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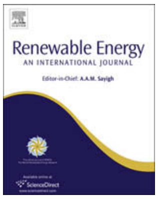

Integrated power characteristic study of DFIG and its frequency converter in wind power generation

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A R T I C L E I N F O

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ABSTRACT

A doubly fed induction generator (DFIG) is a variable speed induction machine. It is a standard, wound rotor induction machine with its stator windings directly connected to the grid and its rotor windings connected to the grid through a back-to-back AC/DC/AC PWM converter. The power generation of a DFIG includes power delivered from two paths, one from the stator to the grid and the other from the rotor, through the frequency converter, to the grid. The power production characteristics, therefore, depend not only on the induction machine but also on the two PWM converters as well as how they are controlled. This paper investigates power generation characteristics of a DFIG system through computer simulation. The specific features of the study are (1) a steady-state model of a DFIG system in *d*–*q* reference frame, (2) a simulation mechanism that reflects decoupled *d*–*q* control strategies, (3) power characteristic simulation for both generator and converter, and (4) an integrative study combining stator, rotor and converter together. An extensive analysis is conducted to examine integrated power generation characteristics of DFIG and its frequency converter under different wind and *d*–*q* control conditions so as to benefit the development of advanced DFIG control technology.

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1. Introduction

A doubly fed induction generator (DFIG) is an adjustable-speed induction machine widely used in modern wind power industry [1,2]. Wind turbine manufacturers are moving to variable speed concepts because of the following reasons: (1) a higher energy yield, (2) a reduction of mechanical loads and a simpler pitch control, (3) an extensive controllability of both active and reactive powers, and (4) less fluctuation in output power [2,3].

However, the performance of a DFIG depends not only on the induction machine but also on the two back-to-back AC/DC PWM converters as well as how they are controlled. In order to comprehend DFIG power generation characteristics under different control conditions, various techniques have been developed. This can be divided into two categories: (1) transient approaches [4–6], and (2) steady-state techniques [7–9]. Transient approaches are essential to study DFIG dynamic performance in a short time period. But, steady-state techniques are important to examine DFIG characteristics in a broader spectrum. Unlike a conventional fixed-speed induction machine, a DFIG delivers power to the grid from both the stator and rotor paths, and its characteristics depend strongly on the *d*–*q* control approaches applied to the rotor- and grid-side converters. Those specific regularities must be considered in the steady-state study of a DFIG system.

The purpose of this paper is to investigate steady-state power characteristics of integrated DFIG and its frequency converter under general *d*–*q* control strategies so as to benefit the development of advanced control technology. Different from conventional steady-state studies [7–9], the main features of this paper are (1) steady-state models of a DFIG system in *d*–*q* reference frame, (2) a steady-state simulation mechanism that reflects general decoupled *d*–*q* control strategies, (3) power simulation for both the generator and the converter, and (4) integrative power characteristic study of DFIG stator, rotor and converter together under different wind and *d*–*q* control conditions.

In the sections that follow, the paper first introduces the operation of a DFIG, its back-to-back PWM converter, and the fundamental converter control principles. Then, steady-state models in *d*–*q* reference frame are developed. Simulation studies are performed to investigate the power generation regularities of a DFIG and its frequency converter under different *d*–*q* control conditions. Then, the models of the two parts are combined together for an integrative study by considering wind power extraction characteristics. Finally, the paper concludes with the summary of the main points.

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2. Doubly fed induction generators and controls

A doubly fed induction generator (DFIG) is a standard, wound rotor induction machine with its stator windings directly connected to the grid and its rotor windings connected to the grid through a frequency converter (Fig. 1) [2]. In modern DFIG designs, the frequency converter is built by two self-commutated current-regulated voltage source PWM converters, rotor- and grid-side converters, with an intermediate DC voltage link. The two back-to-back PWM converters are controlled independently through decoupled *d*–*q* vector control approaches [10,11].

The rotor-side controller consists of a reactive power controller and an active power (or torque) controller [4,10,11]. It operates in either stator-flux or stator-voltage-oriented reference frame [12–14]. Fig. 2 shows an active and reactive power based control mechanism in a stator-flux-oriented frame, in which the *q*-axis current component is for active power control and the *d*-axis component is for reactive power control [11]. The *d*–*q* voltage control signals, the final control action applied to the converter, are obtained by comparing the *d*- and *q*-current setpoints to the actual rotor *d*- and *q*- currents, as shown by the second stage controller in Fig. 2.

The grid-side controller is also a two-stage controller operating in a grid AC voltage reference frame (Fig. 3) [10,15]. Traditionally, the *d*-axis current is used for active power or DC-link voltage control and the *q*-axis current is for reactive power control. The *d* and *q* voltage control signals, generated by comparing the *d*- and *q*-current setpoints to the actual *d*- and *q*-currents to the grid (Fig. 3), are final control actions applied to the converter [10,15].

3. DFIG *d*–*q* steady-state model

A commonly used transient model for an induction machine is the Park model. Using the motor convention, the space vector theory yields stator and rotor voltage and flux equations in the form [16]:

$$\begin{pmatrix} v_{sd} \\ v_{sq} \end{pmatrix} = R_s \begin{pmatrix} i_{sd} \\ i_{sq} \end{pmatrix} + \frac{d}{dt}\begin{pmatrix} \lambda_{sd} \\ \lambda_{sq} \end{pmatrix} + \omega_s \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} \lambda_{sd} \\ \lambda_{sq} \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} v_{rd} \\ v_{rq} \end{pmatrix} = R_r \begin{pmatrix} i_{rd} \\ i_{rq} \end{pmatrix} + \frac{d}{dt}\begin{pmatrix} \lambda_{rd} \\ \lambda_{rq} \end{pmatrix} + \omega_r \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} \lambda_{rd} \\ \lambda_{rq} \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} \lambda_{sd} \\ \lambda_{sq} \\ \lambda_{rd} \\ \lambda_{rq} \end{pmatrix} = \begin{pmatrix} L_{ls}+L_m & 0 & L_m & 0 \\ 0 & L_{ls}+L_m & 0 & L_m \\ L_m & 0 & L_{lr}+L_m & 0 \\ 0 & L_m & 0 & L_{lr}+L_m \end{pmatrix}\begin{pmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{pmatrix} \tag{3}$$

where R_s, R_r, L_{ls}, and L_{lr} are the resistances and leakage inductances of the stator and rotor windings; L_m is the mutual inductance; v_{sd}, v_{sq}, v_{rd}, v_{rq}, i_{sd}, i_{sq}, i_{rd}, i_{rq}, λ_{sd}, λ_{sq}, λ_{rd}, and λ_{rq} are the *d* and *q* components of the space vectors of stator and rotor voltages, currents, and fluxes; and ω_s and ω_r are the angular frequencies of stator and rotor currents. Eqs. (1) and (2) can be combined into complex equations using space vectors as shown by Eqs. (4) and (5).

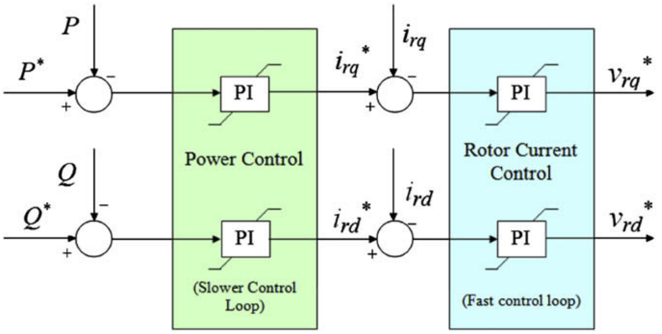

Fig. 2. DFIG rotor-side controller.

$$\vec{v}_{s\_dq} = R_s \vec{i}_{s\_dq} + \frac{d}{dt}\vec{\lambda}_{s\_dq} + j\omega_s \vec{\lambda}_{s\_dq} \tag{4}$$

$$\vec{v}_{r\_dq} = R_r \vec{i}_{r\_dq} + \frac{d}{dt}\vec{\lambda}_{r\_dq} + j\omega_r \vec{\lambda}_{r\_dq} \tag{5}$$

Under steady-state condition and considering $\omega_r = s \cdot \omega_s$, Eqs. (6) and (7) are obtained from Eqs. (3)–(5). Note that, throughout the paper, lowercase letters represent instantaneous time dependent variables and capital ones stand for steady-state values.

$$\vec{V}_{s\_dq} = R_s \vec{I}_{s\_dq} + j\omega_s L_{ls} \vec{I}_{s\_dq} + j\omega_s L_m \left(\vec{I}_{s\_dq} + \vec{I}_{r\_dq}\right) \tag{6}$$

$$\frac{\vec{V}_{r\_dq}}{s} = \frac{R_r}{s}\vec{I}_{r\_dq} + j\omega_s L_{lr} \vec{I}_{r\_dq} + j\omega_s L_m \left(\vec{I}_{s\_dq} + \vec{I}_{r\_dq}\right) \tag{7}$$

The *d*–*q* steady-state equivalent circuit (Fig. 4) can then be obtained from Eqs. (6) and (7). Using the motor convention, the stator real and reactive power is (8). The rotor loss power is (9). The air gap power is (10). There is an additional complex power item (11), which is absorbed by the rotor from the rotor-side converter. The air gap power (10) is composed of the power converted to mechanical form (P_{conv}), the rotor copper losses (9), and the power absorbed by the injected rotor voltage source. Thus, (12) allows computation of the power converted to mechanical form based upon the defined sign conventions. In Eqs. (8)–(12), and throughout this paper, passive sign convention is applied to the stator, rotor, and rotor-/grid-side converters. Hence, positive real or reactive powers imply that the induction machine is absorbing from the grid by the stator path, the rotor path, or the converters. Negative

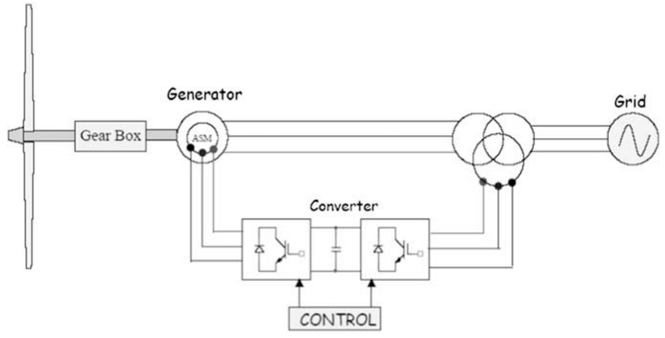

Fig. 1. Configuration of a DFIG wind turbine.

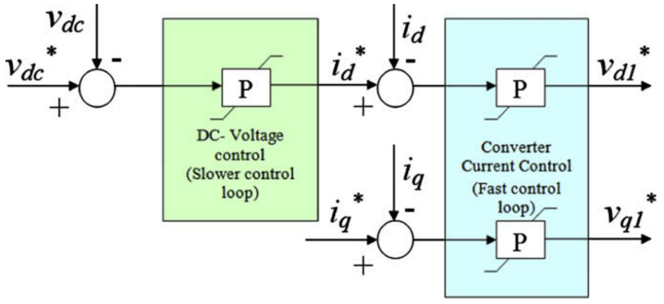

Fig. 3. DFIG grid-side controller.

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