Performance of DFIG Variable Speed Wind Turbines under Grid Fault Conditions

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Abstract- DFIG–wind turbine is an integrated part of distributed generation system. Therefore, any abnormalities associates with grid are going to affect the system performance considerably. Taking this into account, the performance of double fed induction generator (DFIG) variable speed wind turbine under network fault is studied using simulation developed in MATLAB/SIMULINK. Simulation results show the transient behavior of the double fed induction generator when a sudden short circuit at the generator bus is introduced. After the clearance of the fault the control schemes manage to restore the wind turbine's normal operation. The controller performance is demonstrated by simulation result both during fault and the clearance of the fault.

Index terms: DFIG, Wind turbine, rotor side converter, grid side converter and Short circuit

NOMENCLATURE

ρ: air density (Kg/m³).
A: turbine rotor swept area (m²).
U: wind speed (m/s).
β: pitch angle.
λ: tip speed ratio.

\( C_p(\lambda, \beta) \): is the power coefficient that depends on both, pitch angle \( \beta \) and tip speed ratio \( \lambda \).

\( \omega_T \): the turbine rotor angular speed (rad/s).
\( \omega_G \): generator angular speed (rad/s)

\( R_T \): the wind turbine rotor radius (m).
\( J_G \): generator inertia (Nms²/rad).
\( D_T \): turbine friction damping (Nms/rad).
\( K_a \): shaft stiffness (Nm/rad).
\( T_T, T_G \) and \( T_a \): turbine, generator and shaft torques (N m).
\( \theta_T, \theta_G \): turbine and generator angular positions (rad).

\( V_{ds}, V_{qs} \): d- and q- axis stator voltages respectively
\( V_{dr}, V_{qr} \): d- and q- axis rotor voltages respectively.
\( I_{ds}, I_{qs} \): d- and q- axis stator currents respectively.
\( I_{dr}, I_{qr} \): d- and q- axis rotor currents respectively.
\( \psi_{ds}, \psi_{qs} \): d- and q- axis stator flux linkages respectively.
\( \psi_{dr}, \psi_{qr} \): d- and q-axis rotor flux linkages respectively.

\( R_s, R_r \): Stator and rotor resistances respectively.
\( L_s, L_r \): Stator and rotor leakage inductances respectively.
\( L_m \): Mutual inductance of stator and rotor.

\( \omega_m, \omega_r, \omega_s \): Mechanical, synchronous and rotor speeds respectively.

\( P_m, P_r, Q_r \): Mechanical, stator active and rotor reactive powers respectively.
The doubly fed induction generator variable speed wind turbine introduces itself as a very attractive option for installations with a fast growing market demand. The fundamental feature of the DFIG is that the power processed by the power converter is only a fraction of the total wind turbine power, and therefore its size, cost and losses are much smaller compared to a full size power converter [1]. The increase in electrical power generation from wind power is likely to affect the operation of the networks, especially the power system stability. When a fault occurs, the grid connected wind turbine should restore its normal operation without disconnection from the grid. The reason is that the disconnection of wind turbines may cause an important loss of generation that may threaten the power system stability.

This paper studies the transient response of variable speed Wind turbines with DFIG during fault condition and after the clearance of short-circuit fault at the generator bus. A simulation model of a 1.5MW wind turbine with DFIG is presented, and the control schemes of the wind turbine are described in detail. The simulation results show how the control schemes effectively manage to restore the wind turbine’s normal operation after the clearance of an external short-circuit fault.

II. DYNAMIC MODELING

The general turbine model with DFIG is shown in Fig. 1. This model consists of a wind turbine, gearbox and a DFIG with IGBT converter connected between rotor winding and grid through three phase injecting transformer.

A. Wind Turbine Model

The turbine model consists of number of sub-models including aerodynamic model, two mass model and pitch angle controller model.

1) Aerodynamic Model

The aerodynamic model of a wind turbine is determined by its power speed characteristics [2-3]. Wind turbine power depends on both the rotor speed and wind speed. The captured power is given by the following equation

\[ P_r = \frac{1}{2} \rho A_{rot}^2 C_p(W) \]  

(1)

Then tip speed ratio is defined as:

\[ \lambda = \frac{\omega R}{u} \]  

(2)

One way to get \( C_p \) is by using look up table [4]. Another way is by approximating \( C_p \) by using a non-linear function [5]. The second method is used in this study because it gives more accurate results and is faster in simulation.

\[ C_p(W) = 0.22 \left( \frac{W}{15} \right)^{-3} - 0.48 \]  

(3)

Where, \( \lambda \) is given by:

\[ \lambda = \frac{1}{k \times 10^{0.095}} \]  

(4)

2) Two Mass Model

In stability analysis, when the system response to heavy disturbances is analyzed, the drive train system must be approximated by at least a two mass spring and damper model. A lumped model is presented in Fig. 2 [6]. It includes, generator inertia \( J_G \), turbine friction damping \( D_T \) and generator friction damping \( D_J \), and this lumped model is simple and it is considered as a more exact simulation model.

\[ T_p = K_{rot}(\theta_p - \theta_q) - D_T \omega_p - J_I \frac{d\omega_p}{dt} \]  

(5)

\[ K_{sh}(\theta_p - \theta_q) - T_g - D_J \omega_p = J_J \frac{d\omega_p}{dt} \]  

(6)

\[ T_{sh} = K_{sh}(\theta_p - \theta_q) \]  

(7)

The idea of using a two-mass mechanical model is to get a more accurate response from the generator and the power converter during grid faults and to have a more accurate prediction of the impact on the power system.

3) Pitch Angle Controller

Pitch angle controller has a task to increase or decrease the pitch angle in order to limit the generated power \( P_s \) to the rated power \( P_s \). Fig.(3) shows the pitch angle control loop. It should be taken into account that the pitch angle \( \beta \) cannot change immediately, but only at a slow rate due to the size of the rotor blades. The rate of change limitation is very important during grid faults, because it decides how fast the aerodynamic power can be reduced in order to prevent over-speeding during faults. In order to get realistic simulation, the rate is limited to \( 7^\circ/s \) [7] and the pitch angle is limited to \( 90^\circ \) [5]. Also the effect of servo time constant \( T_s \) must be considered.

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is modeled as a voltage 

The main task of the RSC is to track the maximum power point (MPP) of the wind turbine and to control the reactive power required by the electric utility. RSC modeling contains four main parts which are neglected [7-8]. 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. RSC modeling contains four main parts which are represented in the following sections.

1) Maximum Power Point Tracking

The power is controlled in order to follow a pre-defined power-speed characteristic, named tracking characteristic. This characteristic is illustrated by the ABCD curve in Fig. 4 superimposed to the mechanical power characteristics of the turbine obtained at different wind speeds. The actual

\[ V_{ds} = R_d I_d + \frac{d}{dt} \psi_d + \omega_c \psi_q \]

(9)

\[ V_{qr} = R_q I_q + \frac{d}{dt} (\omega_c - \omega_p) \psi_d + \omega_c \psi_q \]

(10)

\[ V_{dq} = R_q I_q + \frac{d}{dt} (\omega_c - \omega_p) \psi_d - \omega_c \psi_q \]

(11)

The flux linkage equations of the stator and rotor can be related to their currents and are expressed as follows:

\[ \psi_s = l_s I_s + \frac{d}{dt} l_m I_q + l_m \psi_q \]

\[ \psi_d = l_d I_d + l_d \psi_q \]

\[ \psi_q = l_m I_q + l_m \psi_d \]

\[ \psi_{d*} = l_{d*} I_{d*} + l_{d*} \psi_{q*} \]

Where, \( l_{d*} = l_{d*} + l_m \) and \( l_{q*} = l_{q*} + l_m \)

The electromagnetic torque developed by the DFIG is related to the torque supplied by the turbine and can be expressed as

\[ T_e = \frac{2P}{2} \left( \psi_s I_q - \psi_q I_s \right) = 2\pi \frac{d}{dt} \psi_d + \omega_c \psi_d \]

(13)

Where, \( T_m \) is positive for motoring operation and negative for generator operation. The active and reactive power produced in the stator

\[ P_s = \frac{3}{2} \left( \psi_{d*} I_{d*} + \psi_{q*} I_{q*} \right) \]

(14)

\[ Q_s = \frac{3}{2} \left( \psi_{q*} I_{d*} - \psi_{d*} I_{q*} \right) \]

(15)

B. Doubly Fed Induction Generator Model

In order to investigate the actual behavior of the DFIG, dynamic equation needs to be considered for more realistic observation and the dq representation of an induction machine leads to control flexibility. The dynamic behavior of the DFIG in synchronous reference frame can be represented by the Park equations. The stator and rotor voltages are expressed as follows:

\[ V_{q*} = R_q I_q + \frac{d}{dt} \psi_q + \omega_c \psi_d \]

(8)

C. Rotor Side Converter Controllers

Rotor side converter (RSC) is modeled as a voltage source converter. The switching dynamics of IGBT switches are neglected [7-8]. 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. RSC modeling contains four main parts which are represented in the following sections.

Fig.1 variable speed DFIG with IGBT converter [1].

Fig.2 Two mass model of wind turbine.

Fig.(3) Pitch angle controller

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speed of the turbine is measured and the corresponding mechanical power of the tracking characteristic is used as the reference power for the power control loop. The tracking characteristic is defined by four points: A, B, C and D. From zero speed to speed of point A the reference power is zero. Between point A and point B the tracking characteristic is a straight line. Between point B and point C the tracking characteristic is the locus of the maximum power of the turbine. The tracking characteristic is a straight line from point C and point D. The power at point D is one per unit (1 p.u.). Beyond point D the reference power is a constant equal to one per unit (1 p.u.).

2) Stator Voltage-Oriented Control of DFIG

In the stator-voltage oriented frame the d-axis of the reference frame is aligned along the stator-voltage space vector. If the grid voltage applied to the stator is constant, then the stator q axis voltage would be zero and the d-axis voltage would be constant. This means, \( V_{q0} = 0 \), \( V_{d0} = V_{s} \) and \( \psi_{q0} = \psi_{s} \), \( \psi_{d0} = 0 \). Stator magnetizing current space vectors can be put in terms of the stator and rotor space vectors expressed in the stator voltage oriented reference frame as [9]:

\[
I_{m3} = I_{d3} + I_{q3} \tag{16}
\]

Then \( I_{d3} = I_{d} \)- \( \tag{17} \)
and \( I_{q3} = I_{m3} + I_{q} \)- \( \tag{18} \)

Then according to the stator voltage reference frame the stator active and reactive power will be as follow:

\[
R_{s} = \frac{3}{2} V_{d3} I_{d3} \tag{19}
\]

\[
Q_{s} = - \frac{3}{2} V_{q3} I_{q3} \tag{20}
\]

Substituting from (17) and (18) into (19) and (20) then

\[
R_{s} = \frac{3}{2} V_{d3} I_{d} \tag{19}
\]

\[
Q_{s} = - \frac{3}{2} V_{q3} (I_{m3} + I_{q}) \tag{22}
\]

From (19) and (22) as the stator voltage and the magnetizing current are constant then the stator active power can be controlled by the direct axis rotor current \( I_{d0} \) and the stator reactive power can be controlled by the q-axis rotor current \( I_{q0} \).

3) Torque Regulator

The relation between the torque, stator flux and the rotor current is obtained from the following equation [9]:

\[
T_{e} = \frac{3}{2} (\psi_{d0} I_{q0} - \psi_{q0} I_{d0}) \tag{23}
\]

By aligning the d-axis of the reference frame along with the grid voltage position \( V_{q0} = 0 \). Then \( \psi_{d0} = 0 \) and substituting in the torque equation yields

\[
T_{e} = \frac{3}{2} \psi_{d0} I_{d0}, \quad \text{or} \quad I_{d0} = \frac{2}{3} \psi_{d0} \psi_{q0} \tag{24}
\]

The value of \( \psi_{q0} \) can be obtained from (9) as:

\[
\psi_{q0} = \left( V_{q0} - R_{s} I_{d0} \right) ( - \omega_{e} ) \tag{25}
\]

So by using the reference value of the generated torque the reference value of the direct axis rotor current can be obtained from (24) and this is shown in fig.5.

4) Reactive Power Regulator

Equation (22) shows a direct relationship between the reactive power \( Q \) and \( I_{q0}^{*} \). So, \( I_{q0}^{*} \) can be used to produce the reactive power required by the system operator. The value of \( I_{q0}^{*} \) can be obtained from comparing the actual and reference values of the reactive power as shown in fig.6. the reference values of the RSC voltages is obtained from \( I_{q0}^{*} \) and \( I_{q0}^{*} \) in the current regulator of the RSC as shown in fig.7.

![Fig.4 tracking characteristics of the wind turbine](image)

![Fig.5 torque regulator](image)

![Fig.6 reactive power regulator](image)
The main function of the grid side converter (GSC) is to control the DC link voltage and to control the active and reactive power from the DC link to the grid side. If the dc voltage $V_{dc}$ is greater than its reference value $V_{dc}^{*}$ this means that more power must be moved from the DC link to the electric utility via the grid side converter. The dc link voltage is controlled by vector control scheme with the reference frame oriented along the grid voltage vector position [10-11]. This scheme permits independent control of the DC link voltage and the reactive power. The active and reactive power from the GSC to the electric utility is obtained from the following:

$$R_t = \frac{3}{2}(V_{dc}I_{dg} + V_{dc}I_{eg})$$  \hspace{1cm} (26)

$$Q_{dc} = \frac{3}{2}(V_{dc}I_{dg} - V_{dc}I_{eg})$$  \hspace{1cm} (27)

Substituting $V_{qs}=0$ in (26) and (27) yields:

$$P_t = \frac{3}{2}V_{dc}I_{dg}$$  \hspace{1cm} (28)

$$Q_{dc} = -\frac{3}{2}V_{dc}I_{eg}$$  \hspace{1cm} (29)

It is clear from these two equations that the active and reactive power from the GSC can be controlled independently by $I_{dg}$ and $I_{eg}$ respectively. The control of dc voltage is shown in fig.8.

The voltage at the leg of the GSC is obtained from the following equation:

$$[V_{qgc}] = [V_{gc}] - R_g[I_{dg} - L_{dg} \frac{d}{dt}[I_{dg}]]$$  \hspace{1cm} (30)

Using Park's transformations yields:

$$[V_{qgc}] = [V_{dc}] + \omega_L L_{dg} \frac{d}{dt}[I_{dg}] - R_g[I_{dg}] - L_{dg} \frac{d}{dt}[I_{dg}]$$  \hspace{1cm} (31)

The cross coupling effect is represented by $\omega_L L_{dg}$ and $\omega_L L_{eg}$. The block diagram describing this logic is shown in fig.9.

### III. SIMULATION RESULTS

The response of variable speed wind turbine and its control when subjected to three phase short circuit at the generator bus (worst case). The dynamic simulation is not affected by the wind profile because it can be considered constant during the fault period.

Fig. 10 shows the response of stator voltage, current, active power, reactive power and rotor current for average wind speed of 14 m/s.

The 3-phase short circuit has been introduced at time instant 10 s. The fault has been modeled by a stator voltage reduction down to zero for a time of 0.3 s.

The stator power due to the occurrence of fault first decreases to zero, then after clearing the fault it rapidly rises in the positive direction up to 2.45MW and then starts to oscillate until it reaches its steady state value before fault.

The stator reactive power due to the occurrence of fault first rises to 1Mvar, then after the clearing the fault it increases negatively to 1.6Mvar and then decreases rapidly to reach its reference value of 0Mvar (unity power factor).

A high transient stator current due to the occurrence of fault first increases negatively to -3.5 pu, then after clearing the fault it increases to 1.6 pu and then starts to decay until it reaches its steady state value before fault.

The rotor current due to the occurrence of fault first increases to 4.3 pu, then after clearing the fault it increases to 2 pu and then starts to decay until it reaches its steady state value before fault.

Fig. 11 shows the response of DC bus voltage, rotor rotational speed ($\omega$), and pitch angle ($\beta$) for the same wind speed.

The DC bus voltage due to the occurrence of fault and due to high rotor current increases to 2300V, then after clearing the fault it decreases until reach 1100V and then starts to decay until reaches its steady state value before fault (1150V).

As wind speed (14m/s) is higher than the rated wind speed of the turbine (11 m/s), the pitch angle of the turbine blades...
is set to 8.7º to obtain rated power. Due to the fault occurrence the power falls to zero, then the blade angle increases to reach 10.3º. After the fault clearance the power increases over the rated value then the pitch angle decreased again and as the power oscillates around the rated value the blade angle will also oscillate around its steady state value. At the same wind speed the DFIG rotor rotational speed and the blade angle will take approximately the same profile.
Fig.11 DC bus voltage (V), rotor rotational speed (pu) and pitch angle.

IV. CONCLUSION

Discussion of the dynamic modeling and associated control strategy of a DFIG based wind turbine has been presented. The stator voltage oriented vector control scheme is incorporated with the DFIG control to realize the fast and accurate control. Active power production by the DFIG is controlled through the d-axis rotor current while reactive power through q-axis rotor current.

Transient behavior of a DFIG variable speed wind turbine connected to the network and controlled by vector control has been studied. The transient simulation results are for a 1.5MW DFIG under a three-phase short circuit at the generator bus.

V. Appendix

TABLE 1 PARAMETERS OF THE SIMULATED DFIG

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>1.5MW</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>575V</td>
</tr>
<tr>
<td>Rs</td>
<td>0.023 pu</td>
</tr>
<tr>
<td>Rr</td>
<td>0.016 pu</td>
</tr>
<tr>
<td>Lls</td>
<td>0.18pu</td>
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<tr>
<td>Lm</td>
<td>2.9 pu</td>
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<tr>
<td>Inertia constant</td>
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VI. References


