Control and Simulation of a Crowbar Protection for DFIG Wind Turbine during Power Systems Disturbance

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Abstract The use of the doubly fed induction generator (DFIG) in modern variable-speed wind turbines has increased rapidly. According to the new grid code requirements, wind turbines generators must remain connected to the grid during grid disturbances so crowbar protections systems is being used to protect the DFIG, this paper introduces a comparison between conventional crowbar protection, series crowbar protection and new protection method, 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.

Keywords: DFIG, Crowbar, Grid fault, Protection

1. Introduction
A Doubly-Fed Induction Generator can realize the variable speed operation and thus maximize the output power from the wind turbine [1]. Doubly fed induction generator (DFIG), is used extensively for high-power wind applications. Half of the world’s leading wind turbine manufacturers use the doubly fed induction generator systems. This is due to the fact that the power electronic converter only has to handle a fraction (20% – 30%) of the total power, i.e., the slip power. This means that if the speed is in the range ±30% around the synchronous speed, the converter has a rating of 30% of the rated turbine power, reducing the losses in the power electronic converter, compared to a system where the converter has to handle the total power. In addition, the cost of the converter becomes lower. DFIG’s ability to control rotor currents allows for reactive power control and variable speed operation, so it can operate at maximum efficiency over a wide range of wind speeds [2]. The main objectives of the proposed controller are tracking the maximum power point (MPP) and providing an independent control of active and reactive powers. Tracking the MPP can be achieved by controlling the pitch angles of the wind turbine blades as an outer control loop to force the wind turbine to work around its maximum coefficient of performance (Cp). The variation of the pitch angle can be achieved by using the aerodynamic characteristics of the wind turbine [3] or fuzzy controller [4]. Active power can be controlled by the quadrature component of the rotor current Iqr while the reactive power can be controlled by the direct axis of the rotor current Idr. The proposed system contains six wind turbines with rating shown in the appendix. Each wind turbine derives a DFIG connected to the electric utility. The system is connected to the electric utility via a step up transformer and a transmission line and another step up transformer as shown in Fig. 1. The proposed control strategy for decoupling active and reactive power is accomplished by using FOC technique and aligning the reference frame along the rotor voltage position. In this case the active and reactive power can be controlled by using Idr and Iqr respectively. 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.

2. DFIG Model and Control
The aerodynamic model of a wind turbine is determined by its power speed characteristics [1]-[5]. Wind turbine power depends on both the rotor speed
and wind speed. The captured power is given by the following equation

\[ P_m = \frac{1}{2} \rho A u^3 C_p(\beta, \lambda) \]

(1)

Where, \( \rho \) is the air density (Kg/m\(^3\)), \( A \) is the turbine rotor cross sectional area (m\(^2\)), \( u \) is the wind speed (m/s), and \( C_p(\beta, \lambda) \) is the power coefficient that depends on both, pitch angle \( \beta \) and tip speed ratio \( \lambda \). The tip speed ratio is defined as:

\[ \lambda = \frac{\omega_T R_T}{u} \]  

(2)

Where, \( \omega_T \) is the turbine rotor angular speed (rad/s), and \( R_T \) is the wind turbine rotor radius (m). The power coefficient \( C_p \) as function of tip speed ratio \( \lambda \) is shown in Figure 2, parameterized in function of the pitch angle \( \beta \). It is evident from Fig. 2. that for maximum energy capture, the maximum power coefficient and, thus, the optimum tip speed ratio should be maintained at all wind speeds. The need to vary the rotor speed in accordance to the wind speed for maximum energy capture, establishes the foundation for the preferred choice of Variable Speed WES.

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 [8]. The converter consists of two conventional voltage source Converters (rotor-side converter RSC and grid-side converter GSC) and a common link DC-bus.
Rotor side converter (RSC) is modeled as a voltage source converter. The switching dynamics of IGBT switches are neglected [31]. The main task of the RSC control system is to track the maximum power point (MPP) of the wind turbine and to control the reactive power required by the electric utility. The rotor-side converter is used to control the wind turbine output power and the voltage measured at the grid terminals. The power is controlled in order to follow a pre-defined power-speed characteristic, named tracking characteristic.

The RSC controls independently the active and reactive power injected by the DFIG into the grid in a stator flux d-q reference frame. Fig. 3 shows the control scheme of the RSC. The q-axis current component \( I_{qr} \) is used to control the active power according to equation (9) and by using a maximum power tracking strategy to calculate the active power reference. The actual speed of the turbine \( \omega_r \) 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 \( P_{ref} \) 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.

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 latter signal is subtracted with its current value \( I_{dr} \) and the error is sent to another PI controller to obtain the reference voltage for the d-axis component.

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. The control of the GSC is performed using the d-q reference frame. Figure 4 shows the control system of the GSC, 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.

![Fig.3 Schematic diagram of RSC control system.](image1)

![Fig.4 Schematic diagram of GSC control system.](image2)
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 in the following sections. The system is tested under a three phase short circuit at the wind farm terminals and compared results are discussed.

3.1 Conventional Crowbar Protection
The function of conventional crowbar when a short circuit occurred the RSC is disabled and bypassed, at the same time external resistors are coupled via the slip rings of the rotor windings instead of the converter as shown in Fig.5, so the controllability of active and reactive power unfortunately lost [10].

3.2 Series Crowbar Protection
As shown in Fig.6 the series crowbar consists of three resistors in parallel with bidirectional static switches connected in series with stator winding, 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 short circuit occurs, 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.

3.3 Outer Crowbar Protection
The construction and operation of the outer crowbar is similar to the series crowbar but the main difference between series crowbar and series outer crowbar is that the outer crowbar connected in series with the DFIG instead of the stator winding only as shown in Fig.7.

4. Simulated Model Description
The wind farm considered in this study has a total installed capacity of 9 MW, consisting of six wind turbines, each having a capacity of 1.5 MW and a rated output voltage of 575V. These wind turbines are variable speed, pitch regulated Doubly Fed Induction Generators (DFIG). An adjustable tower cable will connect the generator output to a pad mounted generator step-up transformer (575V/25 kV), which is located close to the tower base. Medium voltage side of the step-up transformer is connected to the Medium Voltage (MV) bus rated at 25kV. Further stepping up of voltage is done by the main step-up transformer (25/120 kV), which is located at the substation and then connected to the power system (120 kV) at Point of Common Coupling (PCC). The Medium Voltage (MV) bus is connected to the step up transformer via 30Km π section Transmission Line. The simulated disturbance is a three phase fault occurs at the wind farm terminals for 100 ms duration, 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.
As shown from Fig. 8, when the system operate under fault without any protection the stator current reaches about four times the normal current. A protection system using different types of crowbar is used in the system under test. The crowbar protection system is controlled to be activated after 10ms from the fault occurrence and deactivated after another 10ms from fault clearance. In conventional protection system the stator current falls after the crowbar system activation to 1.2 times of normal current. In series crowbar system when crowbar is activated the fault current drops to about 0.2 of normal current but at the moment of crowbar deactivation the fault current reaches about 4 times the normal current again. In outer crowbar system the fault current after crowbar deactivation increased but less than the value in series system.

Fig. 9 shows rotor current variation during fault and as shown, when no protection is used the rotor current increased during the fault period and results in increase in the DC bus voltage. Using conventional crowbar system decreases the rotor current to very small value. Using series and outer crowbar protection keep the rotor current during fault approximately the same as before the fault but in outer crowbar system as the DFIG looks like as feeding a resistive load then the DC bus voltage is decreased as an extra power is needed.

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Fig.10.a shows the DC bus voltage variation for the different methods of crowbar protection. As shown from the figure that without crowbar protection the DC bus voltage, during fault, reaches about 2300V although its rated value is 1150V. This high voltage is the biggest problem as it will cause very high rotor current which will cause damage to the RSC. Fig.10.a shows also that using crowbar protection reduces the DC bus voltage during fault. Conventional and series crowbar protection reduces the voltage to about 1500V but the new method reduces the voltage to about 600V.

Fig.10.b shows the generated active power variation with time. As shown from the figure that conventional and series crowbar protection gives more stable operation as the generated power reaches its prefault value within 150msec, but the generated power in case of outer crowbar protection reaches -6 p.u after fault clearance.

The Electromagnetic torque will fluctuate with variation of the rotor current, this torque will affect on the mechanical stress on the gearbox. Fig.10.c shows the variations of Electromagnetic torque, during the normal operation this torque equals -0.7 p.u (minus sign refers to the electromagnetic torque is in opposed direction with the mechanical input torque), when the grid fault occurs the electromagnetic torque will decrease to -2.7 p.u it will increase to 1.4 p.u then it is decreased and fluctuated during the grid fault. By applying the outer crowbar protection the fluctuation of the electromagnetic torque will decrease and the maximum value of torque after applying outer crowbar protection reaches only 0.5p.u.

5. Conclusion
This paper studies the performance of DFIG wind turbine connected grid during three-phase fault in present of three different crowbar protection systems. The new crowbar protection system used is outer crowbar protection system. The outer crowbar protection system consists of three resistances in parallel with bidirectional static switches which is connected at DFIG terminal. A dynamic model of DFIG wind turbines connected grid is implemented using MATLAB SIMULINK. 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 crowbar in case of 100 ms three-phase fault occurs at wind farm terminals. In this case, the values of stator current, rotor current, active power, DC-link voltage and electromagnetic torque have low fluctuations during and post fault periods. Also, the system returns to the steady state condition in a less time.

References


