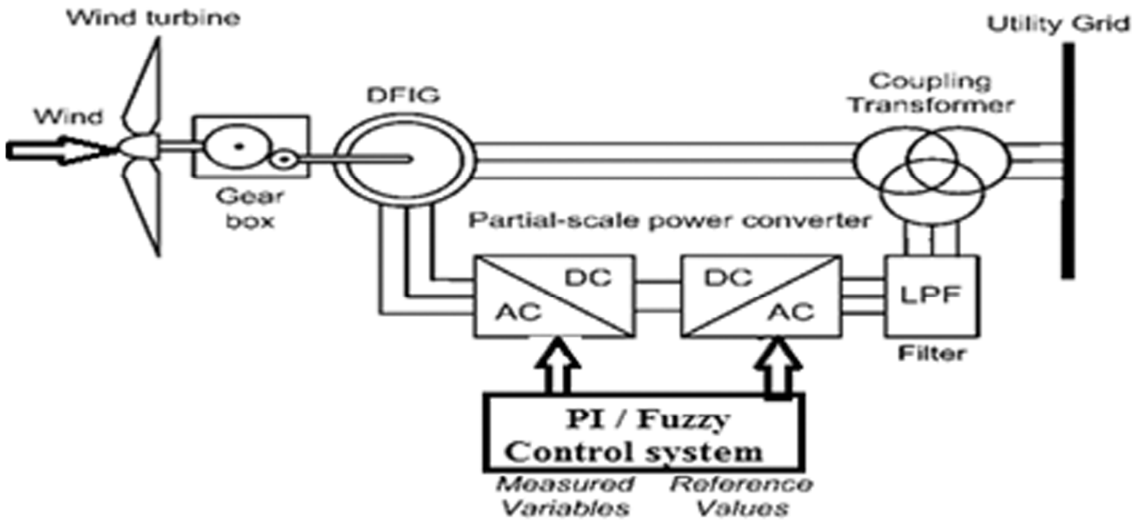


Figure 1: Basic line diagram of a DFIG wind turbine connected to grid

which prevents the wind turbine from excess speed increase during grid faults. The basic line diagram of a DFIG wind turbine connected to grid is shown in Fig.1.

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. In [15] an adaptive fault ride through strategy is proposed for systems with high penetration of wind and maximum power restrictions on the wind farms.

Conventional DFIG technology is based on Proportional-Integral (PI) controllers whose gain parameter is adjusted to obtain the required control which becomes difficult [16] for varying wind speeds. These controllers are required to maintain stator terminal voltage, DC voltage level and reactive power level at GSC and output power level at RSC. However intelligent controllers like fuzzy controller outperforms [17]-[18] the conventional PI controller and hence can be used to enhance the performance of grid connected DFIG wind turbines. In [19], two novel direct power control strategies for a DFIG based wind energy conversion system based on a fuzzy logic controller are proposed.

The paper is organized as follows: Section II presents the modeling of DFIG system. The control technique of DFIG system is given in section III. The details about fault ride through capability are mentioned in section IV. The proposed protection scheme is presented in section V. The fuzzy control system is explained in Section VI. Section VII discusses the results obtained without & with crowbar protection scheme and with PI & fuzzy controllers and is concluded in section VIII.

2. MODELING OF DFIG SYSTEM

The DFIG system is modeled in a decoupled d-q reference frame. The stator and rotor voltages are mentioned below:

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

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

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

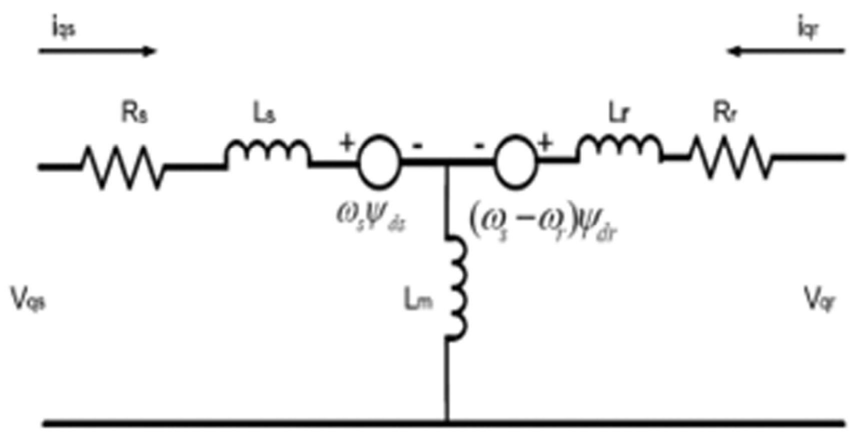
$\psi_r = L_m\, I_s + L_{lr} I_r$

R_s and R_r represent the stator and rotor resistances respectively. L_{ls}, L_{lr} and L_m are the stator, rotor and magnetising 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. Stator and rotor flux linkages are represented as ψ_s and ψ_r.

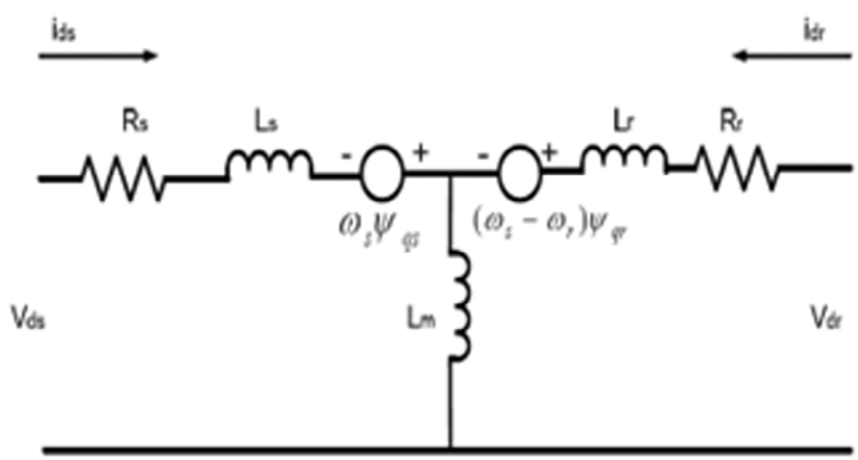
The electrical model of DFIG in dq reference frame is given in Fig. 2 and the equations are given below, where quantities of rotor side are referred to stator side.

Subscripts "s" and "r" refer to stator and rotor side respectively , while "d" and "q" refer to direct and quadrature axes respectively.

$$V_{ds} = R_s i_{ds} + \frac{\psi_{ds}}{dt} - \omega_s \psi_{qs} \tag{3}$$



(a)



(b)

Figure 2: (a), (b). Equivalent circuit of DFIG in dq-reference frame

$$V_{qs} = R_s i_{qs} + \frac{\psi_{qs}}{dt} + \omega_s \psi_{ds} \tag{4}$$

$$V_{dr} = R_r i_{dr} + \frac{\psi_{ds}}{dt} - s\omega_s \psi_{qr} \tag{5}$$

$$V_{qr} = R_r i_{qr} + \frac{\psi_{qs}}{dt} + s\omega_s \psi_{dr} \tag{6}$$

$$\psi_{ds} = (L_{ls} + L_m)\, i_{ds} + L_m i_{dr} \tag{7}$$

$$\psi_{qs} = (L_{ls} + L_m)\, i_{qs} + L_m i_{qr} \tag{8}$$

$$\psi_{dr} = (L_{lr} + L_m)\, i_{dr} + L_m\, i_{ds} \tag{9}$$

$$\psi_{qr} = (L_{lr} + L_m)\, i_{qr} + L_m i_{qs} \tag{10}$$

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

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

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 or 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 a significant role in controlling the energy from available wind and protecting the wind turbine components during grid faults. PI and fuzzy controllers are employed for this purpose.

3.1. Pitch angle Control

Pitch angle control is a very effectual 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 excess speed increase of the wind system, so that the rotor speed stability of the wind generator can be maintained. 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 using a PI controller as shown in Fig. 3.

3.2. Stator side Converter Control

The Stator or Grid side converter is used to regulate the voltage of the DC link 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. Fig. 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.

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 dq-reference frame, the rotor current is decomposed into an active power(d-axis) and a reactive power (q-axis)component. As shown in Fig. 5, actual active power of the generator is compared

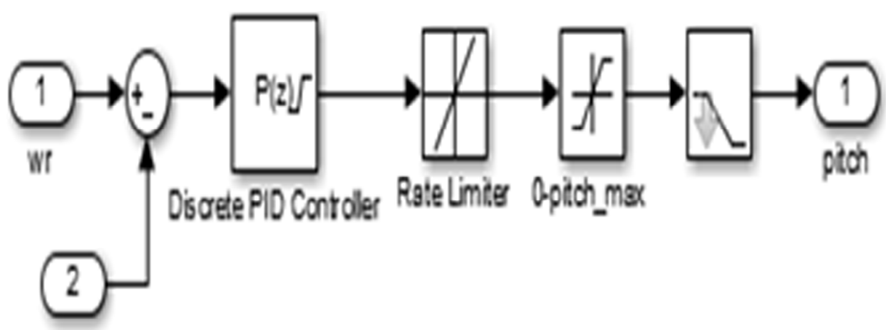


Figure 3: Pitch angle controller

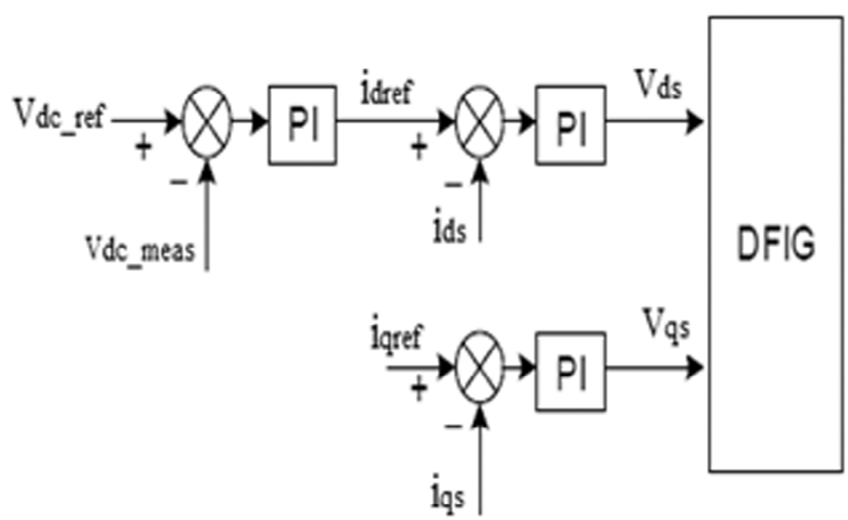


Figure 4: Stator side converter control

with reference value, which is determined by the wind speed. The difference between these two values will go to a PI controller, which is used to generate the required value of d-axis rotor current. Similarly, 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.

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).

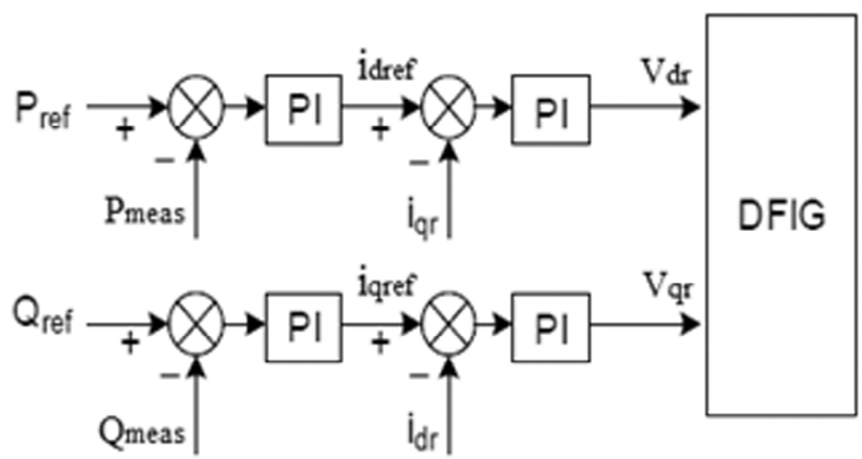


Figure 5: Rotor side converter control

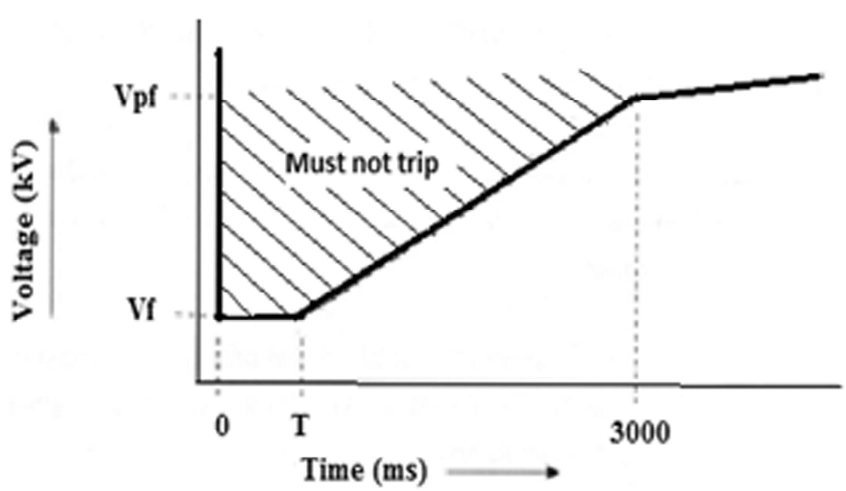


Figure 6: Typical FRT capability requirement

Typical FRT capability [10] requirement, expected from large wind farms is as shown in Fig. 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 I. 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.

5. PROPOSED PROTECTION SYSTEM

A crowbar protection system is one of the methods that is used to enhance DFIG operation during the grid voltage dips. The 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 connected, the rotor side converter pulses are disabled and the machine behaves like a squirrel cage induction machine

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

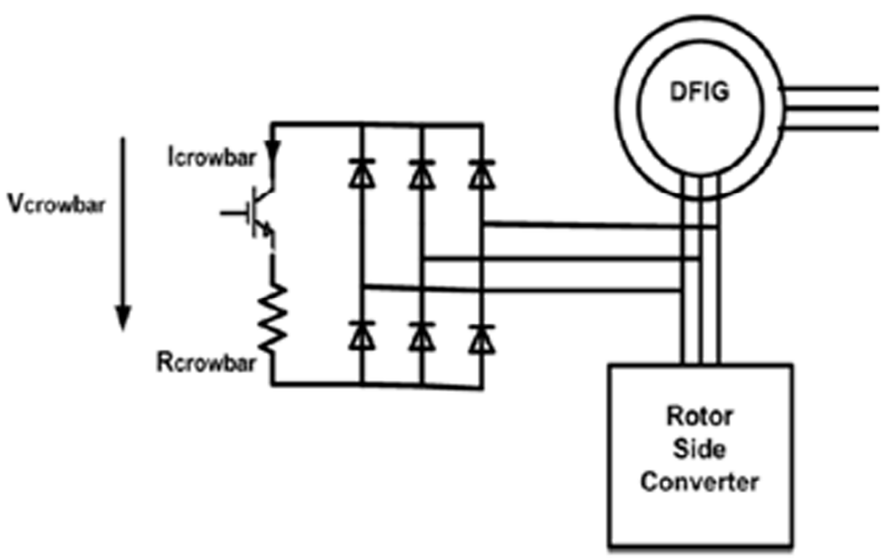


Figure 7: Connection of crowbar in the rotor circuit

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 protection scheme, the DFIG can stay connected to the grid, thus riding through the low voltage area and resume normal 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.

6. FUZZY CONTROL SYSTEM

Conventional PI controller is the most commonly used control technique. But due to differences in various parameters or unpredictable and varying wind speeds, tuning of PI parameters is one of the main problems in this control method. Intelligent control techniques like fuzzy control can be effectively used in place of PI controller to enhance the controllability. Fuzzy logic control process is based on

- Fuzzification of all input values into fuzzy membership functions
- Execution of all applicable rules in the rule base to compute the fuzzy output functions
- Defuzzification of the fuzzy output functions to get crisp output values

In this paper, a Mamdani type fuzzy logic is used for controlling pitch angle, active power and reactive power. It is used as an alternative to the conventional PI controller utilised in GSC, RSC and Pitch angle controller. The two input signals are the error and the derivative of error and the output signal is command derivative. The corresponding fuzzy sets and membership functions are given in Fig. 8.

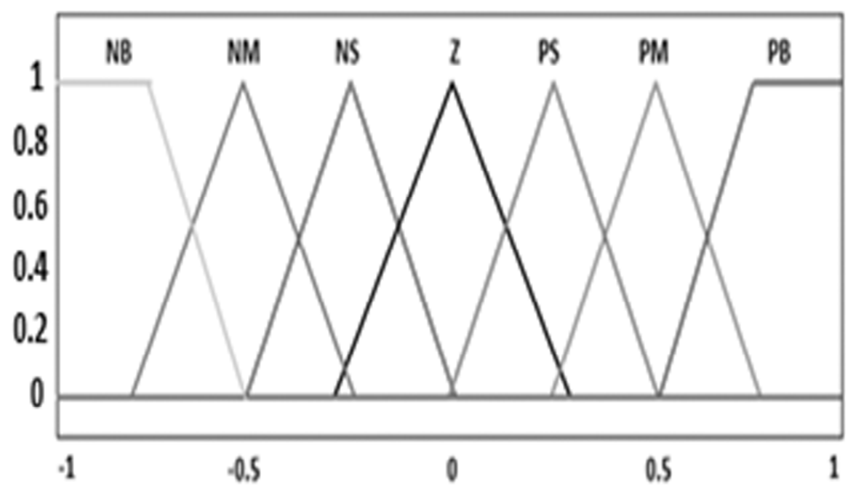


Figure 8: Membership functions for input & output signals

Table 2
Rule Base For Fuzzy Controller

E→ dE↓	**NP**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

For the fuzzy control system, seven membership functions namely, Z = Zero, PS = Positive Small, PM = Positive Medium, PB = Positive Big, NS = Negative Small, NM = Negative Medium, NB = Negative Big are taken for input and output signals. The rule base consists of if-and-then fuzzy logic conditional statements. The corresponding rule base for the fuzzy controller is given in Table.II. The design of these rules is based on an abstract knowledge, which does not require any measurements and deduced from extensive simulation tests [16].

7. RESULTS AND DISCUSSION

A test simulation model of the DFIG system is developed in MATLAB/SIMULINK. The grid is taken as a voltage source of 575 V and the transmission line is represented as a lumped line with a resistance and an inductance of 0.00022 pu and 0.000058 pu. The single line diagram is shown in Fig. 9. The machine parameters as well as the controller parameters are given in the Appendix. A three phase to ground fault is simulated between 0.25 and 0.3 sec. The total simulation time is chosen as 0.5 sec.

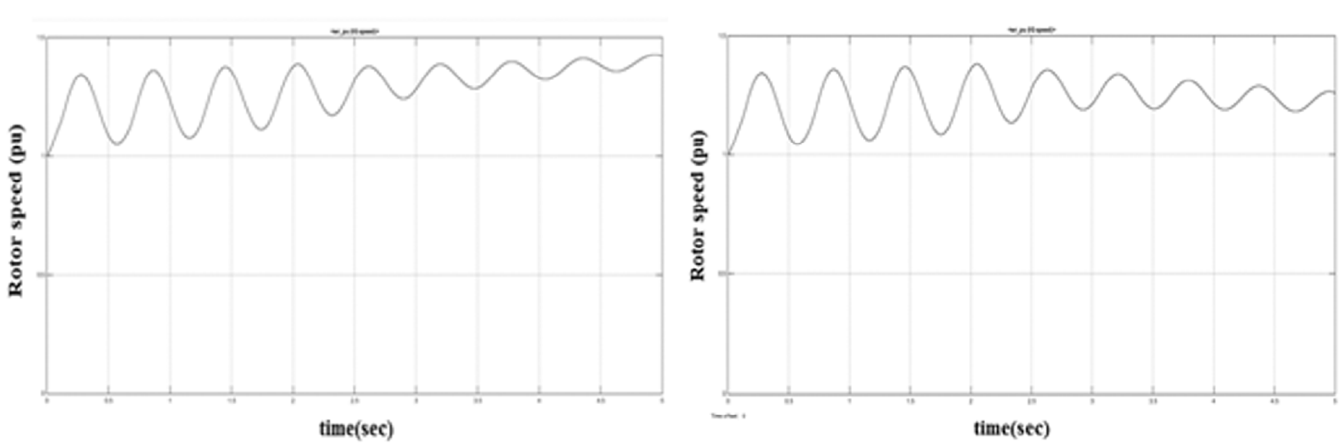
7.1. Effect of pitch angle controller

When a grid disturbance occurs, without pitch angle controller, the rotor speed increases to high values as shown in Fig.10(a). The pitch angle controller is useful at this point to stabilize the rotor speed. From Fig.10.(b) it can be seen that the rotor speed gets stabilized after the occurrence of fault. Thus, the pitch angle controller helps in maintaining rotor speed stability.

7.2. Behavior of DFIG without & with Crowbar protection

For analyzing the behavior of the DFIG system, a three-phase fault lasting for 0.05sec is simulated at the point where the DFIG is connected to the grid. The resulting stator voltage dip without crowbar is shown in Fig. 11(a). It can be seen that the voltage reduces after the occurrence of the fault. But with crowbar protection, the voltage is restored back to the value before the fault as shown in Fig. 11(b).

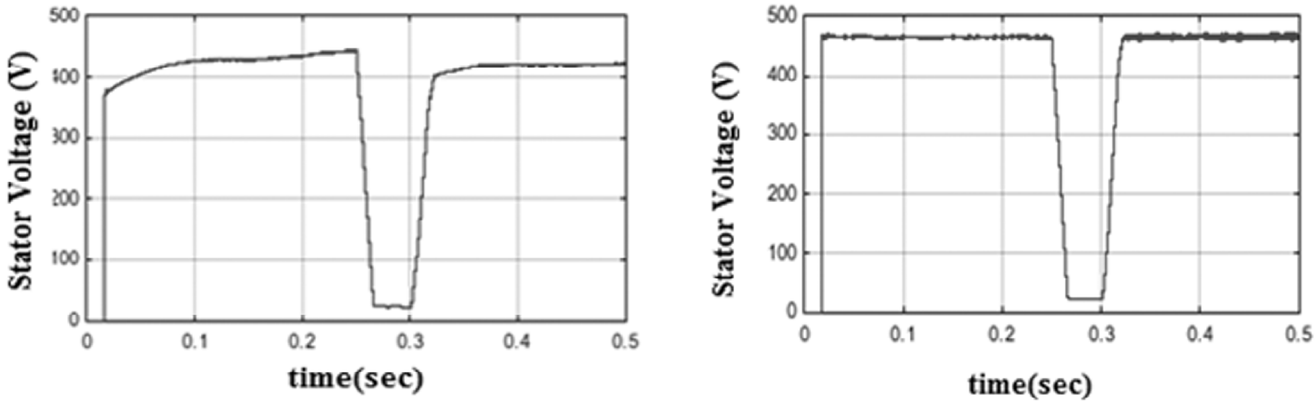
Figure 9: Single line diagram of the test system



(a) **(b)**

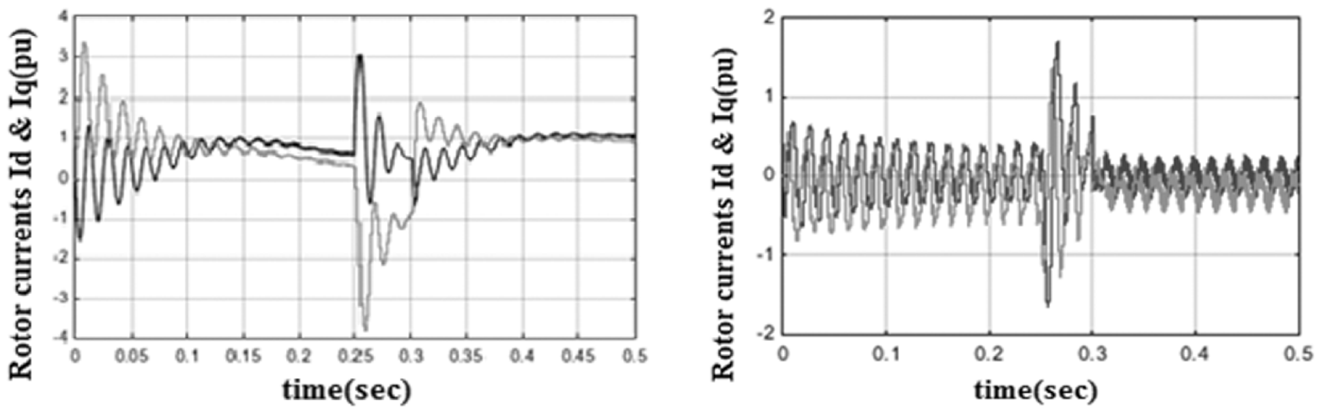
Figure 10: Rotor speed during grid fault (a) without pitch angle controller, (b) with pitch angle controller

This voltage dip due to the 3-phase fault induces high currents in the rotor circuit. In Fig. 12, the d-axis and q-axis component of the rotor current are shown. It can be seen in Fig. 12(a), 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. With crowbar, the rotor oscillations are reduced by 50% of that produced without protection as shown in Fig.12(b). The active and reactive power outputs are shown in Fig. 13 and Fig. 14 respectively. It can be seen that DFIG draws more amount of reactive power during the fault. The output of DC link voltage is shown in Fig. 15.



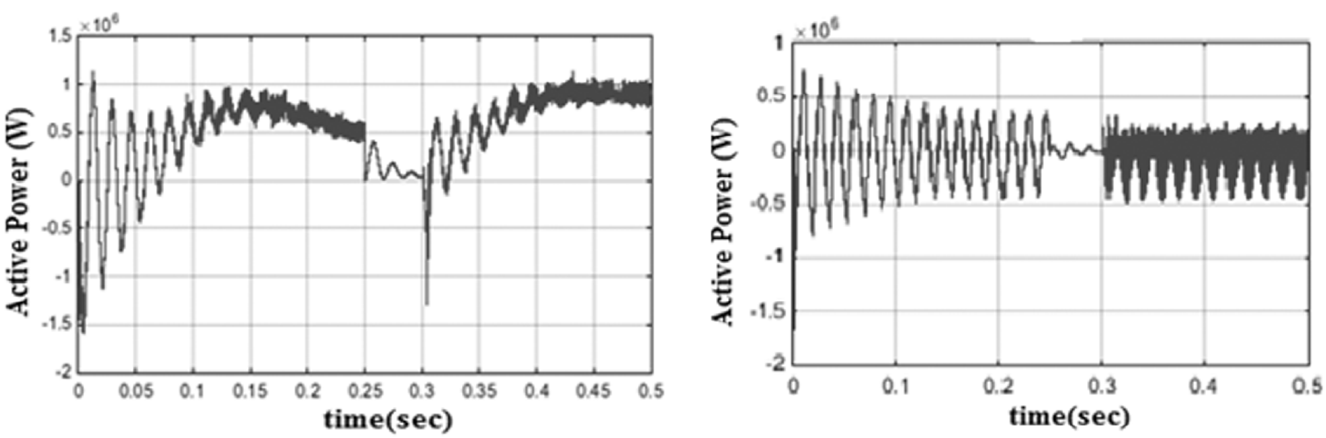
(a) **(b)**

Figure 11: Stator Voltage dip (a) without crowbar (b) with crowbar



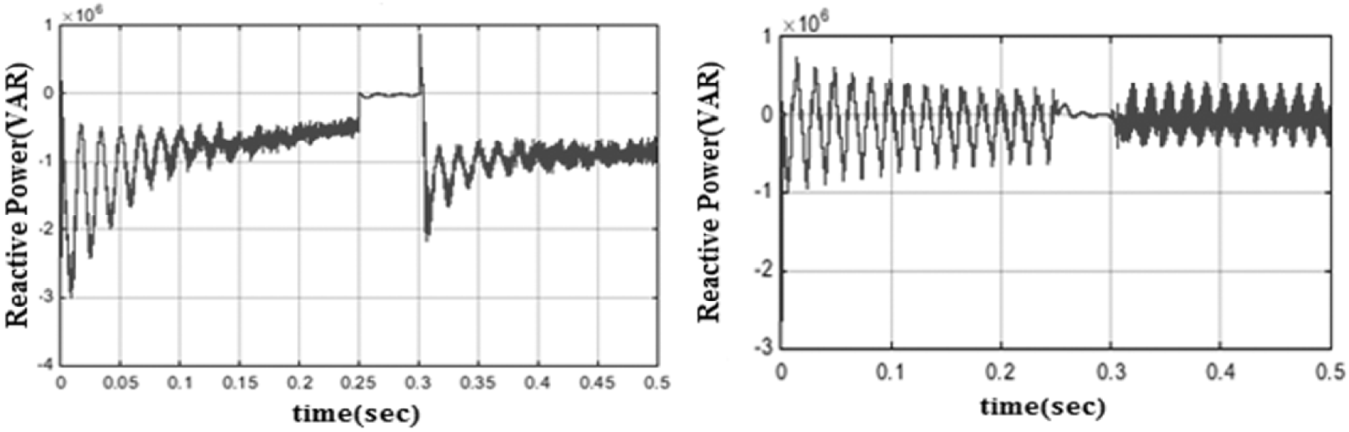
(a) **(b)**

Figure 12: Rotor Currents Id & Iq (a) without crowbar (b) with crowbar



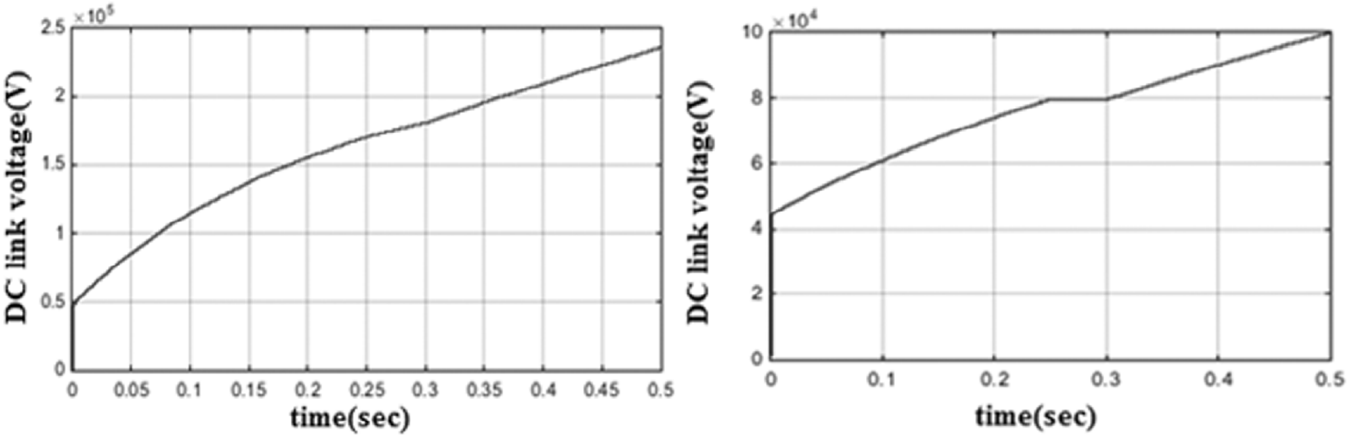
(a) **(b)**

Figure 13: Active Power (a) without crowbar (b) with crowbar



(a) (b)

Figure 14: Reactive Power (a) without crowbar (b) with crowbar

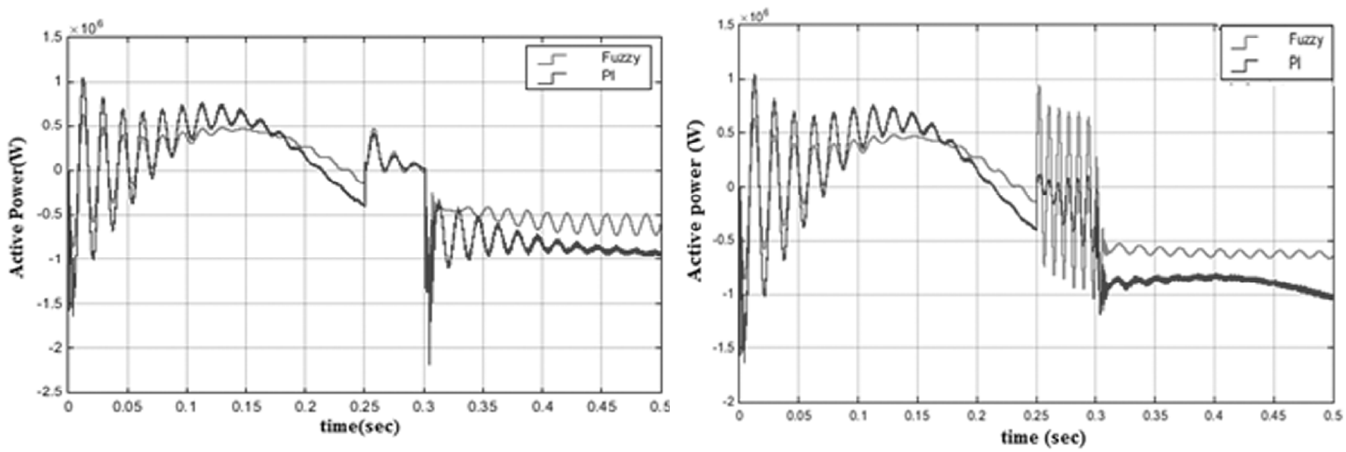


(a) (b)

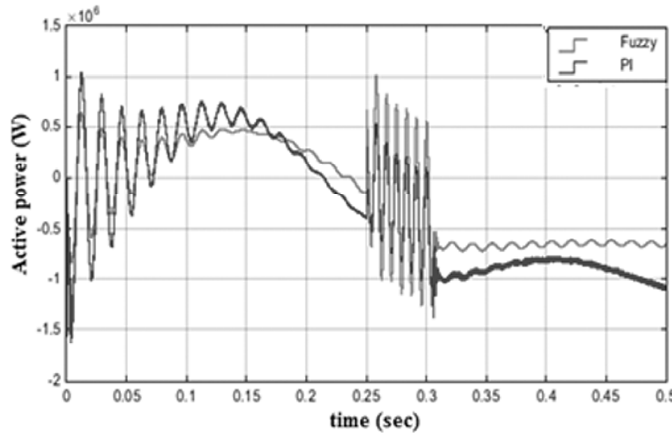
Figure 15: DC link voltage (a) without crowbar (b) with crowbar protection

7.3. Comparison of DFIG with PI and Fuzzy Controllers without crowbar protection

The performance of the grid connected DFIG system without crowbar protection and with PI and Fuzzy controllers, is analyzed for three types of faults: three- phase fault, double-line to ground fault & single-line to ground fault between 0.25s and 0.3s. The output results of active power and rotor currents Id & Iq are shown in the respective figures.

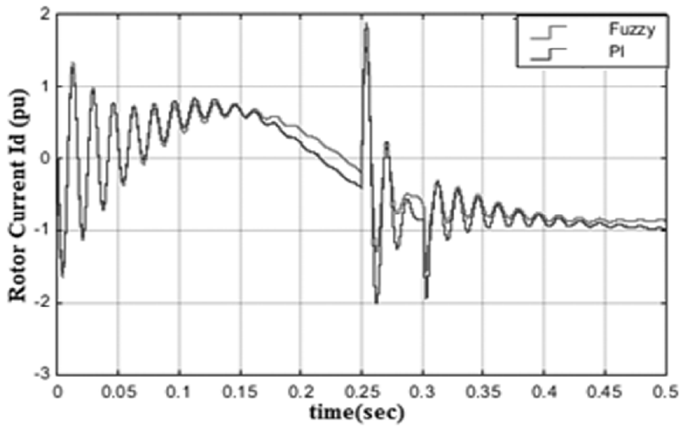


(a) (b)

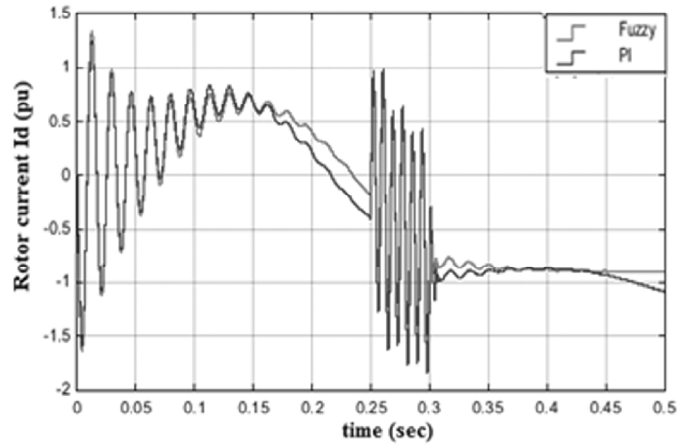


(c)

Figure 16: Active power with PI & Fuzzy Controllers without crowbar for a (a) three-phase fault, (b) double-line to ground fault & (c) single-line to ground fault



(a)



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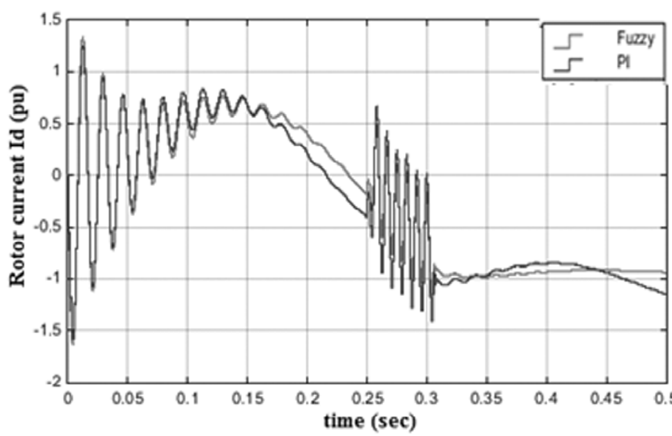
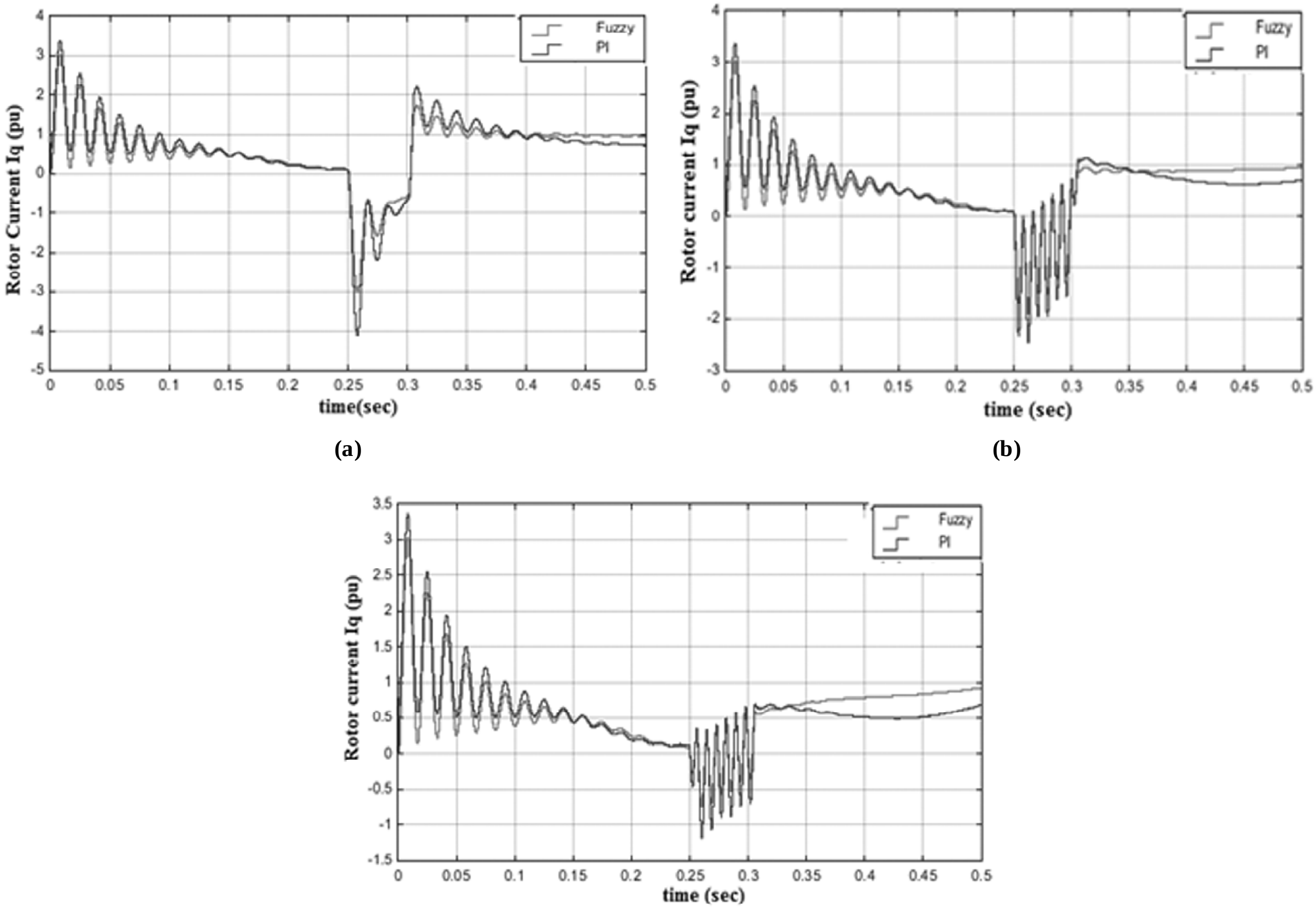


(c)

Figure 17: Rotor Current Id with PI & Fuzzy Controllers without crowbar for a (a) three-phase fault, (b) double-line to ground fault & (c) single-line to ground fault

With intelligent controllers like fuzzy controller, it is shown in Fig.16 that the active power after the fault is increased in comparison to the reduction of power after fault in case of PI controller. Also, the power oscillations during the initial period are reduced to some extent.

A comparison of d-axis and q-axis rotor currents with PI and fuzzy controllers is given in Fig. 17 & Fig. 18. It is evident from the results that the oscillations of these currents are reduced with the use of fuzzy



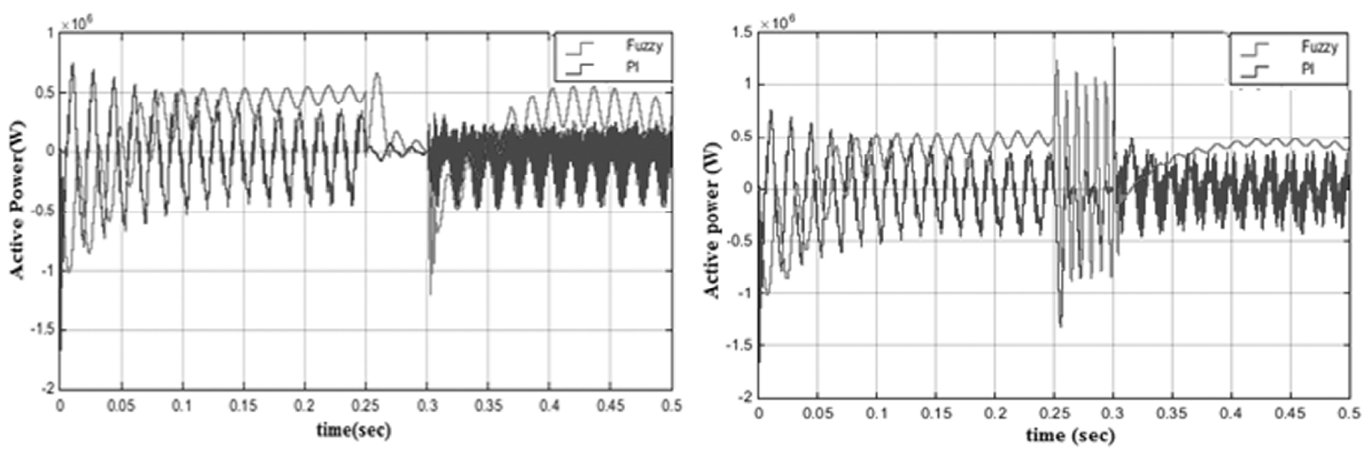
(a) (b) (c)

Figure 18: Rotor Current Iq with PI & Fuzzy Controllers along with crowbar for a (a) three-phase fault, (b) double-line to ground fault & (c) single-line to ground fault

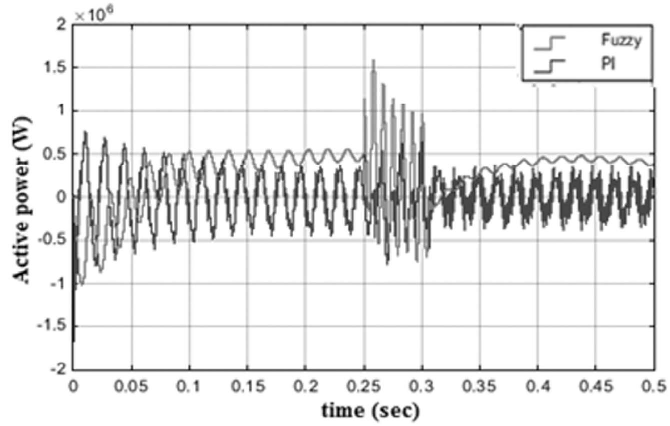
controller. Also they are stabilized to nominal values after the occurrence of 3-phase fault much quickly than when PI controller is used.

7.4. Comparison of DFIG with PI and Fuzzy Controllers along with crowbar protection

Crowbar provides an efficient fault ride through capability to the DFIG system. It enhances the value of power after the occurrence of fault. This is evident from Fig. 19. But with the use of fuzzy controller, the

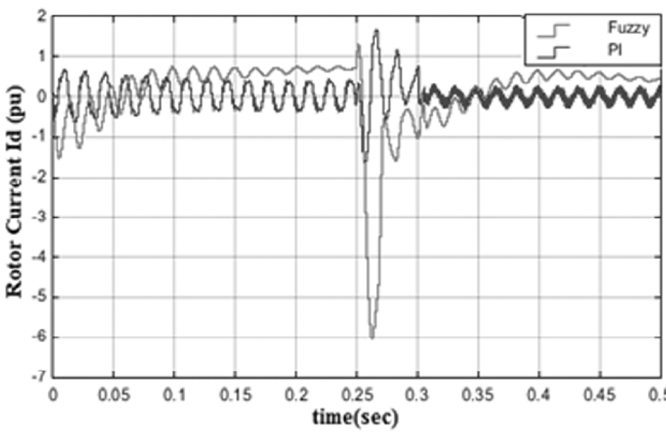


(a) (b)

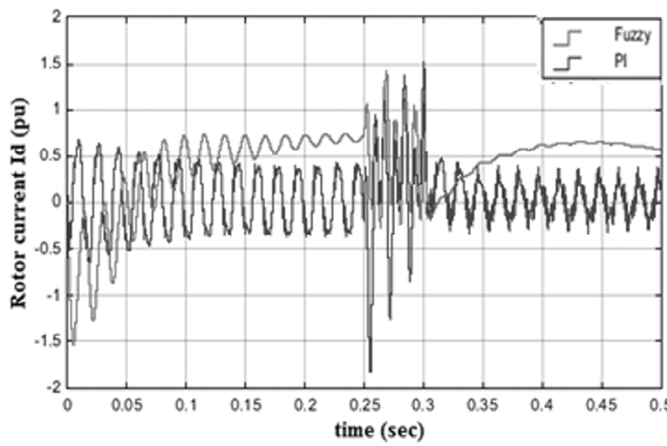


(c)

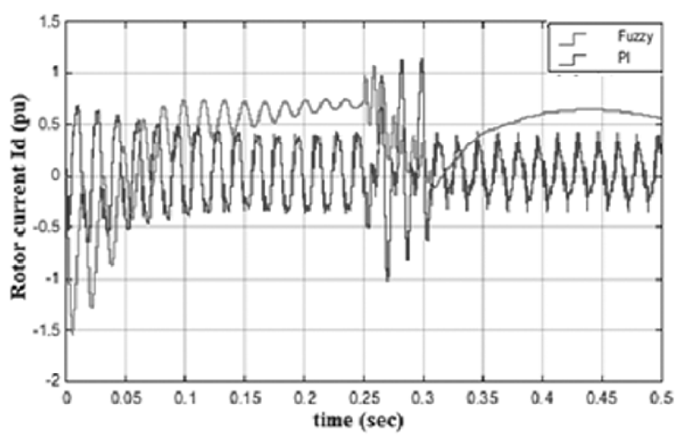
Figure 19: Active power with PI & Fuzzy Controllers along with crowbar for a (a) three-phase fault, (b) double-line to ground fault & (c) single-line to ground fault



(a)



(b)



(c)

Figure 20: Rotor Current Id with PI & Fuzzy Controllers along with crowbar for a (a) three-phase fault, (b) double-line to ground fault & (c) single-line to ground fault

active power oscillations are reduced and its value is also enhanced than that obtained when PI controller is used.

In comparison to d-axis and q-axis rotor currents without crowbar control having high oscillations during the fault period and unequal magnitude before and after fault, these oscillations are damped when

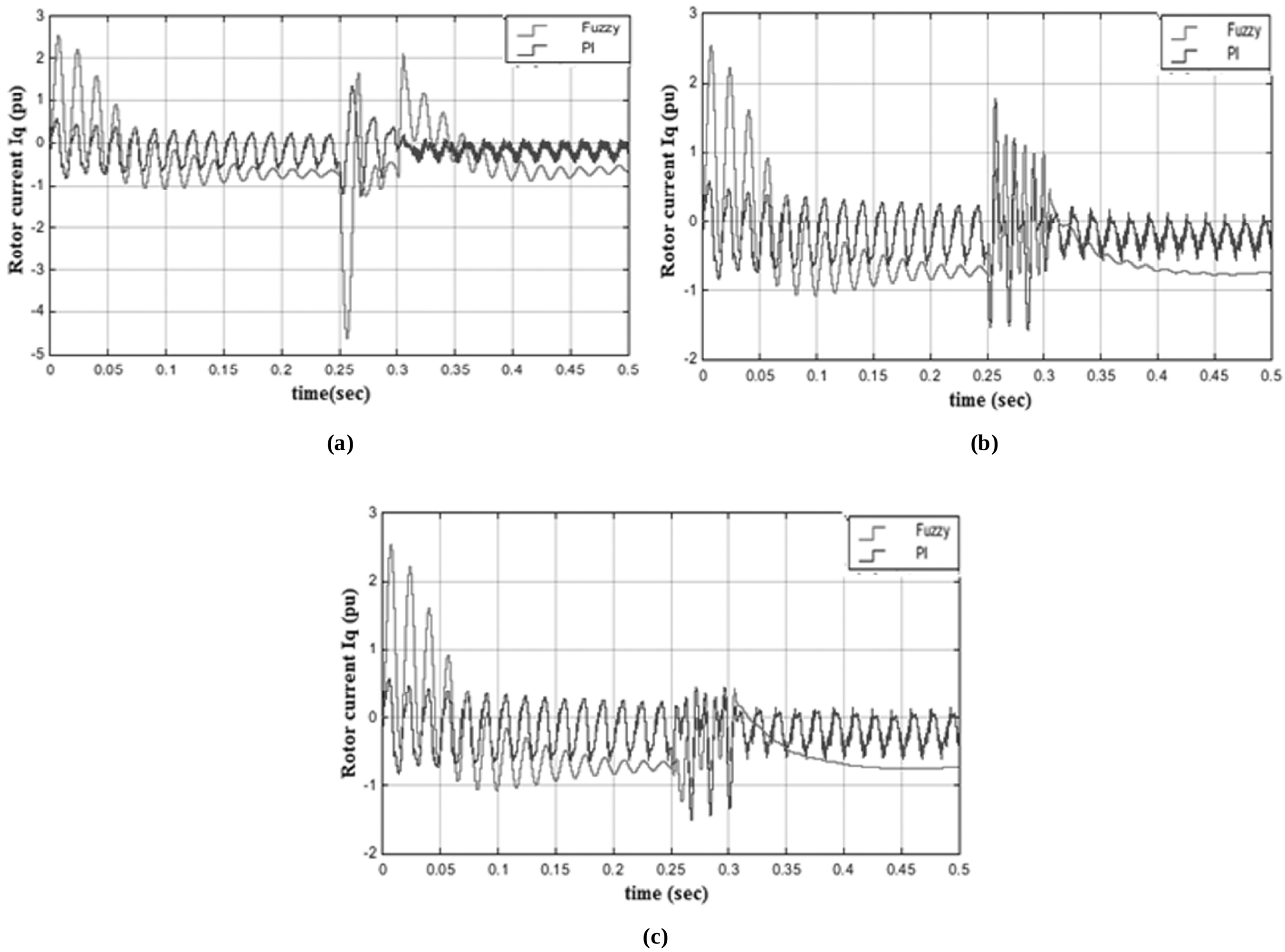


Figure 21: Rotor Current Iq with PI & Fuzzy Controllers along with crowbar for a (a) three-phase fault, (b) double-line to ground fault & (c) single-line to ground fault

crowbar is used. Also their magnitude is maintained same before and after the disturbance. With fuzzy controller, the magnitude of these rotor currents are improved to the nominal value. The results are shown in Fig. 20 & Fig. 21.

8. CONCLUSION

In this paper, the d-q axis modeling of DFIG is implemented using MATLAB/SIMULINK. The performance of DFIG under three phase fault condition with PI Controller is analyzed. To protect the DFIG system from high rotor currents during faults, a crowbar control technique is proposed. The crowbar circuit devaluates the high rotor current oscillations and hence improves the fault ride through capability of the DFIG wind system. To refine the controllability, fuzzy logic controller is designed and implemented using the fuzzy toolbox as an alternative to the PI controller. The active and reactive powers, direct and quadrature axis rotor currents are improved for fuzzy logic controller compared to PI controller for all the three types of fault on the grid. The performance of fuzzy logic controller is found quite satisfactory in improving stability of wind turbine compared to PI controller.

APPENDIX

The machine and control parameters that have been used during the simulations are given below.

Drive Train data

Parameters	*Value*
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

Converter data

Parameters	*Value*
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	0.01μF

Wind Turbine data

Parameters	*Value*
Nominal power	1.5 MW
Stator side Nominal Voltage	575 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	60 Hz
Nominal wind speed	11 m/s

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