Analysis and Simulation of a Crowbar Protection for DFIG Wind Application during Power Systems Disturbances

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Received: June 07, 2011 / Accepted: June 21, 2011 / Published: September 25, 2011.

Abstract: The performance of a 1.5 MVA wind-power Doubly Fed Induction Generator (DFIG) under network fault is studied using simulator developed in MATLAB-SIMULINK. This paper investigates a new control method able to improve the fault-ride through capability of DFIG. In such generators the appearance of severe voltage sags at the coupling point make highlight important over currents at the rotor/stator windings, making the use of crowbar protection device necessary and inevitable in order to protect the machine as well as the rotor side power converter. The simulator consists of the DFIG analytical model, power transformer model and the detailed frequency converter model including crowbar protection device. Simulation results are carried out to show the transient behavior of the DFIG when a sudden voltage dip is introduced with and without the crowbar implementation.

Key words: Wind energy, DFIG (doubly fed induction generator), crowbar, LVRT (low voltage ride through), power network, simulation.

Nomenclature

<table>
<thead>
<tr>
<th>DFIG</th>
<th>Doubly Fed Induction Generator</th>
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<tbody>
<tr>
<td>LVRT</td>
<td>Low Voltage Ride Through</td>
</tr>
<tr>
<td>( P_m )</td>
<td>Mechanical power captured by the wind turbine and transmitted to the rotor</td>
</tr>
<tr>
<td>( P_s )</td>
<td>Stator electrical power output</td>
</tr>
<tr>
<td>( P_r )</td>
<td>Rotor electrical power output</td>
</tr>
<tr>
<td>( P_{gc} )</td>
<td>Cgrid electrical power output</td>
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<tr>
<td>( Q_s )</td>
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</tr>
<tr>
<td>( T_m )</td>
<td>Mechanical torque applied to rotor</td>
</tr>
<tr>
<td>( T_{em} )</td>
<td>Electromagnetic torque applied to the rotor by the generator</td>
</tr>
<tr>
<td>( \omega_r )</td>
<td>Rotational speed of the rotor</td>
</tr>
<tr>
<td>( \omega_s )</td>
<td>Rotational speed of the magnetic flux in the air-gap of the generator, this speed is named synchronous speed. It is proportional to the frequency of the grid and to the number of generator poles</td>
</tr>
<tr>
<td>J</td>
<td>Combined rotor and wind turbine inertia coefficient</td>
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1. Introduction

The growing use of wind energy generates several research activities in broad technical areas. Increasingly, the introduction of wind energy in the network under agreement highlights several important issues, such as security, systems stability and quality of energy produced [1].

With increased penetration of wind power into electrical grids, DFIG wind turbines are largely deployed due to their variable speed feature and hence influencing system dynamics. This has created an interest in developing suitable models for DFIG to be integrated into power system studies. 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. The DFIG wind turbines are nowadays more widely used especially in large wind farms.

The main reason for the popularity of the doubly fed wind induction generators connected to the national networks is their ability to supply power at constant voltage and frequency while the rotor speed varies.

DFIG wind turbine utilizes a wound rotor induction machine while the rotor winding is supplied from frequency converter providing speed control together with terminal voltage and power factor control for the overall system. The transient simulation analysis is also a useful tool for the design of the rotor overcurrent protection. The overcurrent protection circuit, so called crowbar is needed in order to protect the rotor side frequency converter during disturbances in the network [2-3]. The most common approach in dynamic modeling of DFIG for wind turbines is using a space vector theory based model of a slip-ring induction machine [2, 4-5]. This method provides sufficient accuracy also in case when the voltage dips due to one or two phase faults in the network [6-7]. The transient analyses of the DFIG wind-turbine have been studied in Refs. [8-10] where the crowbar is realized by using of six anti-parallel thyristors and with an active crowbar in Ref. [1].

The aim of this paper is to investigate and presents the transient simulation analysis of a 1.5 MVA DFIG for wind power application under a three-phase network short circuit. For dynamic simulation purposes, these investigations are carried out based on well prepared Matlab simulation software’s [11-12].

The paper is organized as follows: Section 2 shows the descriptions of the simulation models. The DFIG simulations under fault and without crowbar are given in section 3 after discussing the safe behavior of the system. Section 4 discusses the simulation results of DFIG system under fault (Low Voltage Ride Through LVRT) and using a crowbar protection device. In this case, it is assumed that the power electronics converters are reacting without any delay. Finally, concluding remarks on the use of such protecting device for DFIG application end the paper.

2. Descriptions of Simulation Models

The wind turbine and the doubly-fed induction generator (WTDFIG) are shown in the Fig. 1. The AC/DC/AC conversion system is divided into two components shown as rotor-side converter (Crotor) and grid-side converter (Cgrid). Crotor and Cgrid are Voltage-Sourced Converters that use forced-commutated power electronic devices (IGBTs “Insulated-gate bipolar transistor”) to synthesize an AC voltage from a DC voltage source. A capacitor connected on the DC side acts as the DC voltage source [13]. A coupling inductor L is used to connect Cgrid to the grid. The three-phase rotor winding is connected to Crotor by slip rings and brushes and the three-phase stator winding is directly connected to the grid [1]. The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings.

The mechanical power and the stator electric power output are computed as follows:
\[ P_m = T_m \omega_r, \quad P_s = T_{em} \omega_s \]  
(1)

For a loss less generator the mechanical equation is

\[ J \frac{d \omega_s}{dt} = T_m - T_{em} \]  
(2)

In steady-state at fixed speed for a loss less generator and

\[ T_m = T_{em} \text{ and } T_m = P_s + P_r. \]  
(3)

It follows that

\[ P_s = P_m - P_r = T_m \omega_r - T_{em} \omega_s = -T_m \frac{\omega_m - \omega_s}{\omega_s} \omega_s \]  
(4)

\[ = -sT_m \omega_s = -sP_t \]

where \( s \) is defined as the slip of the generator,

\[ s = \frac{\omega_s - \omega_r}{\omega_r} \]  
(5)

Generally the absolute value of slip is much lower than 1 and, consequently Fig. 2, \( P_r \) is only a fraction of \( P_s \). Since \( T_m \) is positive for power generation and since \( \omega_s \) is positive and constant for a constant frequency grid voltage, the sign of \( P_r \) is a function of the slip sign. \( P_r \) is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). For super-synchronous speed operation, \( P_r \) is transmitted to DC bus capacitor and tends to rise the DC voltage. For sub-synchronous speed operation, \( P_r \) is taken out of DC bus capacitor and tends to decrease the DC voltage. \( C_{grid} \) is used to generate or absorb the power \( P_{gc} \) in order to keep the DC voltage constant. In steady-state for a loss less AC/DC/AC converter \( P_{gc} \) is equal to \( P_r \) and the speed of the wind turbine is determined by the power \( P_r \) absorbed or generated by \( C_{rotor} \). The power control will be explained below. The phase-sequence of the AC voltage generated by \( C_{rotor} \) is positive for sub-synchronous speed and negative for super-synchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip. \( C_{rotor} \) and \( C_{grid} \) have the capability of generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals [11].

![Fig. 2 The power flow of the wind turbine DFIG [11].](image)

### 2.1 Wind Turbine Model

The wind turbine model is a pitch controlled one. The pitch angle reference \( \beta_{ref} \) is obtained from the DFIG control block.

The torque on the induction generator shaft is given by the wind turbine block in which a look-up table is used in order to deduce the power coefficient \( C_p \). During the whole simulation time, the wind speed is fixed constant and equal to 10 m/s.

### 2.2 Induction Machine Model

In order to simulate accurately the maximum short-circuit current and Low Voltage Ride Through (LVRT) behavior, the fifth order state space model is used as an induction generator model. The induction generator parameters are reported in Ref. [11]. The DFIG wind farm is composed of six aggregated units of 1.5 MW each designation.

### 2.3 Rotor Side Converter

The rotor and grid converters are similar four quadrant ones, and modeled using universal bridge model with IGBTs “Insulated-gate bipolar transistor” connected to induction rotor windings in one side and the power network in the other one.

### 2.4 Crowbar

The SimPowerSystems DFIG model does not include a crowbar protection. This has therefore been
added, with some simplifications. The crowbar is made up of a symmetric three phase y-connected resistance. It is connected to the rotor through a controllable breaker. This is not the real case (in reality, the crowbar may be made up of one resistance fed through a switched rectifier bridge), but it may be sufficient for us to assess the overall impact of a crowbar protection on the LVRT. The breaker is normally open, but it is closed short-circuiting the rotor through the resistance if either the rotor current or the DC-link capacitor voltage becomes too high. At the same time the switching of the RSC “Route Switch Controller” is stopped [10].

The value of the crowbar resistance is chosen according to Refs. [1, 12] as 20 times the rotor resistance. The choice of the crowbar resistance is important because, as we will see, it determines how much reactive power the DFIG will draw while the crowbar is inserted.

2.5 Network Model

The 9 MW wind farm is connected to a 25 kV network, via a 25/0.575 kV transformer. The transformer is rated 12 MVA. A resistive load of 500kw is connected at the wind farm. A high pass capacitor filter is used, the DFIG wind farm is connected to the 120 kV network through a 30 km 25 kV line and a 120/25 kV transformer. All the parameters are keeping the same as given the Matlab/Simulink detailed demo file [11].

3. DFIG Simulations under Fault (LVRT) and without Crowbar

The 3-phase fault located at the connection between 120/25 kV transformer and the 25 kV line, is simulated at \( t = 500 \) ms and removed at \( t = 650 \) ms (see Figs. 3-7).

The transient stator current, rotor current, grid and electromagnetic torque when the crowbar is not implemented and without fault are depicted in figures below shows the detailed stator, rotor and DC-link voltage waveforms.
3.1 Results from DFIG Simulations without Fault and without Crowbar

Figs. 3-7 show the simulated results of DFIG without fault and without crowbar.

3.2 Results from DFIG LVRT Simulations with Fault and without Crowbar

At the fault instant, 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 reduction in the active power. As the stator flux decreases, the magnetization that has been stored in the magnetic field is released. Immediately after fault, the generator starts to absorb reactive power for its magnetization from the power system as shown below in Figs. 8-13. When the voltage in poverty the network side converter is no longer able to transfer power to the rotor side converter therefore received the additional power will be borne by the capacitor voltage, which generates a rapid increase in the DC voltage converter.

The transient stator current, rotor current, grid and electromagnetic torque when the fault is implemented and without crowbar are depicted in figures below shows the detailed stator, rotor and DC-link voltage waveforms.

Due to the resulting high transient currents in the rotor with a peak value more than 2.5 p.u., the DC link voltage rises up and the protection disconnects the rotor from the DC link by turning off all positive side IGBTs and turning on all negative side IGBTs thus short circuiting the rotor. A high transient current can also be observed at the stator side and its amplitude is a bit less than 2 p.u.

The electromagnetic torque due to the transients in the rotor and stator first increases in negative direction down to –1.8 p.u., then rapidly rises in the positive direction up to 1.6 p.u. and then starts to oscillate. At the time instance 5.3 s, the stator of DFIG is disconnected from the network by opening the main circuit breaker because the network fault remains.

The transient stator current, rotor current, grid and electromagnetic torque when the fault is implemented and without crowbar are depicted in figures below shows the detailed stator, rotor and DC-link voltage waveforms.

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4. DFIG Simulations with Fault (LVRT) and with Crowbar

The following Doubly Fed Wind-Power Induction Generator with the Crowbar is shown in Fig. 14.

Simulation of DFIG under network disturbances with the crowbar similarly as in previous case the 3-phase short circuit has been introduced at the time instant 0.5 s and fault has been modeled by a stator voltage reduction down to 35% of the nominal value. The diode bridge crowbar has been modeled according to the description in the previous part. The simulated transient stator current, rotor current, grid and electromagnetic torque, when the crowbar over-current protection is implemented are depicted in figures below.
4.1 Crowbar

The crowbar schema given in Fig. 15 is used to assess the overall impact of protection on the LVRT. The crowbar is made up of one resistance fed through a three phase diode rectifier bridge which is connected to the rotor side via a controllable three phase circuit breaker. The circuit breaker which is normally open will be closed in order to short-circuit the rotor if rotor current of DC-link capacitor voltage are too high. In meantime, the switching of the rotor side converter is stopped.

4.2 Results from DFIG LVRT Simulations with Crowbar

The simulation of the LVRT of a DFIG wind farm has been performed using the described crowbar protection. The results are shown below in Figs. 16-23.
Before the fault, the DFIG wind farm was in steady state with almost no reactive power. When the fault occurs, the crowbar protection is triggered, protecting the RSC which stops switching. The rotor current in the crowbar and the rotor windings decays and the DC-link voltage increases slightly while the crowbar is connected. Notice that the crowbar disconnects and the RSC starts switching while the fault is still active, at about 70 ms after the fault. This is important since it allows the DFIG to feed reactive power (about 0.3 pu) into the network, increasing the voltage. This of course may have a positive effect for the voltage stability of the system. The rotor current in the DFIG windings ($I_{abc\_rot\_IG}$) decreases, while the RSC current ($I_{rot}$) is zero when
the crowbar is active. The RSC voltage is then the voltage over the crowbar. The DC-link capacitor voltage does not increase much just after the fault. However, its increase is very high (2 pu) when the fault is disconnected at 650 ms, even though the crowbar is correctly reinserted to limit the RSC current. This increase, as can be seen, is due to the fact that the DFIG absorbs active power just after the fault is disconnected. This clearly indicates the need for a chopper to be connected across the DC-link capacitor to limit its voltage.

Finally notice that when the fault is disconnected, the DFIG absorbs reactive power, thus decreasing the voltage in the network.

This is due to the fact that, being the crowbar still connected for a long time (because of the high DC-link voltage).

5. Conclusions

Low Voltage Ride Through (LVRT) for DFIG Wind Turbines is a challenge that all wind farm manufacturers and users must resolve taking into account grid codes constraints as dictated by power network transmission system operators (TSOs “Transmission System Operator”). Having different grid codes from one power network operator to another [14], this concern has not yet been fully and globally handled. In order to tackle LVRT issue on a global basis, the ideal solution would be the use of low cost additional materials together with control strategies adaptation at turbine and crowbar levels.

The survival of a wind turbine under default depends on the location of fault, its duration, the fault type as well the method of reactive power compensation. In order to avoid strong currents flowing in the rotor, a crowbar protection system can be activated to dissipate the superfluous active power. This activation will however turn the DFIC into a squirrel cage IG “Induction Generator”, losing its ability to control reactive power. Moreover, if the resistance crowbar is chosen properly (it is suggested that 20 times the resistance of the rotor), it limits the amount of reactive power absorbed by the DFIG when the crowbar is activated (IG).

This paper discusses the behavior of a DFIG wind farm with default highlighting LVRT issues. The dynamic simulation results performed on this variable speed wind turbine show that the wind can survive to the many event of default, which satisfies the tour through low voltage requirement for which it was designed. In order to increase wind energy penetration and guarantee the power network stability in the mean time, new grid codes with even more restrictions during network outages are expected. This will enforce the development of new protection systems able to deliver in the same the needed reactive power. These new systems will have to be taken into account when designing global control strategies.

References

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