Field-Oriented Control of DFIG in Wind Turbine

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ABSTRACT
The increasing size of wind farms requires power system stability analysis including dynamic models of the wind power generation. Doubly-fed induction machines allow active and reactive power control through a rotor-side converter, while the stator is directly connected to the grid. In this paper, a new control of doubly-fed induction machines of field oriented for multilevel inverter is advanced and based on imaginary coordinate. The additional control could be implemented easily with this method, so that the inverter performance could be improved.

KEYWORDS
Wind turbine, Doubly Fed Induction Generator, field oriented, Power System.

1 INTRODUCTION
Due to clean and economical energy generation, a huge number of wind farms are going to be connected with the existing network in the near future. Doubly-fed Induction generator (DFIG) is widely used as wind generator. But as it has some stability problems [1], it is necessary to investigate the stability aspect of Doubly-fed induction generator when connected to the power grid.
Several authors have studied the impact of various wind generators on power system using different tools and softwares. These figures clearly show that there is a strong need for power system stability analysis, including dynamic models of on- and off-shore wind farms. For dynamic power system analysis, different models, from fully detailed to highly reduced order models are proposed in the literature [2],[3], but standard doubly-fed induction machine models for modeling large power systems are still under investigation [4]. Most DFIG wind turbine models that are used in transient analyses represent the generator by means of a two-axis model with constant lumped parameters [5], [6], [7]. A model of DFIG that takes into account the equivalent circuit parameter variation was presented in [8].

2 VARIABLE SPEED WIND TURBINE CONCEPT
The typical DFIG configuration, illustrated in Fig.1 consists of a wound rotor induction generator (WRIG) with the stator windings directly connected to the three-phase grid and with the rotor windings connected to a back-to-back partial scale power converter. [11] The back-to-back converter is a bi-directional power converter consisting of two conventional pulse width modulation (PWM) voltage source converters (rotor side/grid side converter) and a common dc-bus. The transformer connecting the system to the grid has two
secondaries; one winding connecting the stator and the other connecting the rotor. The voltage reduction on the rotor side makes possible to operate at a lower DC bus voltage.

**2.1 Wind turbine rotor model**

The aerodynamic model of the wind turbine rotor is based on the torque coefficient $C_Q$ or the power coefficient $C_P$. The torque coefficient $C_Q$ is used to determine the aerodynamic torque directly by using:

$$T_{wt} = 0.5 \rho R^2 V^3 C_Q$$  \hspace{1cm} (1)

Where:
- $\rho$ Is the air density
- $R$ Is the blade radius
- $V$ Is the wind speed
- $C_Q$ Is the torque coefficient.

Alternatively the aerodynamic torque can be determined using the power coefficient $C_P$ based on:

$$T_{wt} = 0.5 \rho R^2 V^3 C_P$$  \hspace{1cm} (2)

Important to underline that both coefficients $C_P$ and $C_Q$ can be function of the tip speed ratio $\lambda$ for passive-stall wind turbines or function of tip speed ratio $\lambda$ and pitch angle $\theta$ for active stall and variable pitch/speed wind turbines. The parameters for this model are: blade radius, air density, cut-in and cut-out wind speeds. Using a reduced look-up table in respect with the variation of the torque coefficient/power coefficient with the pitch angle ($-10^\circ \leq \theta \leq 10^\circ$) the model for the active-stall wind turbine is obtained.

**2.2 Doubly-fed induction model**

Some of the machine inductances are functions of the rotor speed, whereupon the coefficients of the state-space equations (voltage equations), which describe the behavior of the induction machine, are time-varying (except when the rotor is at standstill). A change of variables is often used to reduce the complexity of these state-space equations. There are several changes of variables, which are used but there is just one general transformation [12]. This general transformation refers the machine variable to a frame of reference, which rotates at an arbitrary angular velocity $\omega_g$. In this reference frame the machine windings are replaced with some equivalent windings as shown in Fig. 2.

![Figure 2. Induction machine windings in the dq arbitrary reference frame.](image)

The six coils obey to the following electric equations:

For the rotor:

$$\begin{bmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix} = \begin{bmatrix} \frac{\phi_{ra}}{\omega} + R_{r} \frac{d}{dt} i_{ra} \\ \frac{\phi_{rb}}{\omega} + R_{r} \frac{d}{dt} i_{rb} \\ \frac{\phi_{rc}}{\omega} + R_{r} \frac{d}{dt} i_{rc} \end{bmatrix}$$  \hspace{1cm} (3)

For the stator:

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \begin{bmatrix} \frac{\phi_{sa}}{\omega} + R_{s} \frac{d}{dt} i_{sa} \\ \frac{\phi_{sb}}{\omega} + R_{s} \frac{d}{dt} i_{sb} \\ \frac{\phi_{sc}}{\omega} + R_{s} \frac{d}{dt} i_{sc} \end{bmatrix}$$  \hspace{1cm} (4)

The transformation of Park is often defined by the $P$ matrix normalized. [6]. The transformation of inverse Park is defined by the $P^{-1}$ matrix. The coefficient $\sqrt{2/3}$ is chosen to give an invariant expression of the electromagnetic torque from the property: $P^{-1} = P'$
The system of PARK that constitutes a dynamic electric model thus for the coil two-phase model:

\[ v_d = R_i_d + \frac{d\phi_d}{dt} + \frac{d\phi_d}{dt} \phi_d \]

\[ v_q = R_i_q + \frac{d\phi_q}{dt} + \frac{d\phi_q}{dt} \phi_q \]

\[
\begin{bmatrix}
  v_{sd} \\
  v_{sq}
\end{bmatrix} =
\begin{bmatrix}
  R_s & 0 \\
  0 & R_s
\end{bmatrix}
\begin{bmatrix}
  i_{sd} \\
  i_{sq}
\end{bmatrix} +
\begin{bmatrix}
  0 & \frac{d}{dt} \\
  \frac{d}{dt} & 0
\end{bmatrix}
\begin{bmatrix}
  \phi_{sd} \\
  \phi_{sq}
\end{bmatrix}
\]

\[
\begin{bmatrix}
  \phi_{sd} \\
  \phi_{sq}
\end{bmatrix} =
\begin{bmatrix}
  L_s & M_L \\
  M & L_r
\end{bmatrix}
\begin{bmatrix}
  i_{sd} \\
  i_{sq}
\end{bmatrix}
\]

Where:

- \( R_s \), \( R_r \), \( L_s \), \( L_r \) are the resistances and inductances of the stator and rotor windings, \( M \) is the main inductance.
- \( v_{sd}, v_{sq}, i_{sd}, i_{sq}, \phi_{sd}, \phi_{sq} \) are the d and q-components of the space phasors of the stator and rotor voltages, currents, and flux.

3 METHOD OF CONTROL BY FLUX-ORIENTED

The objective of this type of control is to achieve a simple model of the DFIG likely to separate the control flux and current flow. The Vector control of induction motor is to direct current vectors and to make the flow behavior of this latter similar to that of a machine DC separately excited (MCC) shown in figure 3.

The electromagnetic torque of DC generator is:

\[ T_{em} = K \phi_i i_a \]

Where K is the constant of DC generator.

The torque electromagnetic of DFIG is given by this expression:

\[ T_{em} = p \frac{M}{L_s} (i_{sq} i_{rd} - i_{sd} i_{rq}) \]

Where \( p \) is the number of pair of poles.

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

3.1 Field-oriented control

The principal of the vector control requires the knowledge of the exact position of the stream to orient at all times and make it coincide with the direct axis "d" at the same synchronous rotating speed. To achieve this, two approaches are possible to know the direct control and indirect control. [13] [14]. In this work, the indirect control is used.

3.1.1 Choice of reference

By choosing two axes d-q repository related to rotating stator field and aligning the stator flux \( \phi_s \) illustration with axis d, we can write:

\[ \phi_{ds} = \phi_s \]

\[ \phi_{qr} = 0 \]

Therefore the torque electromagnetic of DFIG is given by this expression:

\[ T_{em} = -p \frac{M}{L_s} i_{sd} i_{rq} \]

And the current in the stator and rotor is:

\[ i_{ds} = \frac{\phi_s}{L_s} - \frac{M}{L_s} i_{dr} \]

\[ i_{dr} = -\frac{M}{L_s} i_{qr} \]

The power active and reactive is given also in the expression:
In steady state, the terms involving the derivatives of the two-phase rotor currents disappear. We can therefore write:

\[ V_{dr} = R_r i_{dr} - g \omega_s (L_r - \frac{M^2}{L_s}) i_{qr} \]

\[ V_{dq} = R_r i_{dq} + g \omega_s (L_r - \frac{M^2}{L_s}) i_{qd} + g \omega_s \frac{M V_s}{\omega_s L_s} \]  \hspace{1cm} (14)

### 3.1.2 Indirect vector control

The indirect method is to replicate reverse the block diagram of the system to be controlled. This builds a block diagram for expressing the rotor voltages functions and powers.

The proportional-integral (PI) controller used to control the DFIG. The figure 4 shows a closed loop system corrected by a PI controller given in the equation:

\[ R(s) = K_p + \frac{K_i}{s} \]  \hspace{1cm} (15)

Where:

- \( K_p \): is the proportional gain controller.
- \( K_i \): is the integral controller gain

The system consists of a wind turbine consisting of doubly-fed induction generator with a rating of 2MW is connected to infinite bus. Each doubly-fed induction generator is modeled according to figure.1, including the three winding transformer, the induction generator, the grid-side and the rotor-side converter and the intermediate DC circuit.

Figure 7 illustrates the simulation results of synchronous machine; the voltage terminal, the current of generator and the torque electromagnetic oscillations during the integration of wind turbine. As can be noted, after integration the system lost its stability but after a certain time the synchronous machine returned to its not initial operation.
The above figures show the performance of the vector control and reactive power in the stator applied to a doubly fed induction machine.

Proportionality appears between the rotor current quadrature $I_{qr}$ and active power, and between direct current $I_{dr}$ and reactive power.

The quadrature component of flux is almost zero in steady state, which confirms the hypothesis of the vector control. Note the effect of coupling between the two powers $P$ and $Q$, because that $P_{ref}$ pass (0 to -800) to ($t = 1s$) there is a small oscillation in the graph of the power $Q$. 

Figure. 8. Reactive power

Figure. 9. Active power

Figure. 10. Direct current of the rotor

Figure. 11. Quadrature current of the rotor

Figure.12. Direct flux of the stator

Figure. 13. Quadrature flux of the stator
Note that the electromagnetic torque reacts spontaneously when there is a demand for active power, reactive power independent.

5 CONCLUSION
This paper presents a study of variation of integration with a variable speed wind turbine connected in the grid.

In order to investigate the models and methods for the wind turbines system with DFIG, some methods to improve the control of filed oriented are presented.

Using simulations under Matlab-Simulink environment, it has been found that, with the DFIG. The application of the proposed model demonstrates the effect of the control on the grid. Using this model, it is possible to estimate the dynamic characteristics of power system stability. All these observations underline the importance of tool for integration of the wind turbine in power system.

Moreover, for future work, the transient stability of the multi-machine power system including wind farms combined with this model to improve the power system stability should be studied.

REFERENCES


