Analysis of Doubly-Fed Induction Generator Based Wind Turbine System with Crowbar Protection under Grid Disturbances

[1] Thwai Thwai Htay, [2] Wunna Swe, [3] Zin Mar
[1]Ph.D. Candidate, [2]Professor and Head, [3]Ph.D. Candidate
[1, 2, 3] Department of Electrical Power Engineering,
[1, 2, 3] Mandalay Technological University, Mandalay, Myanmar
Email – [1]thwaihtay@mtu.edu.mm, [2]swethunay@ytu.edu.mm , [3]zinmar@mtu.edu.mm

Abstract: *Doubly Fed Induction Generator DFIG is nowadays widely used in variable speed wind power plants. The DFIGs are sensitive to grid voltage disturbances and require additional protection for the rotor side power electronic converter, like crowbar protection. A DFIG model with crowbar protections was implemented in Matlab/Simulink. This paper investigates the impact of fault ride through on the stability of DFIG wind turbine with and without crowbar protection. The variations of rotor current, rotor speed, DC-link voltage, active power and reactive power of the DFIG wind turbine are investigated. The active crowbar is control to limit the rotor current and dc-link voltage. So the rotor current is decreased and DC-link voltage is decreased to about 1.74 times of normal value. Simulation results based on Matlab/Simulink are discussed.*

Key Words: *DFIG, Crowbar Protection, Rotor Current, DC-link Voltage, Active Power, Reactive Power, Wind power*

1. INTRODUCTION:

With the increase in penetration of wind in power generation, the dynamic behavior of the power system will change because of various technologies used for wind and conventional generators. The doubly-fed induction generator (DFIG) is the most widely used device for wind power generation. DFIG is a popular wind turbine (WT) system due to advantages like it can operate in generator and motor mode for both sub and super-synchronous speed mode, also speed variation of ±30% around synchronous speed can be obtained, and the size of the converter is related to the selected speed range. As the penetration of wind power continually increases, more wind turbines are required to stay grid connected during a grid fault to maintain the reliability during and after a short-term fault [1]. The capability of WT to stay connected to the grid during voltage dips is called as the low-voltage ride-through (LVRT) capability. In order to fulfill the LVRT conditions for DFIG based WTs, there are two important conditions to be considered during a fault condition. The first is the over-current that can occur in rotor and stator circuits, and then the second is over voltage in the DC-link, both leads to the unbalanced energy that cannot be transmitted into the grid [2]. The high rotor current flows through the rotor side converter (RSC) causing damage to the converter and DC-link. The DC-link voltage rises as its capacitors are charged above their nominal voltage. Some means of protection is required to prevent the converter from high inrush current faults.

A DFIG grid connected model using Matlab/Simulink is considered [1], [2]. A crowbar circuit is added to the model to limit the faulty current from reaching the RSC, in order to protect the back to back converter. The crowbar may comprise of an uncontrolled rectifier, IGBT switches and a resistor that will short circuit the rotor windings. The crowbar is triggered when the dc bus voltage or the fault rotor currents become too high, and then it works for a preset period of time, or until the grid fault is cleared. The performance of the proposed system is studied during steady state, and during three phase grid fault with and without the crowbar protection.

2. DFIG SYSTEM MODEL AND CONTROL:

The schematic diagram of a DFIG connected to grid is shown in Figure 1. It consists of a wound rotor induction generator with back-to-back voltage source converters linking the rotor to the grid. The back-to-back converter consists of a Rotor Side Converter (RSC) and a Grid Side Converter (GSC) connected to the grid. The RSC is used to control the generator speed and reactive power, while the GSC is used to control DC-link voltage and reactive power exchange with the grid [4].

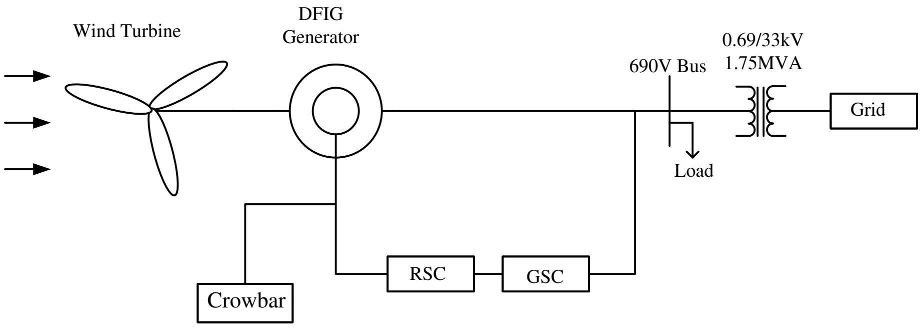


Figure 1. Schematic diagram of the DFIG with crowbar protection [4]

2.1. Rotor Side Converter Control System

The RSC controls independently the active and reactive power injected by the DFIG into the grid in a stator flux dq-reference frame. Figure 2 shows the control scheme of the RSC. The q-axis current component Iqr is used to control the active power using a maximum power tracking strategy to calculate the active power reference [3].

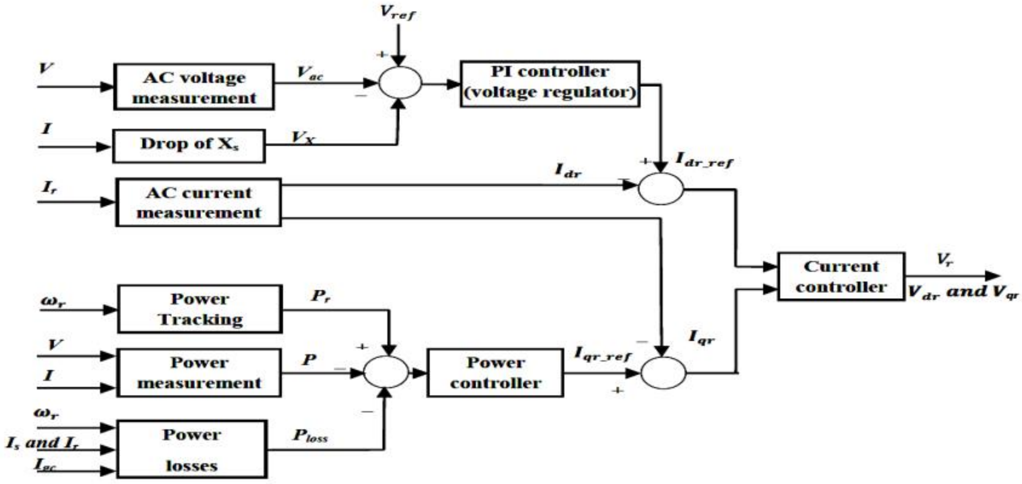


Figure 2. Schematic diagram of rotor side converter control system [3]

The actual speed of the turbine ω_r is measured and the corresponding mechanical power of the tracking characteristic is used as the reference power for the power control loop. The reference value for the active power P_r is compared with its actual value P and the error is sent to a PI controller which generates the reference value for the q-axis current I_{qr_ref}. This signal is compared to its actual value I_{qr} and the error is passed through a second PI controller determining the reference voltage for the q-axis component V_{qr}. The d-axis is used to control the reactive power exchanged with the grid, which in normal operation is set to zero in order to operate with unity power factor. In case of disturbance, if the induced current in the rotor circuit is not high enough to trigger the over-current protection, the RSC is set to inject reactive power into the grid in order to support the voltage restoration. In such case, the actual voltage V at the collection bus is compared to its reference value V_{ref} and the error is passed through a PI controller to generate the reference signal for the reactive power of the DFIG. Similar to the control strategy of the q component, the error between the reactive power reference and its actual value is passed through a PI controller to determine the reference value for the d-axis current I_{dr_ref}. This signal is compared to the d-axis current value I_{dr} and the error is sent to a third PI controller which determines the reference voltage for the d-axis component V_{dr}.

2.2. Grid Side Converter Control System

Figure 3 shows the control system of the GSC which is used to regulate the DC link voltage between both converters. In normal operation, the RSC already controls the unity power factor operation and therefore the reference value for the exchanged reactive power between the GSC and the grid is set to zero. In case of disturbance, the GSC is set to inject reactive power into the grid whether the RSC is blocked or is kept in operation. The control of the GSC 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 d-axis current $I_{d\_gsc\_ref}$. This latter signal is subtracted with its current value I_{d_gsc} and the error is sent to another PI controller to obtain the reference voltage for the d-axis component. As for the q-axis current, its reference value depends whether the system operates in normal operation or during disturbance.

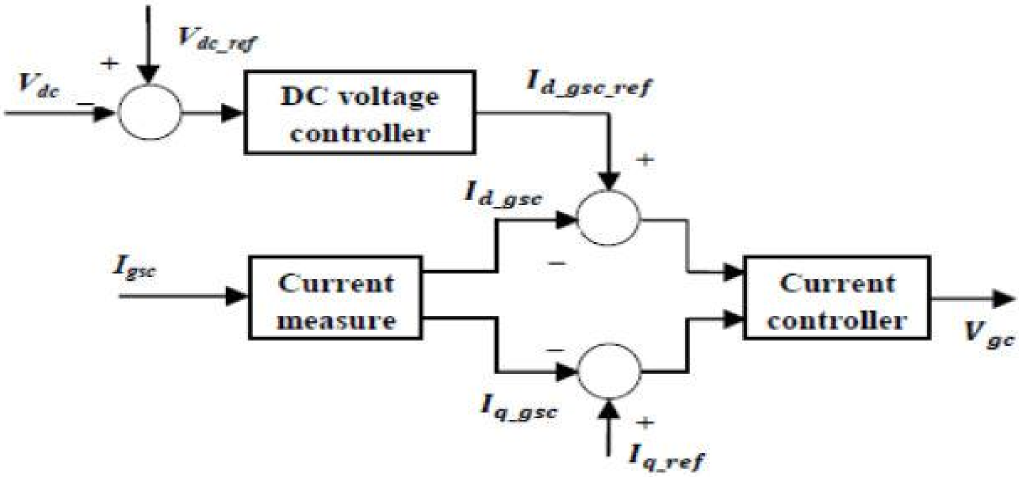


Figure 3. Schematic diagram of grid side converter control system [3]

In case of disturbance, the actual AC-side voltage of the GSC is compared with its reference value and the error is passed through a PI controller which generates the reference signal for the q-axis current. This reference signal is compared to its current value and the error is sent to a second PI controller which establishes the reference voltage for the q axis component. During normal operation, the strategy does not present limitations with the control of the DC link voltage since the q-axis current is set to zero and therefore the converter capacity is only used to control the DC link voltage.

3. CROWBAR PROTECTION:

The function of the (rotor) crowbar is to short-circuit the rotor through a resistance if the rotor currents exceed threshold values. Once the crowbar protection is activated, the IGBTs of the rotor-side converter are all switched off and integrators of the controllers (e.g. power-outer loop controllers of the RSC) are reset to zero, i.e. the rotor blocks. Consequently, the DFIG system behaves as a squirrel-cage induction generator with a high resistance including additional rotor resistors.

The typical crowbar arrangements are shown in Figure 4. The crowbar circuit can be designed by placing two pairs of anti-parallel thyristors per phase connected to the rotor terminals (see Figure 4.a) or by using a combination of a diode bridge (rectifier) including a single thyristor and a rotor crowbar resistance, R_{cb}, (see Figure 4.b) [5]. The crowbar configurations seen in Figure 4.a and Figure 4.b are unable to quickly stop the rotor transient currents limiting the rotor-side converter restarting process. This is considered undesirable from the point of view of the fault ride-through technique [6]. An active crowbar shown in Figure 4.c is proposed in [5, 7] to resolve this issue. In an active crowbar arrangement, the rotor current can be stopped by using a forced commutation of the GTO-thyristor or an IGBT [6]. In this paper, the crowbar circuit depicted in Figure 4.c is used as a rotor crowbar protection of the DFIG-based wind turbine system.

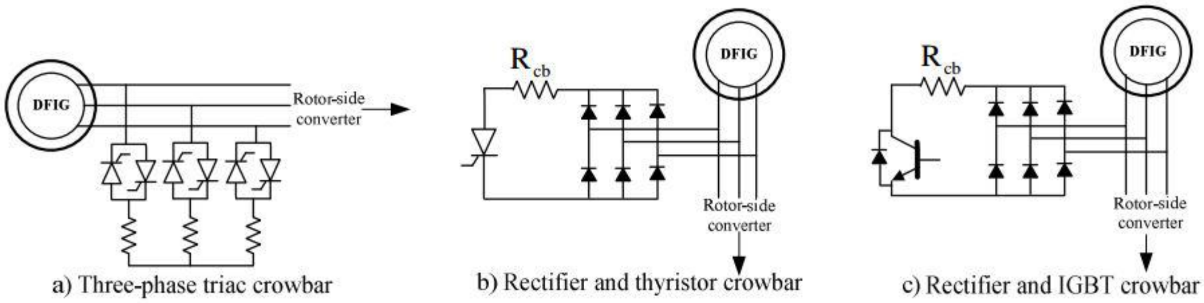


Figure 4: Typical rotor crowbar configurations [5-7]

4. CROWBAR IMPLEMENTATION:

A crowbar circuit is connected between the rotor circuit and rotor-side converter to provide a bypass for the high transient rotor current which is induced by voltage dips in the grid, where the RSC is disabled. As illustrated in Figure 5, the crowbar is made up of a switched bridge connected to a resistance.

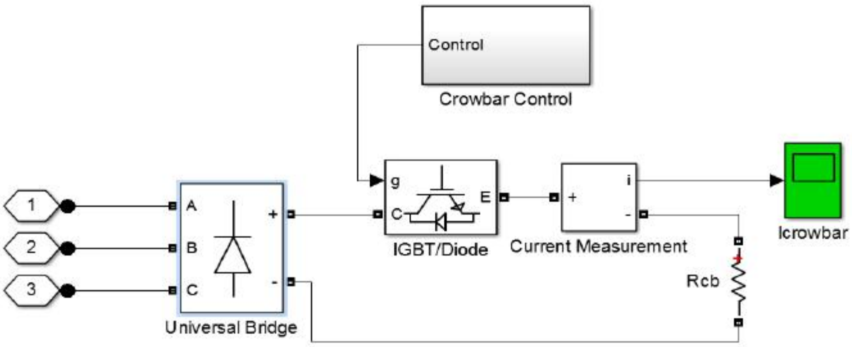


Figure 5. Crowbar circuit implementation in Simulink [8]

The active crowbar is designed to protect the DFIG against overvoltage and to limit the rotor current during grid faults [8]. The proposed active crowbar control is illustrated in Figure 6. The proposed control actives the crowbar and deactivate the RSC if the rotor current, i_r, exceeds the threshold value, i_{th}, or if the DC-link voltage, V_{dc}, exceeds the threshold value, V_{dc-th}.

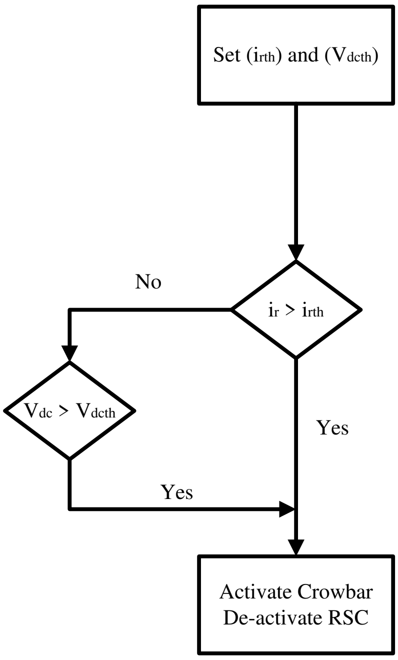


Figure 6. Active Crowbar Control Flowchart [8]

5. CASE STUDIES:

The simulated power system in Matlab/Simulink consists of a 1.5 MW DFIG connected to a 33 kV grid through a 30 km transmission line. The DFIG wind turbine is generating the rated power at a constant 9 m/s wind velocity. The generator data used in simulations are presented in Table 1. Simulink model of a 1.5MW DFIG wind turbine is shown in Figure 7.

Table 1. Wind Generator Parameters

Nominal Power	1.5 MW
Line to line voltage	690 V
Frequency (f)	50 Hz
Stator Resistance(R_s)	0.0084 pu
Stator Leakage Inductance,L_{1s}	0.167 pu
Rotor Resistance(R_r)	0.0083 pu
Rotor Leakage Inductance, L_{1r}	0.1323 pu
Magnetizing Inductance (L_m)	5.419 pu
Pole Pairs	2
Rotor Speed	1800 rpm
Rated Slip	-0.2

A voltage dip occurs at time instant 1 s and lasts for 100 ms. The generator is equipped with crowbar protection that is turned on when the rotor current exceeds the threshold value or when the DC voltage exceeds the threshold value. When the crowbar protection is activated, the Crotor is turned off, while the Cgrid remains in operation.

The three-phase to ground fault is located at the point of common coupling (PCC). The applied fault is initiated at t = 1s and cleared at t = 1.1s. The dc-link voltage is set to 1150V. The threshold values for the rotor current and the dc-link voltage are set at 1.5pu and 1.3pu, respectively. Three case studies are carried out to investigate the dynamic performance of the active crowbar. The two cases are dedicated to study the system performance with and without crowbar being activated.

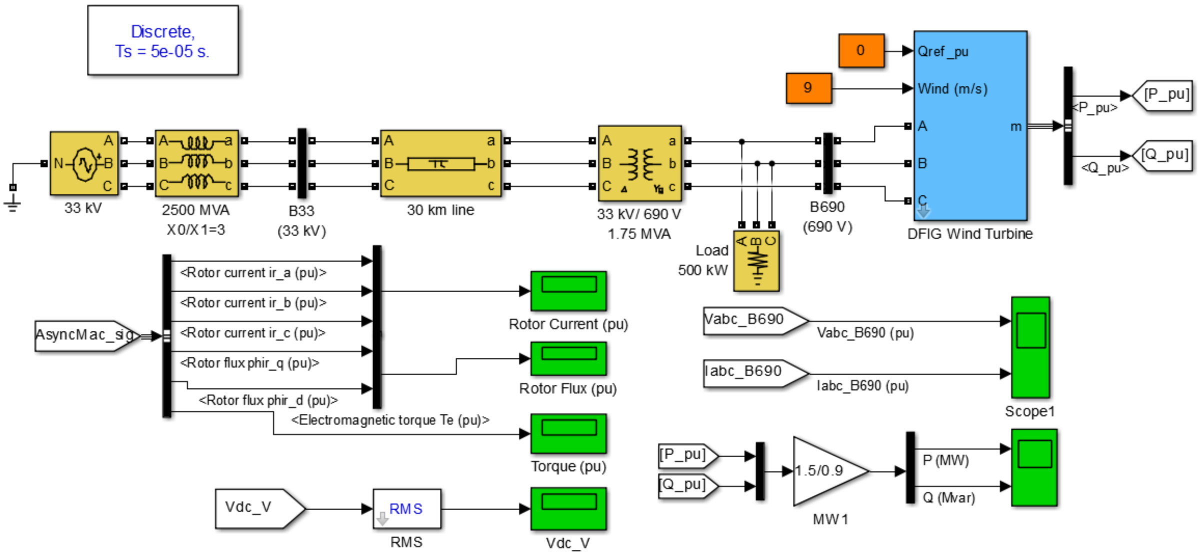


Figure 7. Simulink Model of Proposed System

5.1. System without Crowbar Protection

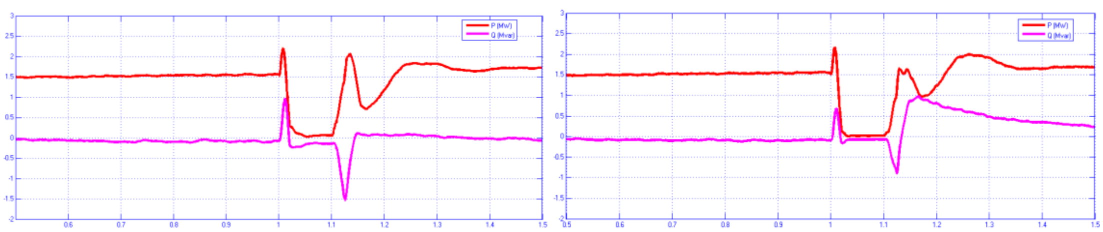
A three-phase fault is applied at t = 1s for 100 m sec at the PCC without activating the crowbar. To meet the grid code requirements, the back-to-back converter of the DFIG is controlled to feed reactive power to grid during the fault until successful recovery. As a consequence of the sudden grid fault, the stator voltage drops and stator currents increases, to a value that is corresponding to the reactive power fed from the DFIG.

5.2. System with Crowbar Protection

The same fault was applied to the system, but with activating the crowbar. When the rotor current exceeds its threshold setting, the rotor is short circuited through the crowbar resistance and the DFIG behaves as a squirrel cage. Moreover, to keep the dc-link voltage within the rated limits, the crowbar is activated during the instants of fault incidence and clearance. Activation of the crowbar lasts for a few milliseconds depending on the threshold values of rotor current and dc-link voltage. When the crowbar is deactivated, the RSC reconnects. Thus, the back-to-back converter is under control during the fault period.

6. SIMULATION RESULTS:

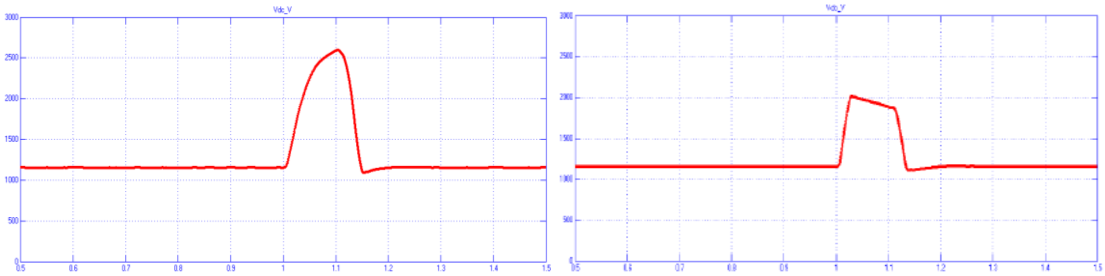
A three phase fault occurs at time t=1s at the DFIG terminals when it is supplying 1.5 MW of power to the grid. The active power rapidly decreases to zero after the fault. The active and reactive powers generated from the wind are shown in Figure 8(a). During the whole simulation time, the wind speed is constant and equals to 9 m/s. At the start of the voltage dip DFIG inject a burst of reactive power into the grid and at the end of the dip (voltage recovery) it absorbs a burst of reactive power from the grid.



(a) (b)

Figure 8. Active and Reactive Power during Grid Fault (a) Without Crowbar Protection (b) With Crowbar Protection

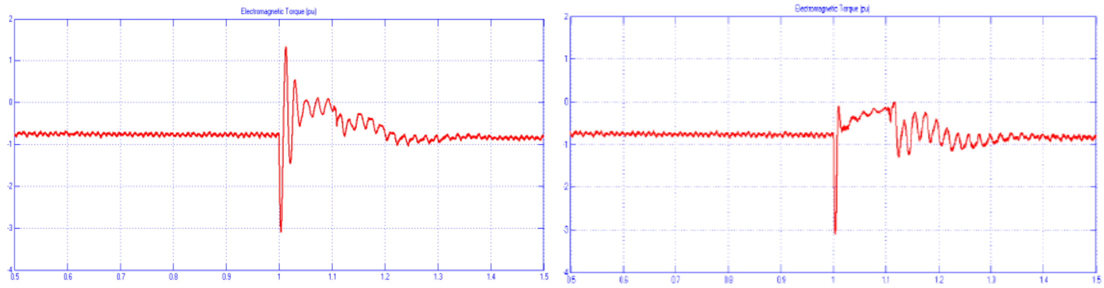
Figure 9 shows the DC-link voltage during fault with and without crowbar protection. The DC-link capacitance equals 10 mF with nominal voltage of 1150 V. During fault occurrence, the grid voltage falls and the GSC is not able to transfer the power from the RSC to the grid. Therefore, the additional energy goes into charging the DC-link capacitor and thus its voltage rises rapidly. When the system operates without crowbar protection, the DC-link voltage is increased to 2600 V during fault period. When the crowbar resistance is triggered at the instant of 1.01 s, the DC-link voltage value is 2000 V and starts to decrease for the case of crowbar protection.



(a) (b)

Figure 9. DC-link Voltage during Grid Fault (a) Without Crowbar Protection (b) With Crowbar Protection

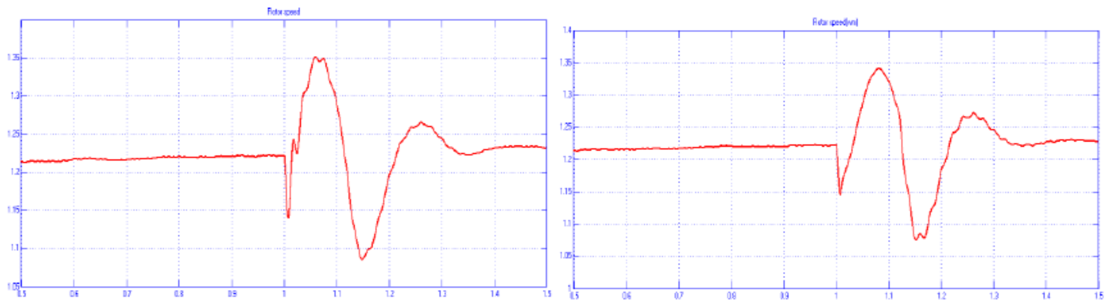
The electromagnetic torque will fluctuate with the rotor current, this torque will affect on the mechanical stress on the gearbox as shown in Figure 10(a). When the grid fault occurs the electromagnetic torque will decrease to -3 pu and then it will increase to 1.5 pu. After that it is decreased and fluctuated during the grid fault. By using the crowbar protection, the fluctuation of the electromagnetic torque will decrease as shown in Figure 10(b).



(a) (b)

Figure 10. Electromagnetic Torque during Grid Fault (a) Without Crowbar Protection (b) With Crowbar Protection

After fault occurrence, the rotor speed is decreased from 1.21 pu to 1.16 pu and then the rotor speed is increased rapidly to 1.35 pu as shown in Figure 11(a). After fault occurrence and before the crowbar is activated, the rotor speed is decreased from 1.21 pu to 1.15 pu. The rotor speed is increased rapidly after activating of crowbar resistance as shown in Figure 11(b). The rotor speed is varied according the crowbar resistance value.



(a) (b)

Figure 11. Rotor Speed during Grid Fault (a) Without Crowbar Protection (b) With Crowbar Protection

The peak rotor current exceeds more than the nominal value as shown in Figure 12. Currents reach values of 5 pu in rotor circuits, the decay exponentially subjecting the rotor side converter to very large stresses which are not acceptable because they may destroy the rotor side converter. The activation of the crowbar limits the rotor current as shown in Figure 13. Since the rotor-side converter is disconnected, the high rotor current is prevented from harming the converter. The current through the converter during fault period is shown in Figure 14. As it can be seen, the converter is turned off when the crowbar is activated and the current through the converter is zero.

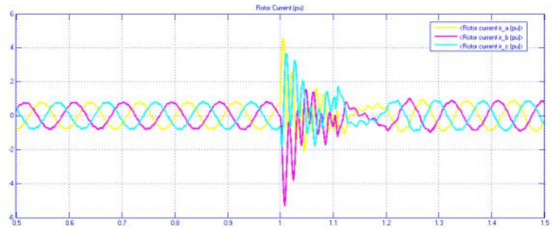


Figure 12. Rotor Currents during Grid Fault

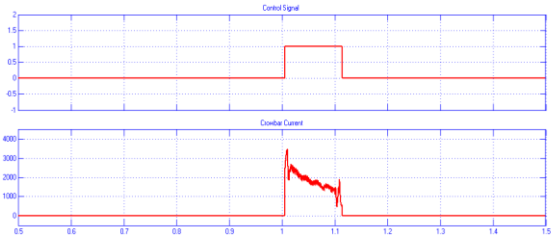


Figure 13. Control signal and Crowbar Current during Grid Fault with Crowbar Protection

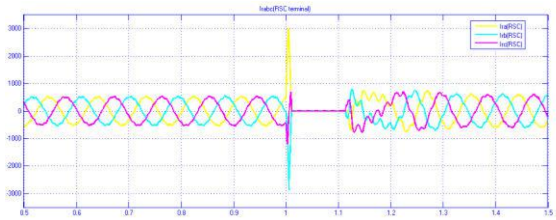


Figure 14. Electrical current through the rotor-side converter of the DFIG

7. CONCLUSION:

This paper investigates the performance of DFIG wind turbine connected grid during three-phase fault in presence of crowbar protection system. A dynamic model of 1.5 MW DFIG wind turbine connected grid is implemented using SimPowerSystem toolbox. The DFIG rotor current, rotor speed, active power, reactive power and DC-link voltage are investigated in steady state and fault state conditions. The over current in the rotor windings and over voltage in the DC bus can be well limited through an active crowbar circuit. In this paper, a three phase fault is applied at the PCC to investigate the system behavior with and without the active crowbar protection for 100 ms duration. The crowbar protection resistance is activated after fault occurrence with delay time of 10 ms. Also, it will deactivated after fault clearance with delay time of 10 ms. It shows that absence of crowbar resistance leads to high rotor current 5pu, high DC-link voltage reaches value of about 2.26 times of its normal value and more reactive power fluctuations during and post fault periods. When the crowbar protection is used, rotor current is decreased and DC-link voltage is decreased to 2000V while rotor speed is increased and when the crowbar is activated, the current through the converter is zero. When the crowbar protection is not used, the generated active power value during fault is more than that in the cases of using crowbar resistances. After fault clearance and reconnection of RSC, the DFIG can provide reactive power support to the grid and thus help in stabilizing of the grid voltage. During post fault period, the absorbed reactive power by the wind generators is decreased when the crowbar protection is used. Finally, the rotor current, rotor speed, DC-link voltage, active power and reactive power have low fluctuations during and post fault periods.

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