2nd International Conference on Energy Systems and Technologies
18 – 21 Feb. 2013, Cairo, Egypt

ASSESSING BEHAVOIR OF THE OUTER CROWBAR PROTECTION WITH THE DFIG DURING GRID FAULT

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Using of the doubly fed induction generators (DFIG) in modern variable-speed wind turbines increased rapidly. According to the new grid code requirements, wind turbines generators must remain connected to the grid during grid disturbances so protections systems is being used to protect the DFIG. This paper introduces a new proposed protection method which is named the outer crowbar protection. Operation and dynamic behavior of the outer crowbar protection with the DFIG during grid fault will be illustrated in this paper, this paper also introduces strategy of choice the optimum value of the outer crowbar resistance which achieves the stable performance of the DFIG during the grid.

Keywords: *Doubly fed induction generator, grid fault, crowbar protection, grid requirement.*

1. INTRODUCTION

Wind energy is a reliable, natural and renewable electrical power supply. The high installed capacity of today’s wind turbines and decreasing plant costs have shown that wind power can be competitive with conventional more heavily polluting fuels in the long term. Wind power growth with a 20% annual rate has been experienced the fastest growth among all renewable energy sources since five years ago. It is predicted that by 2020 up to 12% of the world's electricity will have been supplied by wind power so Wind generation is becoming the most development.

Renewable generation technology in the world during 2008, 27 GW of wind generation capacity was added to power networks around the world, indicating a 25% annual average growth rate in wind energy capacity [1]. DFIG has recently received much attention as one of preferred technology for wind power generation. Compared to a full rated converter system, the use of DFIG in a wind turbine offers many advantages, such as reduction of inverter cost, the potential to control torque and a slight increase in efficiency of wind energy extraction [2]. DFIGs offer several advantages when compared with FSIGs. These advantages, including speed control, reduced flicker, and four-quadrant active and reactive power capabilities, are primarily achieved via control of the rotor side converter (RSC), which is typically rated at 30% of the generator rating for a given rotor speed operating range of 0.75-1.25 p.u [3-4]. The DFIG is very sensitive to any grid disturbances, if a severe voltage dip occurred due to grid fault , high currents will pass through stator and rotor windings and also a very high DC voltage would be induced in converter circuit, it may lead to damage the converter circuit and the DFIG windings, Crowbar protections systems is essential to avoid the disconnection of the doubly fed induction wind generators from the network during faults and to protect the DFIG from the dangerous effects of the electrical fault. This paper presents a new proposed crowbar protection method which named outer crowbar ,and discusses the dynamic behavior of DFIG with different values of outer crowbar resistances value, the optimum value of the outer crowbar resistance was determined according to behavior of the DFIG during fault.

2. DFIG MODEL AND CONTROL

All wind turbines perform the function of converting mechanical to electrical energy for transportation via the electric transmission network. The energy conversion process begins with the energy input source: the wind, which obeys certain aerodynamic characteristics. The following section introduces the principles of extracted power from the wind to the turbine, the mechanical power that the turbine extracts from the wind and applied to the electrical subsystem for conversion is given by the following relationship

$$P_m = 0.5\ C_p\ (\lambda, \beta)\ \pi\rho\ R^2V^3 \qquad (1)$$

where (P_m) is the mechanical power and it is a function of the wind speed (V), the blade radius (R), the density of the air (ρ), and the performance coefficient of the rotor blades (C_p) which depends on tip-speed ratio (λ) and pitch angle (β). The tip speed ratio could be given from equation (2) where, (ω) is the angular speed of the turbines rotor Fig. 1 shows the variation of output power with different wind speeds [5].

$$\lambda = \frac{\omega R}{V} \qquad (2)$$

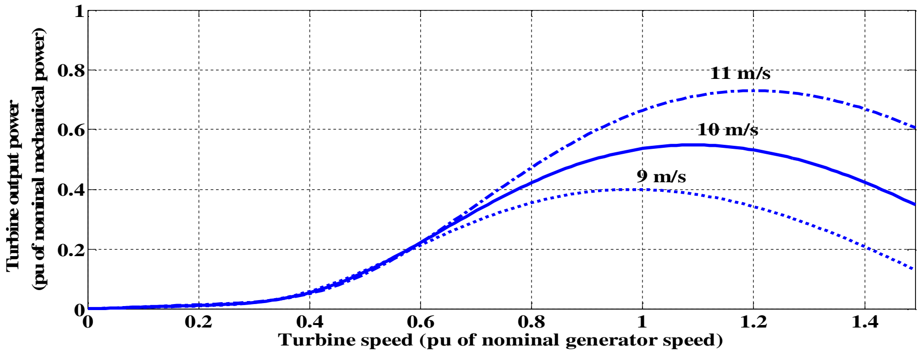


Figure 1. Turbine power characteristic

A DFIG system is essentially a wound rotor induction generator with slip rings, the stator directly connected to the grid and the rotor interfaced through a back-to-back partial-scale power converter. The DFIG is doubly fed by means that the voltage on the stator is applied from the grid and the voltage on the rotor is induced by the power converter [6]. The converter consists of two conventional voltage source converters (rotor-side converter RSC and grid-side converter GSC) and a common link DC-bus, as illustrated in Fig. 2.

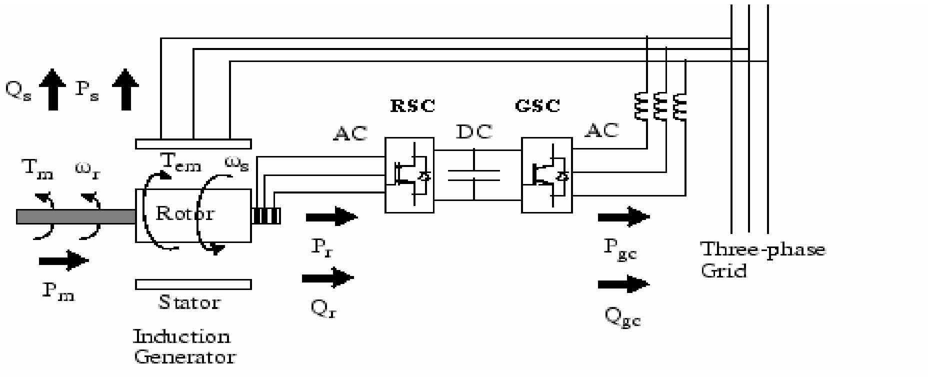


Figure 2. Typical construction of DFIG

The stator output powers of DFIG is given from equation (3), (4) where P_s , Q_s are the stator active and reactive powers respectively where L_s, L_m are stator and magnetizing inductances and Ψ_{ds} direct stator flux ,V_s stator voltage , I_{qr} and I_{dr} are the d-q axis rotor

$$P_s = -\frac{3}{2}\,\frac{L_m}{L_s}\,V_s\,I_{qr} \qquad (3)$$

$$Q_s = \frac{3}{2}\left[\frac{V_s\Psi_{ds}}{L_s} - \frac{V_s L_m}{L_s}\,I_{dr}\right] \qquad (4)$$

The RSC controls independently the active and reactive power injected by the DFIG into the grid in a stator flux d-q reference frame. The GSC 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.

3. PROTECTION OF THE DFIG

When a short circuit occurred at terminal of DFIG a simple protection system is used to limit the high induced currents and increasing of the DC-link voltage of the converter, this system is the crowbar protection system. There are many types of crowbar protections system: conventional crowbar, series crowbar and a new protection method, named the outer crowbar, the operation of these protections are illustrated:

3.1 Conventional Crowbar

The function of the conventional crowbar protection system when a short circuit occurred the RSC is disabled and bypassed , at the same time external resistors is coupled via the slip rings to the rotor winding instead of the converter as shown in Fig. 3, so the controllability of active and reactive power gets unfortunately lost[7].

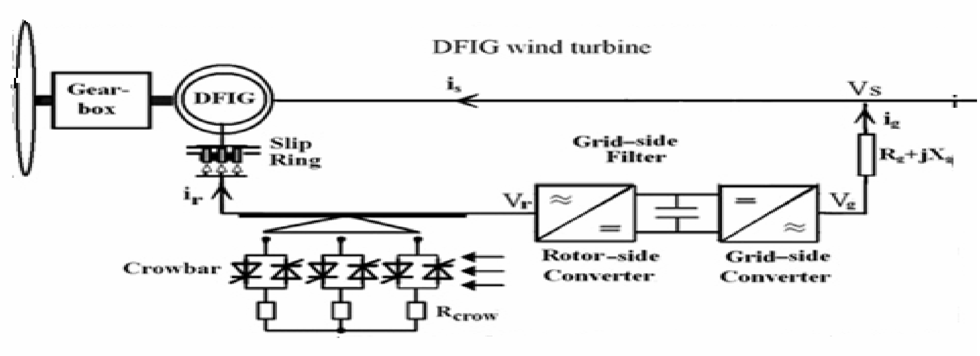


Figure 3. Schematic diagram of the conventional crowbar

3.2 Series Crowbar

As show in Fig. 4 the series crowbar consists of three resistances in parallel with bidirectional static switches connected in series with the stator windings, these switches are triggered when a short circuit is detected at the DFIG terminals. In normal operations, the static switches remain closed and the stator current will not pass through crowbar resistance. When a short circuit occurred, the switches are turned off. In this state, the stator current will pass through crowbar resistance and the crowbar resistance will be in series with the stator [8].

3.3 Outer Crowbar

It is the new proposed protection method. The construction and operation of the outer crowbar is similar to the series crowbar but the main difference between the series crowbar and the outer series crowbar is the outer crowbar connects in series with the DFIG instead of stator windings only, as shown in Fig. 5.

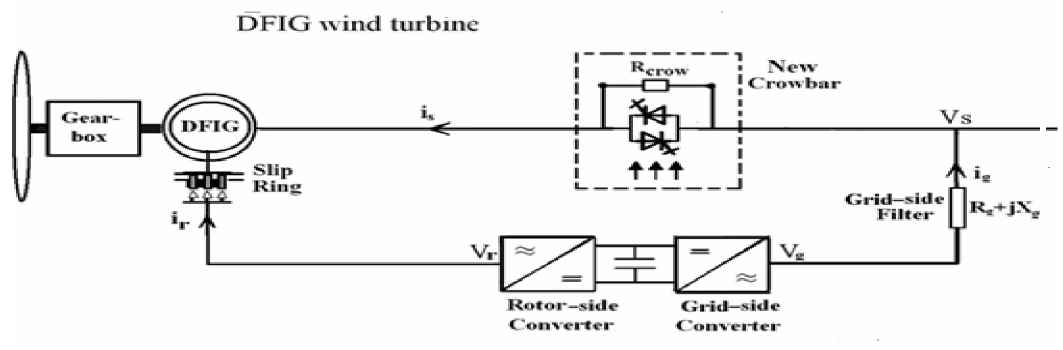


Figure 4. Schematic diagram of the series crowbar

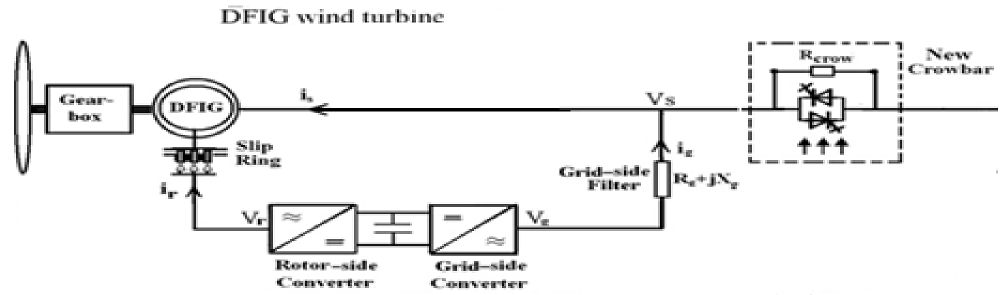


Figure 5. Schematic diagram of the outer crowbar

4. SIMULATED MODEL

To demonstrate the effect of a grid fault on a DFIG wind farm connected grid a detailed time domain model is investigated. Fig. 6 shows the single line diagram of the studied system. It consists of six 1.5 MW wind turbines connected to a 25-kV distribution system exports power to a 120-kV grid through a 30 km transmission line. The stator windings are connected directly to the 60 Hz grid while the rotor is fed at variable frequency through the RSC converter. The GSC is connected to the grid by a line filter to reduce the harmonics caused by the converter, all data of the DFIG and system parameters are shown in appendix A.

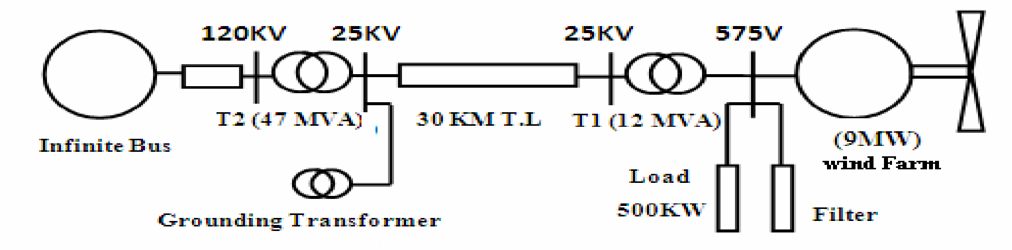


Figure 6. Simulated power system

Where the protection system detects it after 10 ms from its occurrence, before the fault occurrence bidirectional static switches are being turned on so there is no current will pass through the crowbar resistance but if the protection system detected the grid fault the static switches will turn off hence the current will pass through the crowbar resistance as mentioned before then the outer crowbar will deactivate after 10 ms from fault clearance, The simulation cases is performed for different value of outer crowbar resistances as shown in Table 1.

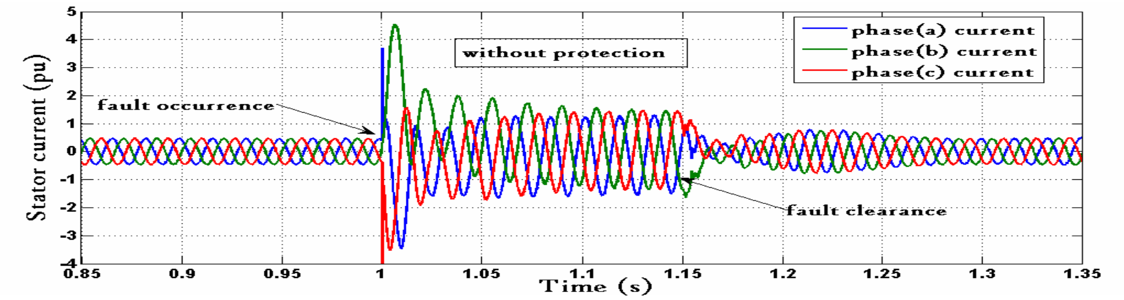
Table 1. Studied cases of the simulated model

Case 1	Without protection
Case 2	Outer crowbar = stator resistance
Case 3	Outer crowbar = 5× stator resistance
Case 4	Outer crowbar = 50× stator resistance
Case 5	Outer crowbar = 100× stator resistance

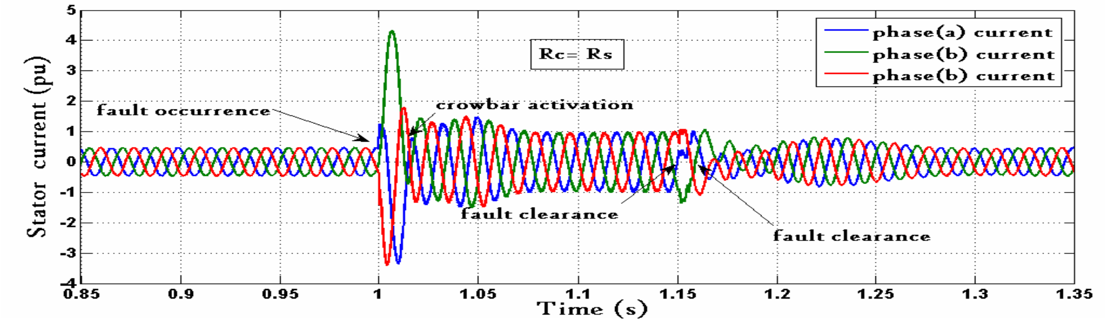
The new crowbar protection method (the outer crowbar protection) will be applied and the stator current, rotor current, electromagnetic torque, DC-link voltage, active power are monitored during grid disturbances.

5. PERFORMANCE OF CROWBAR PROTECIONS WITH THE DFIG

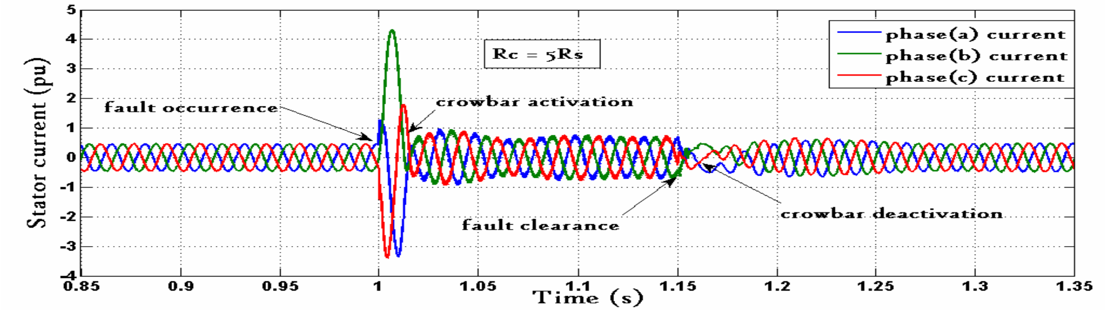
Fig. 7 shows variation of the stator current with different values of outer crowbar resistance, During steady state condition, the stator current value is 0.5 p.u while during fault period, the stator current increased to 3.694 p.u, 4.5 p.u and 3.43 p.u for the phases a, b and c respectively when the crowbar resistance is not activated for all studied cases. Fig. (7-a) shows the stator current variation when the crowbar resistance is not used. It is clear that the stator current is distorted during fault and it increased more than 1 p.u this value is not accepted. As shown in Fig. 7 the stator current is affected by the value of outer crowbar resistance during and post fault periods. If the value of the outer crowbar resistance (Rc) equaled the stator resistance the stator current would be 1.2 p.u during the fault then it decreased to 1 p.u, by increasing of the outer crowbar resistance the stator current will decrease. As shown in Fig. (7-d), if the outer crowbar resistance equaled 50 times of the series crowbar resistance ,the stator current would increase after crowbar deactivation to 1.7 p.u ,1.6 p.u for the phases b and c respectively these value is high and may wrongly activate the crowbar protection again, in the same way the stator current will increase after fault clearance to 2.4, 2.1 p.u for the phases b and c respectively if the outer crowbar resistance equaled 100 times of the stator resistance as shown in Fig. (7-e) the stator current. The optimal outer crowbar resistance value equals 5 times of stator resistance where the current has a little variation during fault period as shown in Fig. (7-c) Also after fault clearance, it has no considerable increase compared with the other cases.



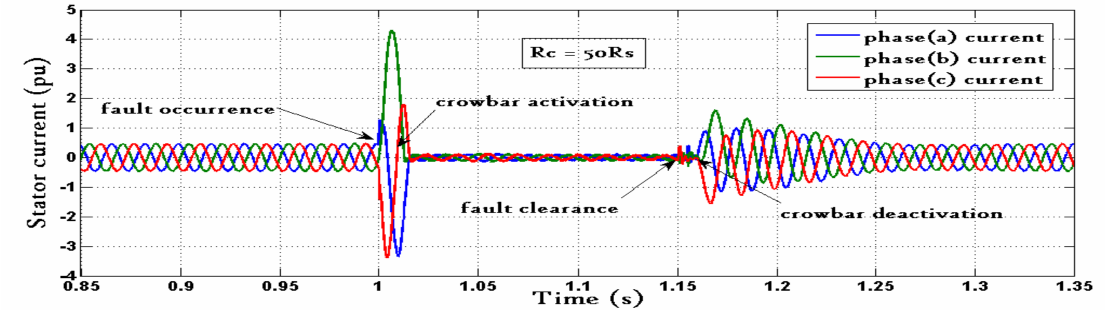
(a)



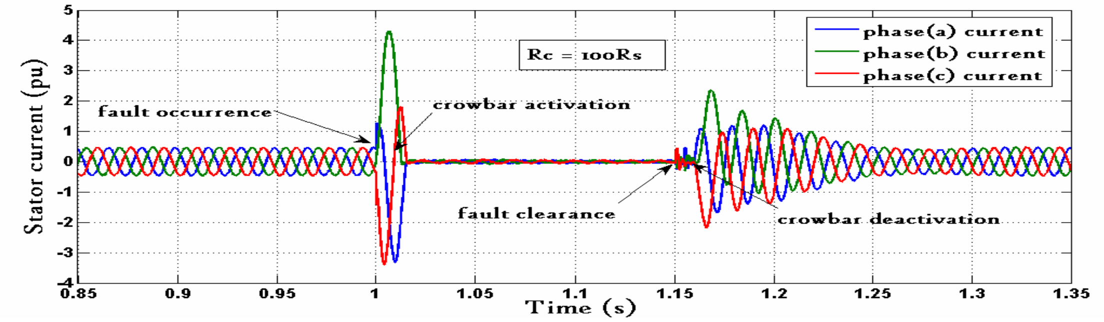
(b)



(c)

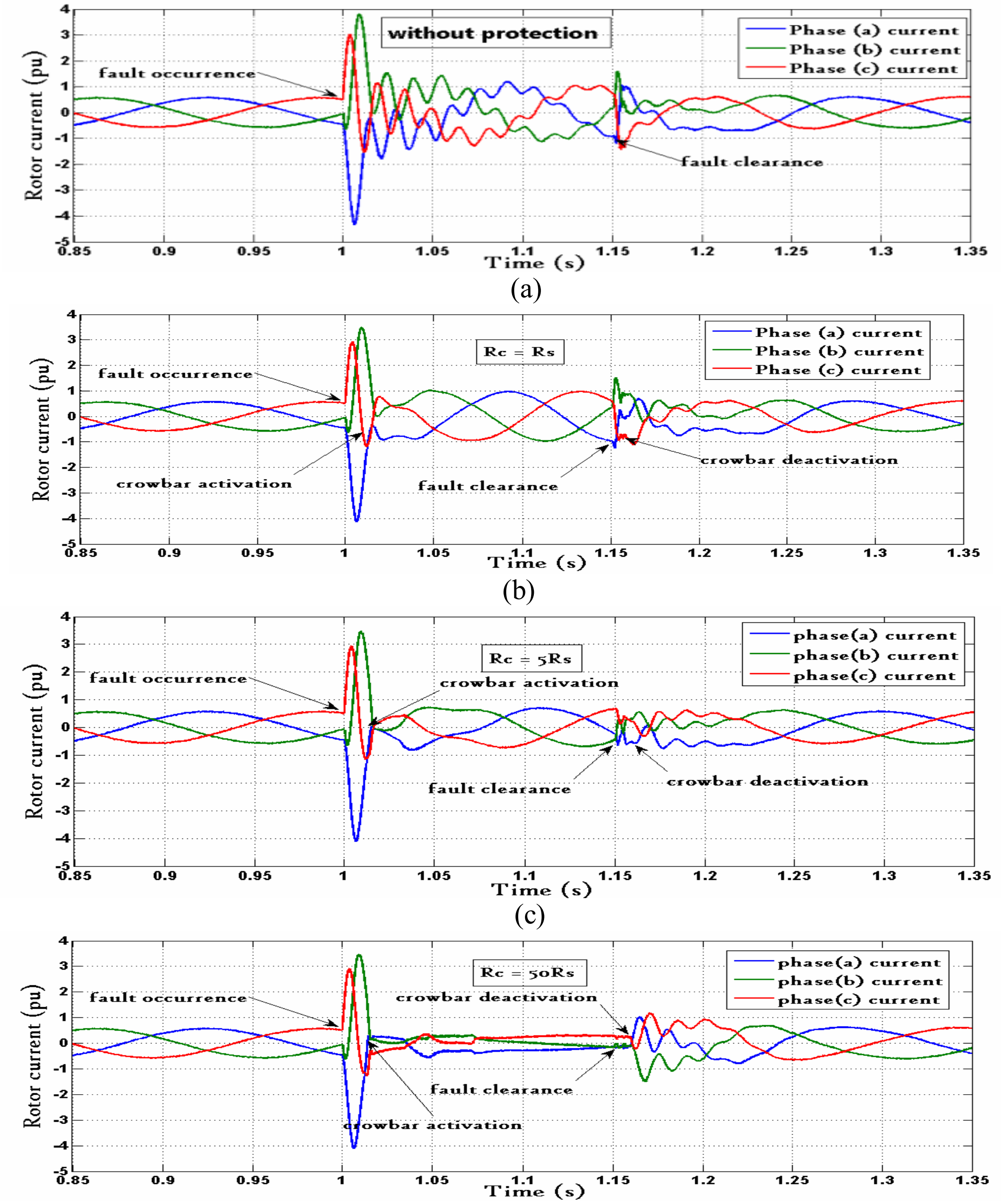


(d)



(e)

Figure 7. Stator current variations of the DFIG during fault for different values of the outer crowbar resistance

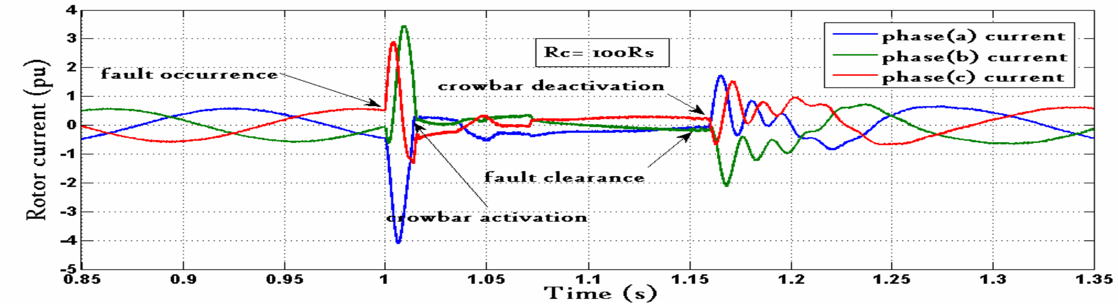


(a)

(b)

(c)

(d)



(e)

Figure 8. Rotor current variations of the DFIG during fault for different values of the outer crowbar resistance

Fig. 8 shows the variations of the rotor current with the proposed outer crowbar resistance. During steady state condition, the rotor current value is 0.5 p.u while during fault period, the rotor current is increased to 4.35 p.u, 3.8 p.u and 3 p.u for the phases a, b and c respectively, when the crowbar resistance is not activated for all studied cases. Fig. 8 (a) shows the rotor current variation when the crowbar resistance is not used. It is clear that the rotor current is distorted during fault period. After fault clearance, the rotor current is increased to 0.99 p.u, 1.6 p.u and 1.4 p.u for the phase a, b and c respectively. As shown in Fig. 8, the rotor current is affected by the value of outer crowbar resistance during and post fault periods, by increasing the value of the outer crowbar resistance the rotor current decreases during the grid fault. It is clear that the optimal outer crowbar resistance value equals 5 times of stator resistance where the current has a little variation during fault period as shown in Fig. 8(c). Also after fault clearance, it has no considerable increase compared with the other cases.

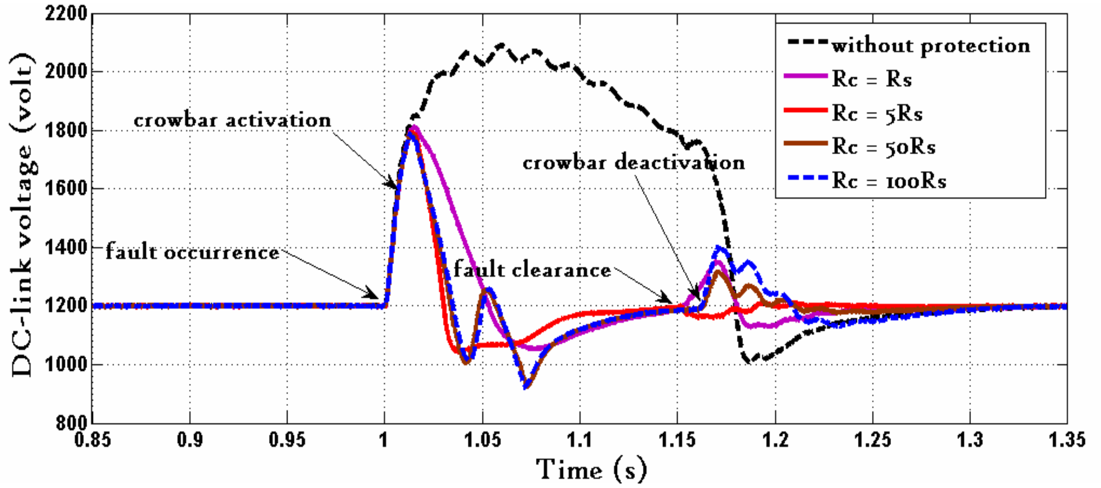


Figure 9. DC-link voltage variations of DFIG during fault for different values of the outer crowbar resistance

The main function of the crowbar system is protecting of the converter circuit from high voltages. Fig. 9 shows the variations of the DC-link voltage during fault with different outer crowbar resistances. The DC-link capacitance equals 60 mF with nominal voltage of

1200 V. When the system operates without crowbar resistance protection system, the DC-link voltage is increased to 2090 V during fault period this value considers very high. When the outer crowbar resistance equals the stator resistance, the DC-link voltage is increased to 1710 V then it is decreased to 1052 V during fault period, after fault clearance, the DC-link voltage is varied between 1350 V and 1135 V then it returns to steady state condition. When the outer crowbar resistance equals 5 times of the stator resistance, DC-link voltage is decreased to 1042 V during fault period and it returns to steady state condition during fault period. The fluctuation of the DC-link voltage is increased during and post fault periods when the outer crowbar resistance increased to 50 and 100 times of stator resistance, the DC-link voltage has a little variation during fault period and also after fault clearance at outer crowbar resistance value equals 5 times of stator resistance as compared with the other cases.

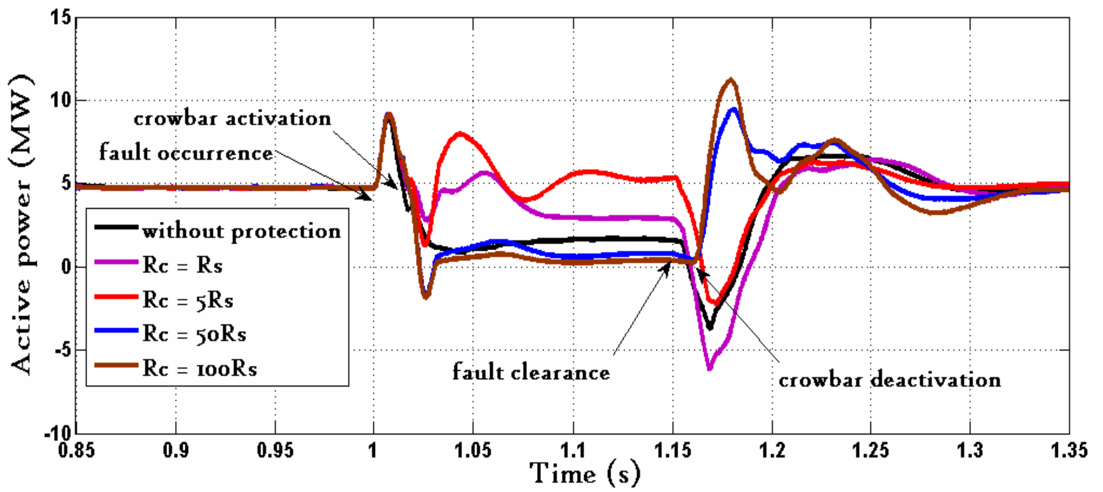


Figure 10. Active power variations of DFIG wind farm during fault for different values of the outer crowbar resistance

It is preferred captured more active power during the grid fault from generation units for utilizes and to avoid the cascaded disconnection of units during fault. Fig. 10 shows the variation the generated active power of the DFIG wind farm with the outer crowbar protection .Firstly the pre fault period is the steady state operation, the generated power produced by the DFIG wind farm produces 4.8 MW. When the fault occurs, the generated power increases to 8.93 MW for all studied cases then decreases. The active power decreases to 1.68 MW when the crowbar protection is not used. When the outer crowbar resistance equals stator resistance the active power decreases to 2.9 MW during the grid fault, after deactivation of the crowbar the power decrease to -6.04MW, then it returns to steady state. When the outer crowbar resistance equals 5 times of stator resistance, the active power increases to 7.9 MW then it decreases to 5.2 MW during the grid fault. After deactivation of the crowbar, the active power decreases to -2.1 MW then it returns to steady state. When the outer crowbar resistance equals 50 times of stator resistance, the active power decreases to 0.59 MW, after deactivation of the crowbar, the active power increases to 9.4 MW then it returns to steady state. When the outer crowbar resistance equals 100 times of stator resistance, the active power decreases to 0.28 MW, after deactivation of the crowbar, the active power increases to 11.19 MW then it returns. From above result, the optimum value of outer crowbar resistance when it equals 5 times of stator resistance because the DFIG produces more power compared with other cases during fault.

6. CONCLUSIONS

This paper studies the performance of DFIG wind turbine connected grid during three-phase fault in present of proposed outer crowbar protection system. The outer crowbar protection system consists of three resistances in parallel with bidirectional static switches which are connected at DFIG terminals. A dynamic model of DFIG wind turbines connected to grid is implemented using SimPowerSystem toolbox. The variations of stator current, rotor current, generated active power, DC-link voltage and the electromagnetic torque are investigated during and post fault periods. Several dynamic simulations are carried out for different terminal crowbar resistance values in case of 150 ms three-phase fault occurs at wind farm terminals. The simulation scenario is performed without crowbar protection and with outer crowbar resistances equal 1, 5, 50 and 100 times of stator resistance. The simulation results show that the system is more stable when the outer crowbar resistance equals 5 times of stator resistance. In this case, the values of stator current, rotor current, active power, DC-link voltage have low fluctuations during and post fault periods. Also, the system returns to the steady state condition in a time less than that of the other studied cases,and more active power could be capatcured by the DFIG at this value.

7. APPENDIX

APPENDIX A. DFIG DATA AND POWER SYSTEM DATA

DFIG parameters	
Rated power (MW)	1.5
Rated voltage (V)	575
Rated frequency (Hz)	60
Stator resistance (pu)	0.004843
Rotor resistance (pu)	0.004377
Stator leakage inductance (pu)	0.1248
Rotor leakage inductance (pu)	0.1791
Mutual inductance (pu)	6.77

Transmission line parameters	
Positive sequence resistance (ohm/km)	0.1153
Zero sequence resistance (ohm/km)	0.413
Positive sequence inductance (henries/km)	0.00105
Zero sequence inductance (henries/km)	0.00332
Positive sequence capacitance (farads/km)	11.33e-9
Zero sequence capacitance (farads/km)	5.01e-9

Transformer(T1) parameter	
Rated power (MVA)	12
Turns ratio	575V/25KV

Impedance (pu)	0.0017+j0.05

Transformer(T2) parameter

Rated power (MVA)	47
Turns ratio	25KV/120KV
Impedance (pu)	0.00534+j0.16

Grid impedance

Impedance (pu)	0.0004+j0.004

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