Analysis of Doubly-Fed Induction Generator driven by Wind Turbine

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Abstract- The doubly-fed induction generator driven by a Wind Turbine has recently received a great attention from the industrial and scientific communities, due to easily produces a fixed frequency voltage from the stator windings when the rotor is driven at variable speed and the excitation power electronics converter feeding the rotor windings can be rated at a fraction of the nominal power of the generator. This paper provides the design and analysis of doubly-fed induction generator (DFIG) for wind energy conversion systems (WECS), this model is proposed for the seamless operation. The control on Grid side converter (GSC) and Rotor side converter (RSC) through detailed simulation will be studied on a 1.5-MW wind turbine.

Keywords—Doubly fed induction generator (DFIG), Grid side converter(GSC), Rotor side converter (RSC), wind turbine (WT).

I. INTRODUCTION (HEADING 1)
The doubly fed induction generator (DFIG) based wind turbines are nowadays more widely used in large wind farms. The main reasons for the increasing number of DFIGs connected to the electric grid are low converter power rating and ability to supply power at constant voltage and frequency while the rotor speed varies. The DFIG concept also provides possibility to control the overall system power factor.

The majority of a large capacity machines (>1 MW) are available for General Electric-Wind. The power electronic converters enable control over the generator operating characteristics such as speed and reactive power. [1]

The wind turbine can operate in one of two ways. The first is to have a relatively fixed rotational speed, in which an increase in wind speed can slightly increase the rotor speed above the synchronous speed and thus varying the slip. This is based purely on the torque-speed relationship of an induction machine. A speed controller is used to vary the pitch of the wind turbine blades during high wind speeds to reduce the power intake and protect the wind turbine.

By optimizing a term called tip speed ratio we can optimize the ratio of wind speed to rotor speed:

$$\lambda = \frac{\omega_{tip}}{\omega_{wind}}$$  

(1)

where \(V_{tip}\) is the velocity of the blade tip and \(V_{wind}\) is the wind velocity. The tip velocity can be calculated from:

$$V_{tip} = \Omega \cdot r$$  

(2)

Where \(\Omega\) is the mechanical speed of the wind turbine and \(r\) is the radius of the circle of rotation (in this case the length of the wind turbine blade).

The various configurations for fixed and variable speed wind turbine generators can be broken down into four main types to be described in the following sections:

1. Fixed Speed Wind Turbine (FSWT) with induction generator.
2. Variable Speed Wind Turbine (VSWT) with variable rotor resistance.
3. VSWT with DFIG.
4. VSWT with Full-Power Converter (FPC).

1-Fixed Speed Wind Turbine (FSWT) with induction generator:
A fixed speed WT consists of a conventional, directly grid coupled squirrel cage induction generator .has low cost, maintenance free, and operational simplicity. The slip and hence the rotor speed of a squirrel cage induction generator varies with the amount of power generated. These rotor speed variations are very small, approximately 1 to 2 % of the rated speed. Therefore, this type of wind energy conversion system is normally referred to the constant or fixed speed WT.

2. VSWT with variable rotor resistance:
The rotor speed can then be controlled by varying this resistance, thus making this arrangement a variable speed wind turbine (VSWT). Capacitor banks are still required to compensate for the reactive power consumption.
3. VSWT with Doubly-Fed Induction Generator:
In the doubly fed induction generator, a back-to-back voltage source converter feeds the three-phase rotor winding. In this way, the mechanical and electrical rotor frequencies are decoupled, and the electrical stator and rotor frequencies can be matched independently on the mechanical rotor speed. The power electronics devices used in doubly-fed induction generators: this power is supplied to or from the generator rotor windings, which is typically about 30% of the generator rated power. Consequently, the power electronics devices in variable-speed wind turbines using doubly-fed induction generators typically need only to be about 30% of the size of the power electronics devices used for comparatively sized three-phase synchronous generators. This reduces the cost of the power electronics devices, as well as the power losses in these device.[2]

II. MATHEMATICAL MODEL OF THE DFIG

To analyze the transient and steady-state performance of the wound rotor induction machine with the six-terminal stator, it is modeled in d-q reference frame rotating at synchronous speed. The voltage and flux equations of the induction machine with the six-terminal stator in d-q reference frame can be written as follows:

\[
V_{sd} = R_s I_{sd} + \frac{d\varphi_{sd}}{dt} - \omega \varphi_{sq} \\
V_{sq} = R_s I_{sq} + \frac{d\varphi_{sq}}{dt} + \omega \varphi_{sd} \\
V_{rd} = R_r I_{rd} + \frac{d\varphi_{rd}}{dt} - (\omega - \omega_r)\varphi_{rq} \\
V_{rq} = R_r I_{rq} + \frac{d\varphi_{rq}}{dt} + (\omega - \omega_r)\varphi_{rd} \\
\varphi_{sd} = L_s I_{sd} + L_m I_{rd} \\
\varphi_{sq} = L_s I_{sq} + L_m I_{rd} \\
\varphi_{rd} = L_r I_{rd} + L_m I_{sd} \\
\varphi_{rq} = L_r I_{rq} + L_m I_{sq}
\]

where represents the d-axis and q-axis components of respective variables $V_{sd}$ and $V_{sq}$ represent the voltages available at the grid side of the stator terminals, $V_{rd}$ and $V_{rq}$ represent the rotor terminal voltages. The variables $I_{sd}$ and $I_{sq}$ represent the stator currents, while $I_{rd}$ and $I_{rq}$ represent the rotor currents. $R_s$ and $R_r$ represent the stator and rotor resistances referred to stator while $L_s$ and $L_r$ represent the stator and rotor self-inductance $L_m$ and mutual
The electromagnetic torque can be written as:

\[ T_e = I_{sq}\phi_{sd} - I_{sd}\phi_{sq} \] (14)

The q axis is aligned with the stator voltage. This implies that \( v_{sd} = 0 \) and \( v_{sq} = v_{s} \). This approach is useful for doubly fed machines where the control is performed by a means of the rotor voltage. The stator voltage is the grid voltage, which is approximately constant in a stable grid. The rotor voltage is referred to the same frame. It consists in general of two non-zero d–q components. This d–q frame orientation decouples the active power from reactive power and they can be controlled independently.

The stator active power \( P_s \) and reactive power \( Q_s \) are expressed as follows:

\[ P_s = V_{sq}I_{sq} \] (15)
\[ Q_s = V_{sq}I_{dq} \] (16)

Where \( \lambda_i \) is given by:

\[ \frac{1}{\lambda_i} = \frac{1}{\lambda_i + 0.08\beta} - \frac{0.035}{\beta^2 + 1} \] (20)

The power of the wind can be expressed by the following equations:

\[ P_w = \frac{1}{2}\rho\pi R^2 V_{wind}^3 \] (18)

\[ P_{m} = C_p (\lambda, \beta) \cdot P_w \] (17)

The aerodynamic model with DFIG

The mechanical power output that a turbine can produce is given by:

\[ P_{m} : \text{Mechanical output power of the turbine (W)}. \]
\[ C_p : \text{Performance coefficient of the turbine}. \]
\[ \rho : \text{Air density (kg/m3)}. \]
\[ A : \text{Turbine swept area (m2)}. \]
\[ V_{wind} : \text{Wind speed (m/s)}. \]
\[ \lambda : \text{Tip speed ratio of the rotor blade tip speed to wind speed}. \]
\[ \beta : \text{Blade pitch angle (deg)}. \]
\[ C_p (\lambda, \beta) = 0.22\left(\frac{116}{\lambda_i} - 0.4 \beta - 5\right)e^{-\frac{12.5}{\lambda_i}} \] (19)

The optimum turbine speed producing maximum mechanical energy for a given wind speed is proportional to the wind speed.
D. Operation and Control of DFIG

The DFIG-WT allows full control of active and reactive power using rotor and grid side voltage source converters. In super-synchronous operation, both the rotor and stator supply power. The partial amount of power produced by the rotor depends on the slip, which can be shown as $p_r = -S_p s$. In normal operation, the rotor power is supplied to the dc-link through the RSC, and then injected to the grid (GSC). [3]

a) ROTOR SIDE CONVERTER CONTROLLER

The stator of DFIG is connected directly to the grid. The rotor of DFIG is connected to the grid through AC/DC/AC frequency converter. The simulation program is carried out in a numerical simulation, using one of Matlab toolboxes, Simulink. All the system components are simulated using this program blocks. control the electromagnetic torque and the reactive power produced by DFIG independently, in normal mode of operation RSC is controlled in a synchronously rotating d-q reference frame with d-axis aligned to stator flux vector. [4]

The rotor-side converter provides a variable rotor voltage, which is controlled in its d- and q-component and is therefore used for independent active and reactive power control. [5]

b) GRID SIDE CONVERTER CONTROLLER

In the grid side converter controller, the voltage of bus B1 Vabc and the grid converter currents Iabc-grid-conv are transformed into the d–q quantities Vdq and Idq respectively. A dc bus voltage regulator is used to produce Idref. The inputs of the dc bus voltage regulator are the reference dc bus voltage Vdcref and the actual value of dc bus voltage Vdc. Vdc is compared with Vdcref to yield the voltage error which feeds a PI controller to get Idref. A current regulator is used to produce the reference voltages $V_{dq}^*$. These d–q voltages can be transformed into abc quantities to produce the control signals of the grid converter. These control signals feed three phase PWM generator to produce the firing pulses to the grid converter.

Fig. 9. The model system.

Fig. 10. Rotor side converter control.

Fig. 11. Grid side converter control.
IV. SIMULATION OF DOUBLY-FED INDUCTION GENERATOR

A. Model and Parameters

![Diagram of DFIG model]

Fig. 5. Simulink model of DFIG.

**TABLE I. parameters for Doubly-fed induction generator data**

<table>
<thead>
<tr>
<th>number of units</th>
<th>active power for each unit (MW)</th>
<th>total active power (MW)</th>
<th>stator voltage (V)</th>
<th>rotor voltage (V)</th>
<th>nominal frequency (HZ)</th>
<th>stator resistance (Pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1.5</td>
<td>9</td>
<td>575</td>
<td>1975</td>
<td>60</td>
<td>0.023</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>stator inductance (Pu)</th>
<th>rotor resistance (Pu)</th>
<th>rotor inductance (Pu)</th>
<th>mutual inductance (Pu)</th>
<th>Number of pole pairs</th>
<th>Inertia constant</th>
<th>Friction factor (Pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.18</td>
<td>0.016</td>
<td>0.16</td>
<td>2.9</td>
<td>3</td>
<td>0.685</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**TABLE II. parameters for wind turbines data**

<table>
<thead>
<tr>
<th>Number of units</th>
<th>mechanical power of each unit. (MW)</th>
<th>base wind speed (m/s)</th>
<th>Base rotational speed (of base generator speed) (Pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1.5</td>
<td>11</td>
<td>1.2</td>
</tr>
</tbody>
</table>
B. Results

Fig. 6. The voltage $V_{abc}$-B575 (pu).

Fig. 7. The current $I_{abc}$-B575 (pu).

Fig. 8. Active power of DFIG (MW).

Fig. 9. Reactive power of DFIG (MW).

Fig. 10. The DC link voltage $V_{dc}$.

Fig. 11. The voltage $V_{abc}$-B25 (pu).

Fig. 12. The current $I_{abc}$-B25 (pu).

Fig. 13. The generator speed $\omega_r$ (pu).
The result show the performance of the DFIG as the voltage and current after the DFIG and the voltage and current at bus 25kv. The voltage is stable at (1pu). the result also show the active power of the wind farm (9MW) and reactive power of the DFIG (0MW). the result also show the DFIG speed (1.2pu) and the dc voltage (1150v).

V. FUZZY LOGIC CONTROL:

For a good performance of DFIG based wind farm. The PI controller in the dc bus voltage regulator is replaced by the FLC. In FLC, the reference dc bus voltage Vdcref is compared with the actual voltage Vdc to obtain the voltage error eVdc(t) as shown in Fig. 6. Also this error is compared with the previous error eVdc(t - 1) to get the change in error ΔeVdc(t). The inputs of FLC1 are eVdc(t) and ΔeVdc(t). The output of the proposed controller is ΔIdref(t) which is added to the previous state of current Idref(t - 1) to obtain the reference current Idref(t). The membership functions are defined off-line, and the values of the variables are selected according to the behavior of the variables observed during simulations. The selected fuzzy sets for FLC. The control rules of the FLC are represented by a set of chosen fuzzy rules. The fuzzy sets have been defined as: NL, negative large, NM, negative medium, NS, negative small, ZR, zero, PS, positive small, PM, positive medium and PL, positive large respectively. [6]

![Fig.14. The Fuzzy Logic Control.](image1)

![Fig.15. The membership functions of FLC.](image2)

VI. RESULT USING FUZZY LOGIC CONTROL

![Fig.6. The voltage Vabc- B575 (pu).](image3)

![Fig.7. The current Iabc- B575 (pu).](image4)

![Fig.11. The voltage Vabc- B25 (pu).](image5)

<table>
<thead>
<tr>
<th>eVdc</th>
<th>NL</th>
<th>NM</th>
<th>NS</th>
<th>ZR</th>
<th>PS</th>
<th>PM</th>
<th>PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔeVdc</td>
<td>NL</td>
<td>PL</td>
<td>PL</td>
<td>PM</td>
<td>PM</td>
<td>PS</td>
<td>PS</td>
</tr>
</tbody>
</table>

TABLE III. The rules of FLC
The fuzzy logic controller is found to enhance the performance of DFIG based wind farm. The dc voltage is enhanced by comparing to conventional PI controller. The response is fast with minimum overshoots. Moreover, the steady state error after the clearance of fault is rigorously reduced when the fuzzy logic controllers are used.

### TABLE IV. Transient of dc voltage

<table>
<thead>
<tr>
<th>Controller</th>
<th>Maximum value</th>
<th>Minimum value</th>
<th>Ripple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional controller</td>
<td>1168v</td>
<td>1131v</td>
<td>35v</td>
</tr>
<tr>
<td>Fuzzy logic control</td>
<td>1150.4</td>
<td>1149.9</td>
<td>0.5v</td>
</tr>
</tbody>
</table>

### TABLE V. Steady state of dc voltage

<table>
<thead>
<tr>
<th>Controller</th>
<th>Maximum value</th>
<th>Minimum value</th>
<th>Ripple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional controller</td>
<td>1154v</td>
<td>1142v</td>
<td>12v</td>
</tr>
<tr>
<td>Fuzzy logic control</td>
<td>1150.5v</td>
<td>1149.5v</td>
<td>1v</td>
</tr>
</tbody>
</table>

### VII. CONCLUSION

This paper has presented the modeling and simulation of wind turbine driven DFIG which feeds power to the utility grid. Wind turbine modeling, back-to-back converter system and basic vector-control has been described in order to extract maximum possible mechanical power from the wind according to the wind velocity. The results show that DFIG fed by wind turbines are necessary when output power becomes higher than 1 MW to reduce cost.

A dynamic model of the DFIG was derived to develop a vector controller to decouple dynamically active and reactive power control. Simulations show excellent response of the DFIG independent of speed, and the performance of DFIG has been improved using FLC technique.

### REFERENCES


