Analysis and vector control of a cascaded doubly fed induction generator in wind energy applications

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Abstract - This paper presents recent studies of the dynamic and steady state performance of the cascaded doubly-fed induction generator for wind energy applications. The modeling methodology based on dynamical equivalent circuits is given in this paper for the design of the CDFIG controller, the CDFIG can be an attractive alternative to conventional double output wound rotor induction generators. The system employs two cascaded induction machines to eliminate the brushes and copper rings in the traditional DFIG. In this case, Cascaded induction generators require lower maintenance. In CDFIG both stators of connected machines are accessible. The control strategy for flexible power flow control is developed. The independent control of the active and reactive power flows is achieved by means of a tow quadrant power converter under the closed-loop stator flux oriented control scheme. The Matlab simulation software is used for a preliminary investigation of CDFIG.

Keywords: Cascaded doubly fed Induction Generators - Variable speed generator, Vector control - Closed loop speed Control - Active-power and reactive power adjust, Power flow diagrams - Simulation.

1. INTRODUCTION

The expression doubly fed applies generally to machines where electrical power can be fed or extracted from two accessible three-phase windings, [11]. Recent research [2-8] has revealed that the brushless doubly-fed induction generator (CDFIG) or its functionally identical twin, the CDFIG, is a possible alternative to the conventional inverter-fed induction machine drive, especially in minimizing the overall drive cost for limited speed range applications. Recently the doubly fed induction generators (DFIG) became the popular configuration in variable speed wind energy applications [1]. The development and use of the DFIG machines was dictated by the need for wide operational range as well as the necessity to allow flexible power flow control, grid integration as well as economic reasons [2-8]. The use of the DFIG machines, however, increased the long term cost and complexity of the wind energy generation. The disadvantage associated with the wound-rotor induction machines is that the slip rings and carbon brushes have to be systematically maintained [6, 3]. Typical faults of slip rings and brushes are: the increased surface roughness of the rings or the brush contact face, break out of carbon material from the brushes and decreasing contact pressing forces which lead to increased brush sparking and significant performance deterioration [6]. Since wind turbines are installed in remote places, the maintenance costs for such remote installations are significant, [6, 9]. The cost of maintenance for traditional DFIG based wind generators increased the pressure to seek other alternative generator systems...

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One of such alternatives is offered by the CDFIG as shown in Fig. 1. In this configuration, the rotor energy is transferred by using a second fractional induction machine (control machine), which is directly coupled to the main generator (power machine) through the back-to-back connection of rotor circuit (or both cage) [3, 4]. A number of studies have been conducted on the performance modeling of the CDFIG. The results have been presented in simulation results only.

![Fig. 1: CDFIG configuration for wind power generation](image)

The objective of this research is to present a new brushless technique for the indirect vector control of a CDFIG. This method is suitable for grid-connected variable speed BDFIGs. This paper presents the analysis and the simulated results using Matlab / SimPowerSystems / Simulink for control of the grid connected operation, where the power flow is controlled into the grid.

### 2. ANALYSIS OF THE CDFIG

The CDFIG is based on two DFIMs, mechanically and electrically coupled, as it is shown in Fig. 1. The two machines are inverse coupling sequences [12], and a rigorous analysis (using ideal models of DFIMs). This is the aim of Section II, and it allows one to describe the power flow through the two machines in order to evaluate qualitatively the generator efficiency. Then, it will also be possible to discuss on complementary constraints related to the CDFIG design for an integration of the two machines into a single frame [12].

Thereafter, modeling (Section III) is oriented by these preliminary results, more particularly concerning coupling sequence between rotor windings. A model of a realistic generator is established using a graphical representation of the system, adapted to the end-user point of view: an electrical scheme. The representation proposed in this paper (dynamical-equivalent circuit representation) is not limited to the classical case of sinusoidal steady-state operation but it can be applied to a transient description of the system. Then, this model is used for the design of the CDFIG controller will be detailed in Section IV [12].

If the DFIM is conserved, rotor windings must be supplied by another three-phase ac machine: Another DFIM is introduced, as shown in Fig. 3. It is shown that these two DFIMs can be directly connected and finally integrated, giving us a complete brushless solution called cascaded DFIM-CDFIM (more precisely, in this paper, generator-CDFIG). Notice that the global structure of the generator based on a single DFIG can be conserved with the CDFIG: The stator windings of the DFIM N°1 are connected to a
voltage source inverter, and this inverter is supplied by a Pulse Width Modulated (PWM) rectifier connected to a grid [12].

Moreover, in this paper, machine design is not treated, and this part of the problem introduces supplementary constraints. If a compact solution is required as for wind energy equipment, a single-frame CDFIG (SF-CDFIG) can be designed, introducing additional constraints for the numbers of pole pairs in order to avoid direct magnetic coupling between stator windings of the two machines, as shown in Fig. 2, with \( N_p = 2 \) and \( N_c = 1 \), [11].

![Fig. 2: Example of SF-CDFIG or BDFIG [11]](image)

The study presented in the following section is focused on the CDFIG. Indeed, it is necessary to analyze the behavior of this structure with inverse coupling sequence.

This paper is based on a simplified model of the DFIM where copper/iron losses and magnetic leakages are neglected as shown in Fig. 3. Thus, a DFIM is characterized by the following:

\[
\begin{align*}
\omega_s &= \omega_r + p \Omega \\
P_r &= -S \times P_s \\
P_s + P_r &= P_m \\
S \Delta = \frac{\omega_r}{\omega_s} \quad \text{or} \quad S &= \frac{\omega_s - N_p \Omega}{\omega_s}
\end{align*}
\]

![Fig. 3: DFIM in supersynchronous motor/generator convention](image)
According to Fig. 4, neglecting losses, the mechanical power $P_{mc}$ and $P_{mp}$, the rotor power $P_{rc}$ and $P_{rp}$ for either machine, as well as the grid power $P_g$, may be expressed as functions of machine $M_c$ and $M_p$ stator power $P_c$ and $P_p$ and the rotor power $P_{rc}$ and $P_{rp}$ and the supply stator voltage frequencies $\omega_c$, $\omega_2$ ($\omega_p = \omega_g$) and the rotor frequency $\omega_r$.

$$S_c = \frac{\omega_{rc}}{\omega_c}, \quad S_p = \frac{\omega_{rp}}{\omega_p}, \quad S \triangleq \frac{\omega_p}{\omega_c}$$

(5)

$$\omega_c = (N_p + N_c) \times \Omega_m - \omega_p, \quad \omega_p = 2\pi \times f_p$$

(6)

$$\omega_{rc} = \omega_p - N_p \times \Omega_m, \quad \omega_{rc} = N_c \times \Omega_m - \omega_p$$

(7)

$$P_{mc} = (1 - S_c)P_c = -P_p \frac{N_p \Omega}{\omega_p}$$

(8)

$$P_{mp} = (1 - S_p)P_p = -P_p \frac{N_p \Omega}{\omega_p}$$

(9)

$$P_{rc} = -S_c P_c = -P_c \frac{\omega_{rc}}{\omega_c}$$

(10)

$$P_{rp} = -S_p P_p = -P_p \frac{\omega_{rp}}{\omega_p}$$

(11)

$$P_g = P_c + P_p$$

(12)

The rotor power has the same value for both machines, but with opposite polarity, so that $P_{rc} = -P_{rp} = P_r$. Thus, from {Eq. (10)} and {Eq. (11)}, the stator power to the machines may be expressed as a function of the frequencies $\omega_c$ and $\omega_p$.

$$P_c = -P_p \frac{\omega_c}{\omega_p}$$

(13)
From \{Eq. (12)\} and \{Eq. (13)\}, the stator power of power machine may be expressed as a function of the grid power $P_g$ and the supply frequencies $\omega_p$.

$$P_c = P_g \frac{\omega_c}{\omega_c - \omega_p}$$ \hspace{1cm} (14)

$$P_p = -P_g \frac{\omega_p}{\omega_c - \omega_p}$$ \hspace{1cm} (15)

From \{Eq. (10)\} and \{Eq. (14)\}, the stator power for control machine, may be expressed as a function of the grid power $P_g$ and the frequencies $\omega_c$.

$$P_{mc} = -P_g \frac{\omega_c - \omega_r}{\omega_c - \omega_p}$$ \hspace{1cm} (16)

$$P_{mp} = -P_g \frac{\omega_r - \omega_p}{\omega_c - \omega_p}$$ \hspace{1cm} (17)

$$P_g = -(P_{mc} + P_{mp})$$ \hspace{1cm} (18)

Power flow diagrams of the CDFIG are shown in Figs. 5a- and 5b-, respectively.

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![Power flow diagrams](image)

**Fig. 5:** Power flow diagrams: a- typical for ‘supersynchronous’ speeds 

b- typical for ‘hypersynchronous’ speeds

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Fig. 6 shows an illustration of the transfers of powers of the CDFIG with variation speed.

For drawing the steady state per phase circuit the slips of two machines should be defined:

$$S_p = \frac{\omega_p - P_p \omega_m}{\omega_p}, \quad S_c = \frac{\omega_c - P_c \omega_m}{\omega_c}$$ \hspace{1cm} (19)
The steady state CDFIG per-phase equivalent circuit is shown in Fig. 7. Because the two considered machines are assumed identical the sum of rotor resistances and the sum of rotor leakage inductances are modeled in the rotor circuit.

The CDFIG steady-state performance equations on a per-phase basis are as follows:

\[
\begin{bmatrix}
V_{sp} \\
0 \\
V_{sc}
\end{bmatrix} = \begin{bmatrix}
R_s + j\omega_p L_{sp} & j\omega_p L_{mp} & 0 \\
j\omega_p L_{mp} & \frac{R_s}{S_p} + j\omega_p L_r & -j\omega_p L_{mc} \\
0 & -js\omega_p L_{mc} & R_s + j\omega_p L_{sc}
\end{bmatrix} \begin{bmatrix}
I_{sp} \\
I_r \\
I_{sc}
\end{bmatrix}
\]

(20)

Fig. 8 shows the frequencies of the cascade according to speed.

Fig. 9 shows the tensions $V_c$ may vary proportionally to machine $M_p$ Mp supplied frequency $f_c$, in order to maintain a constant $V_c / f_c$ ratio.
3. DYNAMICAL MODEL OF THE CASCADED DOUBLY FED INDUCTION GENERATOR

The behavior of each individual machine (PM and CM) is described by the following:

\[
\begin{align*}
\mathbf{v}_{sp} &= (R_{sp} + L_{sp}(S + j\omega_p))i_{sp} + L_{mp}(S + j\omega_p)i_{rp} \\
\mathbf{v}_{rp} &= (R_{rp} + L_{rp}(S + j\omega_r))i_{rp} + L_{mp}(S + j\omega_r)i_{sp}
\end{align*}
\] (21)

\[
\begin{align*}
\mathbf{v}_{sc} &= (R_{sc} + L_{sc}(S + j\omega_c))i_{sc} + L_{mc}(S + j\omega_c)i_{rc} \\
\mathbf{v}_{rc} &= (R_{rc} + L_{rc}(S + j\omega_r))i_{rc} + L_{mc}(S + j\omega_r)i_{sc}
\end{align*}
\] (22)

{Eq. (21)} and {Eq. (22)} refer to the power and control machines, respectively. Due to the pole pair difference between the two stators, there exists such relations between the electrical speeds of the rotor and stators for the 50 Hz system, which are given in

\[
\omega_p = 2\pi 50
\] (23)

\[
\omega_r = \omega_p - \omega_m P_p
\] (24)

\[
\omega_c = \omega_p - \omega_m (P_p + P_c)
\] (25)

The behavior of the CDFIG can be described in (4) by the combination of {Eq. (21)} and {Eq. (22)} and noting that \( i_{rp} = -i_{rc} \) and \( v_{rp} = v_{rc} \) due to the back-to-back connection of rotors.

\[
\begin{align*}
\mathbf{v}_{sp} &= (R_{sp} + L_{sp}(S + j\omega_p))i_{sp} + L_{mp}(S + j\omega_p)i_{rp} \\
\mathbf{v}_{sc} &= (R_{sc} + L_{sc}(S + j\omega_c))i_{sc} + L_{mc}(S + j\omega_c)i_{rc} \\
\theta &= (R_{rc} + L_{rc}(S + j\omega_r))i_{rc} + L_{mc}(S + j\omega_r)i_{rp} + (R_{rp} + L_{rp}(S + j\omega_r))i_{rp} + L_{mp}(S + j\omega_r)i_{rp}
\end{align*}
\] (26)

It is assumed that the stator has two sinusoidally distributed windings with number of poles \( P_p = P_c \).

There are three initial reference frames (shown in Fig. 10):
a- PW reference $d^p_s, q^p_s$ related to a $P_p$ pole-pair-type distribution, which is used as the overall reference frame.

b- CW reference $d^c_s, q^c_s$ related to a $P_c$ pole-pair-type distribution and located at a mechanical angular position of $\theta_c$ radians from $d^p_s, q^p_s$.

c- Rotor references $d^p_r, q^p_r$ and $d^c_r, q^c_r$ related, respectively, to a $P_p$ and $P_c$ pole-pair-type distributions which are located at a mechanical angular position of $\theta_r$ from $d^p_s, q^p_s$.

Fig. 10: Three-phase. CDFIG model in d-q reference frame, [13, 14]

In a standard practice, the dynamic equation in {Eq. (26)} is usually represented in the selected d-q reference frame. With the assumption of a stiff grid connection, the synchronous reference frame is selected. The stator frame rotates at the speed $\omega_e$ which is shown in Fig. 2. Moreover, Fig. 10 also shows the angle relationship of power machine stator, power and control machine rotors and control machine stator to the selected reference frame. The complete CDFIG dynamic model in d-q reference frame can be given in:

$$
\begin{align*}
\nu^q_{sp} &= R_{sp} i^q_{sp} + \frac{d \Psi^q_{sp}}{d t} + \Psi^d_{sp} \omega_p \\
\nu^d_{sp} &= R_{sp} i^d_{sp} + \frac{d \Psi^d_{sp}}{d t} - \Psi^q_{sp} \omega_p \\
\theta^q_r &= R_r i^q_r + \frac{d \Psi^q_r}{d t} + \Psi^d_r \omega_r \\
\theta^d_r &= R_r i^d_r + \frac{d \Psi^d_r}{d t} - \Psi^q_r \omega_r \\
\nu^q_{sc} &= R_{sc} i^q_{sc} + \frac{d \Psi^q_{sc}}{d t} + \Psi^d_{sc} \omega_c \\
\nu^d_{sc} &= R_{sc} i^d_{sc} + \frac{d \Psi^d_{sc}}{d t} - \Psi^q_{sc} \omega_c
\end{align*}
$$

(27)
Flux linkages are defined by:

\[ \Psi_{sp}^q = L_{sp} i_{sp}^q + L_{mp} i_r^q \]
\[ \Psi_{sp}^d = L_{sp} i_{sp}^d + L_{mp} i_r^d \]
\[ \Psi_{r}^q = L_{mp} i_{sp}^q + L_r i_r^q - L_{me} i_{sc}^q \]
\[ \Psi_{r}^d = L_{mp} i_{sp}^d + L_r i_r^d - L_{me} i_{sc}^d \]
\[ \Psi_{sc}^q = L_{sc} i_{sc}^q + L_{me} i_r^q \]
\[ \Psi_{sc}^d = L_{sc} i_{sc}^d + L_{me} i_r^d \]

The total electric \( T_e \) for BDFIG is the sum of both machines:

\[ T_e = \frac{3}{2} p \left( \Psi_{sp}^q i_{sp}^d - \Psi_{sp}^d i_{sp}^q \right) + p \left( \Psi_{sc}^q i_{sc}^d - \Psi_{sc}^d i_{sc}^q \right) \]

(28)

The electric torque equation is defined by the friction and total inertia of the power and control machines:

\[ T_e = T_L - \left( F_F^p + F_F^c \right) \omega_m - \left( J_p + J_c \right) \frac{d \omega_m}{dt} \]

(30)

The complete CDFIG system defined by {Eq. (27)} – {Eq. (30)} presents an accurate dynamic model of the generator the model can precisely describe the machine dynamic behavior under stiff grid connection.

4. CDFIG CONTROLLER DESIGN

The situation becomes more demanding when a wind turbine is required to produce constant voltage and constant frequency power in a weak grid or non-grid connected, stand alone situation. Special control strategies have to be devised to attain such objectives. Vector control, introduced by Blaschke in 1972, [10].

The developed control strategy is based on a loops control as shown in Fig. 11. Two regulation paths are implemented as in the classical vector control schemes: one control path regulates the \( d \) magnetizing currents and the other one is dedicated to control the \( q \) active currents. In order to obtain a good decoupled control, the PW flux orientation has been selected (\( \Psi_{sp}^d = \left| \Psi_{sp} \right| \) and \( \Psi_{sp}^q = 0 \)). The obtained control strategy for the BDFM is similar to the well-known stator field orientation control used in the DFIM. [11, 13, 14].

5. SIMULATION RESULTS

The CDFIG is first placed in ideal conditions and is driven to 735 rpm. We impose an active power step of \(-4\) kW at \( t = 3 \) s and we observe the response obtained with the PI controller. Also we impose a reactive power step of \( 2 \) kW at \( t = 2 \) s and we observe the response obtained with the PI controller.

Results are presented on figures 12, 13, 14 and 15.

We can notice that the response times are equivalent (about 35 ms). The effect of the active power step on the reactive power shows that the cross-coupling terms. The impact of the active power change on reactive power and on the contrary in the DFTSIG is demonstrated in Fig. 8, where they can be seen that there only exists a transient
disturbance in the reactive and active component (at times 2 and 3 s) while the steady state operation are unaffected. Fig. 9 shows the Power machine stator current.

Fig. 11: CDFIG Controller Structure

Fig. 12: Reactive and active power decoupling

Fig. 13: Power stator current
6. CONCLUSIONS

Owing to its great reliability, CDFIM is an interesting solution for wind energy applications. It has been also shown in this paper that using an appropriate modeling approach based on dynamical equivalent circuit representation; a theoretical and simulation study of the CDFIG dynamic performance in closed loop control of the generator active and reactive powers has been presented. The control system is based on the field orientation principle and the orientation of the power machine stator flux with two PI controllers placed in the power stator field coordinates, where a back-to-back voltage source converter was employed. Moreover, the proposed modeling approach allows the study of power flow. The proposed configuration can be easily implemented with fractional control machine and further with common squirrel cage rotor and dual stator windings.

REFERENCES


