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Direct power control of DFIG based on discrete space vector modulation

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ABSTRACT

This paper presents a new direct power control (DPC) strategy for a double fed induction generator (DFIG) based wind energy generation system. Switching vectors for rotor side converter were selected from the optimal switching table using the estimated stator flux position and the errors of the active and reactive power. A few number of voltage vectors may cause undesired power and stator current ripple. In this paper the increased number of voltage vectors with application of the Discrete Space Vector Modulation (DSVM) will be presented. Then a new switching table in supersynchronous and sub-synchronous frames will be proposed. Simulation results of a 2 MW DFIG system demonstrate the effectiveness and robustness of the proposed control strategy during variations of active and reactive power, machine parameters, and wind speed.

1. Introduction

The most important advantages of the variable speed wind turbines as compared with conventional constant speed system are the improved dynamic behavior, resulting in the reduction of the drive train mechanical stress and electrical power fluctuation, and also the increase of power capture [1]. One of the generation systems commercially available in the wind energy market currently is the doubly fed induction generator (DFIG) with its stator winding directly connected to the grid and with its rotor winding connected to the grid through a variable frequency converter as shown in Fig. 1. One of the most advantages of this system is that the rating of the power converter is one third of that of the generator.

Direct torque control (DTC) of induction machine drives was developed in the mid 1980s [2,3]. DTC is one of the actively researched control schemes which is based on the decoupled control of flux and torque. DTC provides a very fast and precise torque response without the complex field-orientation block and the inner current regulation loop. There have been some DTC based strategies, e.g., voltage vector selection using switching table [2], direct self control [3], and space vector modulation [4].

Based on the principles of DTC strategy, direct power control (DPC) was developed for three-phase pulse width modulation (PWM) rectifiers [5–7]. DPC method is based on the instantaneous space vector theory. More recently, DPC control of DFIG-based wind turbine systems has been proposed [8–11]. DPC directly controls the stator active and reactive powers, it is possible to control the rotor flux space vector amplitude and its relative distance to the stator flux space vector, i.e., a necessary condition for the control of the DFIG. Several authors have already developed DPC techniques that operate at a variable switching frequency [8,9]. The variable switching frequency makes the power converter and the ac harmonic filter complicated and expensive. More recently in [10,11] DPC at constant switching frequency have been developed for the DFIG. Constant converter switching frequency eases the design of the power converter and ac harmonic filter. The proposed strategy in [10,11] needs to calculate rotor flux in each sampling period. The implementation of these methods requires the knowledge of the rotor and stator parameters. The calculation of stator flux angle requires PLL circuit that makes the real time implementation of the proposed algorithm in [10] more expensive. In [11], using three non equal time intervals in each switching period causes the calculation and selection of suitable voltage vector in each time interval to become more complicated. Meanwhile, this method is suitable for low switching frequency applications.

In this paper a new control technique is introduced which allows the performance of DPC scheme in terms of active and reactive power ripple and current distortion to be improved. A DPC with constant switching frequency was proposed. These improvements could be achieved with simple control circuit like the one in [9] without increasing the inverter switching frequency. Practical implementation of this strategy is much easier than that of other DPC with constant switching frequency. The new control algorithm is based on a discrete space vector modulation (DSVM) technique which uses prefixed time intervals within a cycle period. In this way

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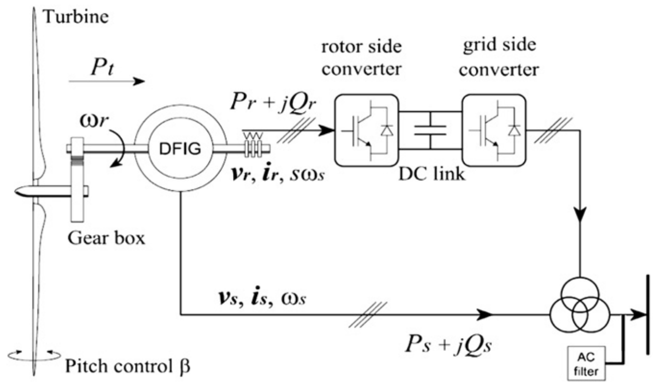

Fig. 1. Schematic diagram of DFIG-based wind generation systems.

a higher number of voltage space vectors can be synthesized with respect to those used in conventional DPC technique. The increased number of voltage vectors allows us to define more accurate switching tables in which the selection of the voltage vectors is made according to the rotor speed, active and reactive power errors. The switching tables are derived from the analysis of the equations linking the applied voltage vector to the corresponding active and reactive power variations. These equations are obtained using a discrete model of the machine and valid for high sampling frequency. Even though, the number of voltage vectors and elements of switching table are increased, but some of the table elements are similar. By suitable selection of the elements from tables discussed in section VI, the complexity of the proposed method is less than the methods of [10,11] and comparable with Ref. [9].

Simulation results on a 2 MW DFIG generation system are presented to demonstrate the performance of the proposed control strategy during variations of rotor speed, active and reactive power, machine parameters, and converter dc link voltage.

2. DFIG equations in the rotor reference frame

The dynamic behavior of a DFIG is described by the following equations written in terms of space vectors in a rotor reference frame:

$$V_s = R_s I_s + \frac{d\Psi_s}{dt} + j\omega_r \Psi_s \tag{1}$$

$$V_r = R_r I_r + \frac{d\Psi_r}{dt} \tag{2}$$

$$\Psi_s = L_s I_s + L_m I_r \tag{3}$$

$$\Psi_r = L_r I_r + L_m I_s \tag{4}$$

where $\Psi_r, \Psi_s, V_r, V_s, I_r, I_s, R_r, R_s$ are the rotor and stator fluxes, the rotor and stator voltages, the rotor and stator currents, and the rotor and stator resistances respectively. Referring to [12], the stator active and reactive power inputs from the network can be calculated as

$$P_s = \frac{3}{2} V_s \cdot I_s \tag{5}$$

$$Q_s = -\frac{3}{2} V_s \times I_s \tag{6}$$

By substitution of (1)–(4) in equations (5) and (6), and neglecting the stator resistance;

$$P_s = \frac{3L_m\omega_1}{2\sigma L_s L_r}(j\Psi_r \cdot \Psi_s) \tag{7}$$

$$Q_s = -\frac{3}{2} j\omega_1 \Psi_s \times \left(-\frac{L_m \Psi_r}{\sigma L_s L_r} + \frac{\Psi_s}{\sigma L_s}\right) \tag{8}$$

where $\sigma = (L_s L_r - L_m^2)/L_s L_r$ and ω_1 is the synchronous angular frequency.

3. Direct active and reactive power control principle

According to (7) and (8)

$$P_s = -\frac{3}{2}\frac{L_m}{(\sigma L_s L_r)}\omega_1 |\Psi_s||\Psi_r| \sin\theta \tag{9}$$

$$Q_s = \frac{3}{2}\frac{L_m}{(\sigma L_s L_r)}\omega_1 |\Psi_s| \left(|\Psi_r|\cos\theta - \frac{L_r}{L_m}|\Psi_s|\right) \tag{10}$$

where θ is the angle between the rotor and stator flux linkage vectors. Hence, the last two expressions show that the stator active and reactive powers can be controlled by modifying the relative angle between the rotor and stator flux space vectors and their amplitudes as shown in Fig. 2.

Stator flux cannot be controlled directly. Neglecting the rotor resistance, the rotor flux variation in the rotor reference frame can be approximated as:

$$\frac{d\Psi_r}{dt} = V_r - R_r I_r \simeq V_r \tag{11}$$

According to (11) the rotor flux moves in the direction of the applied rotor voltage vector, and its speed is proportional to the amplitude of the voltage vector.

From (1)–(4) it is possible to determine the first order differential equation linking the stator flux to the rotor flux, given by

$$V_s + \frac{L_m}{\sigma\tau_s L_r}\Psi_r = \frac{d\Psi_s}{dt} + \Psi_s\left(j\omega_r + \frac{1}{\sigma\tau_s}\right) \tag{12}$$

where $\tau_s = L_s/R_s$ and ω_r is the rotor angular frequency. This equation clearly shows the nature of rotor flux dynamic response based on the stator flux variation. In steady state conditions the stator and rotor flux vectors have the same angular speed, and the angle between these vectors determines the active and reactive power value, as expressed in (9) and (10).

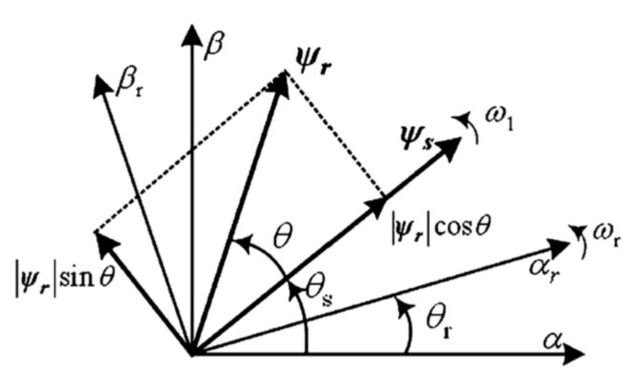

Fig. 2. Stator and rotor flux vectors in stationary and rotor reference frames.