Dynamic Response of Grid-Connected Wind Turbine with Doubly Fed Induction Generator during Disturbances

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Abstract — The use of the Doubly-fed Induction Generator (DFIG) in large wind turbines (MW-class) is growing rapidly. In order to investigate the dynamic response of a wind turbine with DFIG connected to the power system during grid disturbance, a model has been developed. This model includes aerodynamics, the mechanical drive train, the induction generator as well as the control parts. The response of the system during grid disturbances is studied. An inclusion of saturation effect in the generator during faults is also included.

Index Terms—Doubly fed induction generator, saturation, power system stability

I. INTRODUCTION

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.

However, the rotor power converter as a vulnerable part of the DFIG power converter, which has a restricted over-current limit, needs special attention especially during faults in the grid. When faults occur and cause voltage dips, subsequently the current flowing through the power converter may be very high (over-current). During this situation, it is common to block the converter to avoid any risk of damage, and then to disconnect the generator from the grid.

Motivated by the reason above, this paper provides a study of the dynamics of the grid connected wind turbine with DFIG. The paper starts with development of a wind turbine model with DFIG in Matlab/Simulink, followed by simulations of the model during grid disturbance.

In the simulation, the ability of the DFIG to recover terminal voltage after grid disturbance is presented. The response of the DFIG to faults and subsequent action of the over-current protection is described. Two different operation modes, i.e. sub-synchronous and super-synchronous operation, are treated separately. The results from the two operation modes are then evaluated. The inclusion of the saturation effect in the generator to provide better prediction of current magnitude is included as well.

II. MODEL DESCRIPTION

The complete model of a wind turbine with DFIG is constructed from a number of sub models, i.e. turbine, drive train, pitch controller, induction generator, rotor side converter and grid model. A general structure of the model is depicted in Fig. 1. The simulation is carried out for a 2 MW wind turbine. Detailed data of the wind turbine are given in the Appendix.

A. Generator model

The generator is basically a slip-ring induction machine, which can be modeled according to [1] in the following equations

\[
\begin{align*}
\ddot{u}_s &= r_s \dot{i}_s + \frac{d}{dt} \left( \psi_s \right) + j \omega_s \psi_s, \\
\ddot{u}_r &= r_r \dot{i}_r + \frac{d}{dt} \left( \psi_r \right) + j \left( \omega_s - \omega_r \right) \psi_r,
\end{align*}
\]  

(1)

with \( \dot{u}, \dot{i} \) and \( \dot{\psi} \) are the vector of voltage, current and flux as a function of time, and \( r \) is the resistance. Subscripts \( s \) and \( r \) denote the stator and rotor quantities. The speed of the rotor is denoted \( \omega_r \). The equations are given in an arbitrary
reference frame, which rotates at arbitrary speed of $\omega_a$.

The flux and current relations are given as

$$
\bar{\psi}_s = (L_{m} + L_{m}) \bar{i}_s + L_{m} \bar{i}_r
$$

(2.a)

$$
\bar{\psi}_r = (L_{r} + L_{m}) \bar{i}_r + L_{m} \bar{i}_s
$$

(2.b)

with $L_{m}$ as the mutual inductance and $L_{sl}$ and $L_{rl}$ as the stator and rotor leakage inductance, respectively.

In order to obtain more accurate results, the saturation effect can be included in the generator model when needed. The saturation effect can be achieved by varying inductances as a function of current magnitude, $L(\bar{i})$, which is derived from typical saturation curve as shown in Fig. 2.

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**B. The rotor side converter controller**

The rotor side converter is modeled as a voltage source converter type. For simplification, switching dynamic phenomena in the converter are neglected, assuming that switching frequency is infinite.

The purpose of the controller is to regulate the active and reactive power output independently. In order to decouple these two parameters, generator quantities are calculated using vector control technique in a synchronous reference frame fixed to the stator flux [2]. The controller provides set point values of the quadrature and direct axis component of the rotor current ($i_{qr}$ and $i_{dr}$).

The control of active power is realized according to the control diagram as illustrated in Fig. 3 [3].

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A generic model of the voltage and reactive power control is arranged in a cascaded mode [4] as shown in Fig. 4.

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As regards the voltage and reactive power control, DFIG can be operated in two different schemes, i.e. constant reactive power or controlled terminal voltage. In this paper, the first scheme is employed.

**C. Turbine model**

One common way to control the active power of a wind turbine is by regulating the $c_p$ value of the rotor turbine. In the model, the $c_p$ value of the turbine rotor is approximated using a non-linear function according to [5].

$$
c_p(\lambda, \beta) = 0.22 \left( \frac{116}{\lambda} - 0.4\beta - 5 \right) e^{-12.5 \frac{\lambda}{\lambda_i}}
$$

(3)

where $\lambda$ is the tip speed ratio and $\beta$ is the pitch angle. The value $\lambda_i$ is given according to the following relation.

$$
\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta - 0.035} - \frac{1}{\beta^3 + 1}
$$

(4)

The maximum value of $c_p$ can be found using a graphical method, which is 0.438 in this case. This value corresponds to $\beta = 0$ and $\lambda = 6.3$. This tip speed value is assigned as the optimum tip speed. Based on this value, the optimum turbine speed curve at any given wind speed can be obtained. This curve is then used as a reference in the active power control.

**D. Pitch controller**

According to (3), the $c_p$ value can be reduced by increasing the pitch angle $\beta$. However, the pitch angle is not able to reach the set point value immediately. Accordingly, for a more realistic simulation, a rate limiter is implemented in the pitch controller model. In this paper the maximum pitch angle rate is set at 7 degrees/second. The pitch angle controller block diagram is depicted in Fig. 5.
The pitch controller module is employed to limit the rotor speed. For this reason, the pitch controller is active only during high average wind speed. The set point value for the turbine speed is set at 19.1 rpm, which corresponds to the generator speed of 1650 rpm or is equivalent to 10% above the synchronous speed. Owing to the slow reaction of the pitch controller, the set point value cannot be achieved precisely at any time, whereas it is still in an acceptable range around the set point value.

E. Drive-train model

When investigating dynamic stability, the drive-train system in a wind turbine is important to include in the model. The model of the drive-train system consists of two main masses, i.e. turbine mass and generator mass. The two masses are connected to each other with a shaft that has a certain stiffness and damping constant value. The equation of the turbine side is given as

$$2H_t \frac{d\omega_t}{dt} = T_i - K_s \cdot \theta_{tg} - D_s \cdot (\omega_t - \omega_g)$$  \hspace{1cm} (5)

The equation of the generator side is given as

$$2H_g \frac{d\omega_g}{dt} = T_g + K_s \cdot \theta_{tg} + D_s \cdot (\omega_t - \omega_g)$$  \hspace{1cm} (6)

where $H$ is the inertia constant, $T$ is torque and $\omega$ is angular speed. Subscripts $g$ and $t$ indicate the generator and turbine quantities, respectively. The shaft stiffness and damping constant value are represented in $K_s$ and $D_s$. All the quantities are in per unit values. Variable $\theta_{tg}$, in the electrical radian, is the electrical twist angle of the shaft, which is given by

$$\frac{d\theta_{tg}}{dt} = \omega_{base} (\omega_t - \omega_g)$$  \hspace{1cm} (7)

where $\omega_{base}$ is the base value of angular speed.

F. Grid model

The grid model consists of three buses, i.e. the generator bus, the intermediate bus and the infinite bus. The model uses the three-phase momentary representation. The grid parameters are shown in Fig. 6. The grid is calculated in the state-space model, where inductances and faults are modeled as current source. Modeling the faults as current source may cause voltage spikes during the switching of faults. These spikes can be seen in simulation results. However in general, this phenomenon does not influence the dynamics response of the system, and therefore can be neglected.

III. SIMULATION

In the simulation, a three-phase fault is applied at the middle bus. The magnitude of fault is controlled by the selection of an appropriate fault resistance. As stated in the Introduction part, a number of simulations are conducted:

1. In the first simulation, the ability of the DFIG controller to recover terminal voltage after fault clearance is investigated.
2. The second simulation describes the sequence action of the over-current protection during a fault, which leads to converter blocking. The simulations are carried out for two different operating conditions, i.e: super-synchronous and the sub-synchronous operations.
3. The importance of the saturation effect in the model to provide a better prediction of current magnitude during fault is simulated as well.

All the faults in the simulations refer to a three-phase to ground short circuit at the intermediate bus with a certain short circuit resistance value (see Fig. 6).

A. Voltage restoration capability

Before the fault is applied, the active power output of the wind turbine is 0.2 pu while the reactive power output is kept constant at 0 pu. The initial terminal voltage of the DFIG is 1 pu.

A fault, as shown in Fig. 6, is applied at $t=0.1s$ with a short circuit resistance of 0.05 pu for 100 ms duration. It is shown in Fig. 7 that the fault causes the terminal voltage drop at around 0.75 pu. In this case, the fault is not enough to trigger the over-current protection, and therefore the DFIG is able to ride through the voltage dip without action of protection. Approximately 100 ms after fault is cleared the terminal voltage is recovered (back to the steady state value) at 1 pu. This fast voltage recovery is due to the ability of DFIG to control the reactive power.

For comparison, the DFIG is replaced with an identical squirrel cage induction generator that has the same electrical parameters. This new arrangement is then simulated with the same fault as in the previous simulation. As a result, it can be seen in Fig. 7 that until more than 200 ms after fault is cleared, the terminal voltage has not yet reached steady state value.

From this result, it can be concluded that the wind turbine with DFIG is able to recover the voltage level to its nominal
value quickly after the voltage dip. The terminal voltage recovery of the DFIG is somewhat better than the identical squirrel cage induction generator.

Fig. 7. Voltage at generator bus during disturbance: with DFIG (solid) and with squirrel cage induction generator (dotted).

B. Action of protection during sub-synchronous and super-synchronous operation

For a serious fault, the current flowing through the power converter may be too high, which may cause damage to the rotor converter. In order to avoid such a risk, the DFIG is equipped with an over-current protection. In case the rotor current magnitude reaches the setting value of the protection relay, the converter is blocked subsequently.

The setting point of the protection relay is set at 1.5 pu. The following are simulations of the faults followed by subsequent protection sequences during super-synchronous and sub-synchronous operation.

1) Fault during super-synchronous operation

Initially the generator operates at super-synchronous speed where the rotor speed is 1.02 pu. At this moment, the DFIG generates the active power of 0.8 pu while the reactive power is set at zero. The simulation results are depicted in Fig. 8 and Fig. 9. The following events are marked in the figure: the fault is initiated (A), the rotor converter is blocked (B), the generator is disconnected (C) and the fault is cleared (D).

The fault is applied at \( t = 1.1 \) s for 100 ms duration with a short circuit resistance of 0.01 pu. The fault causes the terminal voltage to drop to approximately 0.2 pu. Subsequently, the following sequence takes place.

Shortly after the fault is initiated, the stator current increases rapidly and reaches the setting value of the protection, which is set at 1.5 pu. Subsequently, the converter is blocked and this action is followed by a shorting of the rotor circuit. This series of events take place almost at once after the fault starts. At this moment, the generator behaves like a squirrel cage induction generator.

If the generator is allowed to remain connected to the grid, it tends to absorb a large amount of reactive power, while in the meantime the stator current and the active power fluctuate, particularly after the fault is cleared. The absorption of a large amount of the reactive power may induce instability on the line, especially for large-scale wind parks. A detailed study about the power system stability for a large-scale wind park after disturbance can be found in [6].

Fig. 8. Response of the DFIG during fault in super-synchronous operation followed by the rotor converter being blocked with disconnection (solid) and without disconnection (dotted) of the generator from the grid: (a) terminal voltage, (b) stator current, (c) stator active power and (d) stator reactive power. The following events are marked in the figure: the fault is initiated (A), the rotor converter is blocked (B), the generator is disconnected (C) and the fault is cleared (D).
In order to avoid these circumstances, the turbine is to be disconnected as soon as possible after the instant the converter is blocked.

For this purpose, the generator is disconnected from the grid 47 ms after the converter is blocked. The disconnection action is simply modeled by assigning the stator current to zero. As a result, the stator current, the active and reactive power turn to zero, and consequently the terminal voltage is restored immediately.

The stator current can be reduced more rapidly by the insertion of an external rotor resistance in the rotor circuit shortly after the converter is blocked. The rotor current profile with varying values of external rotor resistance is shown in Fig. 10.

2) Fault during sub-synchronous operation

In the following simulation, the fault is applied during sub synchronous operation. Before the fault takes place, the DFIG operates at the rotor speed of 0.83 pu. The generator produces active power of 0.2 pu and the reactive power is set at neutral. The voltage terminal before the fault is around 1 pu. The responses of the DFIG during the simulation are presented in Fig. 11.

The same fault as in the previous simulation is applied. During the fault, the terminal voltage drops to 0.2 pu. Similarly, the fault initiates the over-current protection action, which is followed by the converter being blocked and shorting the rotor circuit.
When generator disconnection is not ordered, the rotor speed accelerates abruptly towards synchronous speed after the converter is blocked. At this instant, the generator is situated in a motoring operation. As can be seen in the results, the generator absorbs a large amount of active power until it comes into to a generating operation again, when the rotor speed arrives at around 2% above the synchronous speed.

A sudden change of the rotor speed results in shaft oscillation (Fig. 12). This oscillation induces fluctuation in the active and reactive power. Further, these fluctuations prolong the recovery of the terminal voltage after fault clearance.

The sequence of events explained above is not favorable for a grid-connected wind turbine since these events may introduce instability to the network as stated previously. That is the reason why it is necessary to disconnect the generator from the grid. This disconnection should be done immediately after the converter is blocked and before the fault is cleared. In this simulation the disconnection take place at \( t = 1.17 \)s. Fig. 11 shows that terminal voltage can be restored immediately after fault clearance.

C. Effects of saturation

In order to examine the saturation effect of generator inductances on the dynamic response of the DFIG during fault, the following simulation is performed. The simulation basically utilizes the same data as in Section III.A except that the saturation effect is involved in the model. The results of the stator current for both simulations are compared, as shown in Fig. 13.

According to the results, the model with saturation predicts a higher stator and rotor current. The discrepancy between the two results may be even greater for a higher current due to the reduced value of the inductances during operation with saturation. The discrepancy of the stator and rotor current between two models is influenced by: (1) the magnitude of the current and (2) the saturation curve itself.

It should be noted that the current response in the model with saturation is significantly influenced by the leakage inductance \( (L_{sl} \text{ and } L_{rl}) \) rather than by the magnetizing inductance. This is because, during the voltage dip, the magnetizing current is lower than during normal operation. Thus, the magnetizing inductance operates in a linear region. In contrast, during the fault, the generator draws a high current that may cause the leakage inductance to operate at a saturated region.

Therefore, saturation curve identification provides a better prediction of the behavior of the DFIG during fault. Further, the saturation effect cannot be neglected when designing the DFIG protection.

IV. Conclusion

Wind power generation with DFIG provides better performance for terminal voltage recovery after fault clearance owing to its ability to control reactive power. However DFIG is sensitive to severe voltage dips that result in an excessive stator and rotor current, which leads to the rotor converter being blocked.

Blocking of the rotor converter without subsequent disconnection of the generator from the grid may cause voltage instability, particularly for large-scale wind parks. Consequently, the disconnection should be done immediately after the blocking.

The shaft oscillation caused by the fault should be considered when examining the dynamic response of the DFIG. Special attention should be paid to the blocking that occurs when the DFIG operates at far below synchronous speed. Since, in this case, the abrupt change in the rotor speed has more serious impacts on the electrical response of the system.

As regards the saturation effect during fault, it can be seen in the simulation that the peak value of the stator and rotor current in the model with saturation is higher than in the model without saturation. Therefore it is important to take the saturation effect into account, especially when designing a protection setting. However, the prediction of the current magnitude in the model with saturation is characterized by the saturation curve of the generator.
TABLE 1. TURBINE DATA

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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Turbine rotor inertia</td>
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<tr>
<td>Shaft stiffness</td>
<td>2.5 pu/rad</td>
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<tr>
<td>Turbine rotor speed range</td>
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<tr>
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<td>Rotor diameter</td>
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<td>Gear ratio</td>
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TABLE 2. GENERATOR DATA

<table>
<thead>
<tr>
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<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Rated power</td>
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</tr>
<tr>
<td>Rated voltage</td>
<td>690 V</td>
</tr>
<tr>
<td>Rated frequency</td>
<td>50 Hz</td>
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<tr>
<td>Stator resistance</td>
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<tr>
<td>Stator reactance</td>
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<tr>
<td>Mutual reactance</td>
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<td>Rotor resistance</td>
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<tr>
<td>Rotor reactance</td>
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<tr>
<td>Generator rotor inertia</td>
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<tr>
<td>Number of poles pairs</td>
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</table>

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REFERENCES