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VSC-based direct torque and reactive power control of doubly fed induction generator

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ABSTRACT

This paper proposes a novel direct torque and reactive power control (DTC) for grid-connected doubly fed induction generators (DFIGs) in the wind power generation applications. The proposed DTC strategy employs a variable structure control (VSC) scheme to calculate the required rotor control voltage directly and to eliminate the instantaneous errors of active and reactive powers without involving any synchronous coordinate transformations, which essentially enhances the transient performance. Constant switching frequency is achieved as well by using space vector modulation (SVM), which eases the designs of power converter and ac harmonic filters. Simulated results on a 2 MW grid-connected DFIG system are presented and compared with those of the classic voltage-oriented vector control (VC) and traditional look-up-table (LUT) direct power control (DPC). The proposed VSC DTC maintains enhanced transient performance similar to the LUT DPC and keeps the steady-state harmonic spectra at the identical level as the VC strategy when the network is strictly balanced. Besides, the VSC DTC strategy is capable of fully eliminating the double-frequency pulsations in both the electromagnetic torque and the stator reactive power during network voltage unbalance.

1. Introduction

Compared with other solutions such as fixed-speed squirrel-cage induction generators or variable-speed synchronous generators with fully-sized converters, doubly fed induction generators (DFIGs) with partially-sized converters are extendedly employed in modern wind power generation systems, since DFIGs feature variable speed operation, four-quadrant active and reactive power capability, low converter cost and reduced power losses.

Conventional control scheme of grid-connected DFIGs is usually based on either stator-flux-oriented (SFO) [1,2] or stator-voltage-oriented (SVO) [3,4] vector control (VC). The scheme decomposes the rotor current into active and reactive power components in the synchronous reference frame. Decoupled control of the instantaneous stator active and reactive powers is then achieved by regulating the decomposed rotor currents using proportional-integral (PI) controllers. One main drawback for this control scheme is that the performance highly relies on the tuning of PI parameters and the accurate tracking of angular information of stator flux/voltage. Thus, performance may degrade when the stator voltage or flux is not oriented precisely during network disturbances, such as voltage unbalances or/and harmonic distortions. When the grid voltage is unbalanced, improved VC strategies for DFIG based on SFO and SVO have been reported in [5,6] and [7,8], respectively. Due to the existence of negative-sequence stator/rotor voltages and currents during network unbalance, the phase-lock loop (PLL) for tracing positive-sequence stator voltage/flux and the rotor current control scheme should be modified. In [5], a dual rotor current controller based on the decomposing of positive- and negative-sequence components was employed to regulate the rotor positive and negative sequence currents, respectively. While in [6], an exclusively auxiliary PI controller was added to the main PI one so as to provide compensated regulation for the negative-sequence rotor current. Moreover, in order to remove the decomposition process for positive/negative sequence rotor current, a resonant regulator tuned at twice the grid frequency was designed and added to the PI controller [7,8]. As a result, the positive and negative sequence rotor currents were controlled simultaneously in the synchronous reference frame. However, these improved VC strategies [5–8] inevitably bring some modifications to the conventional scheme [1–4] and more or less complicate the system design.

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Regarding the discrete operation of voltage source inverters, direct torque control (DTC), as an alternative to the VC control for induction machines, was proposed in [9,10]. The DTC strategy provides direct torque regulation of induction machine, reduces the complexity of VC strategy, such as complex synchronous coordinate transformation, and minimizes the use of machine parameters. Initially, the basic DTC method directly controls the torque and flux by selecting voltage vectors from a pre-defined look-up-table (LUT) based on the stator flux and torque information. One main disadvantage is that the converter switching frequency varies with operating conditions and torque/flux hysteresis controllers' bandwidths, which significantly complicates power circuit designs and results in obvious torque pulsations [11]. Several efforts have been addressed to solve this problem by incorporating space vector modulation (SVM) technique and, meanwhile, a constant switching frequency was achieved [12–14]. In [12,13] inverter switching duty cycles were generated from torque and flux PI controllers, whereas in [14] they were calculated based on the instantaneous errors of torque and flux within each sampling period. In [15], the inverter's output voltage vectors were selected using the basic DTC switching table while the duration time of every voltage vector was determined by the torque-ripple-minimum strategy.

More recently, based on the principles of DTC, similar DTC or direct power control (DPC) strategies have also been developed to control DFIG-based wind turbine systems [16–21]. In [16] and [17], the methods were based on an optimal switching table by using the information of estimated rotor flux and stator flux, respectively. However, like a basic DTC, LUT-based DPC has switching frequencies varying problem, which changes significantly with the active/reactive power variations, the power controllers' hysteresis bandwidths as well as the machine operating velocities. As a result, the stator side ac filter, preventing switching harmonics from injecting into the connected grid, needs to be designed to absorb the harmonics with broadband frequency spectra and the filter's efficiency is then reduced with increased size and power losses. To tackle with this problem highlighted above, in [18,19], the switching vectors were chosen based on a basic switching table and thereafter their duration times were optimized with the target of reducing pulsations in the torque/active power and flux/reactive power, respectively. Although, a constant switching frequency was achieved, it required complicated online calculations and had oscillating problems when the generator operates around its synchronous speed. Constant switching frequency DPC strategies were developed in [20] and [21], respectively, based on the discrete SVM scheme and a predictive power model. The method in [21], which was implemented in the synchronous reference frame, apparently necessitates the angular information of network voltage and the synchronous coordinate transformations. Besides, when the network voltage is unbalanced, these DPC strategies may generate significant harmonics in the stator currents or obvious pulsations in the active/reactive powers and electromagnetic torque [22].

In order to solve the problems aforementioned, this paper presents a novel direct torque and reactive power regulation scheme for grid-connected DFIGs using nonlinear variable structure control (VSC) approach. The VSC approach features simple implementation, disturbance rejection, strong robustness and fast responses [23–28]. The design principles of VSC and its applications to electrical drive systems were initially proposed in [23]. Then, a new variable-structure position control law was proposed in [24] for a DC motor based on a time-varying switching line, so as to guarantee the existence of a sliding mode from the beginning of the shaft motion. While as to the sensorless torque and flux control of induction machines, a continuous sliding-mode controller without chattering of control input was employed in the stator flux regulator and rotor flux observer [25]. By combing the features of sliding mode control (SMC) and fuzzy logic control (FLC), reference [26] proposed a practical approach to the robust speed control of electrical drives by using a trajectory reference for the switching function to compensate for the system gain, later in [27] sliding mode approach was used to define the optimum values of the scaling factors for a fuzzy logic controller, which was tested in a server control of DC machine drives. More recently in order to obtain a high-accuracy positioning of a six-phase induction machine in both healthy and faulted modes, both SMC and FLC have been implemented simultaneously and separately [28] in the inner loop to cope with the plant parameter variations due to the loss of one to three phases, and in the external loop to deal with the plant parameter variations due to the changes in mechanical configuration.

Consequently, in this paper, the proposed VSC-based DTC is capable of simply regulating the instantaneous torque/active and reactive powers without any rotor current control loops and synchronous coordinate transformations involved. The required rotor control voltage can be directly obtained in the stator stationary reference frame and SVM technique is employed to achieve constant switching frequency. Thus, enhanced transient performance similar to the traditional LUT-DPC is obtained and steady-state stator/rotor current harmonic spectra are kept at the same level as the classic VC strategy due to the use of SVM module. In addition, by using the proposed VSC-DTC, the DFIG system operates satisfactorily without any pulsations in the electromagnetic torque and stator reactive power, and with no harmonics in the stator currents when the network voltage is unbalanced.

The rest part of this paper is organized as follows. Section 2 gives dynamic behavior of a grid-connected DFIG in the stator stationary reference frame and the associated instantaneous stator active and reactive power flows. With traditional LUT DPC briefly described, VSC-based DTC strategy is proposed, designed and analyzed in Section 3. Section 4 presents the simulated results to demonstrate the performance of the proposed DTC strategy. Finally, the conclusions are drawn in Section 5.

2. Dynamic behavior of a DFIG in the stator stationary reference frame

The equivalent circuit of a DFIG, represented in the stator stationary reference frame, is shown in Fig. 1. As shown, in the stator stationary reference frame the stator and rotor flux linkage vectors can be given as

$$\begin{aligned} \psi^{\rm s}_{{\rm s}\alpha\beta} &= L_{\rm s}\boldsymbol{I}^{\rm s}_{{\rm s}\alpha\beta} + L_{\rm m}\boldsymbol{I}^{\rm s}_{{\rm r}\alpha\beta} \\ \psi^{\rm s}_{{\rm r}\alpha\beta} &= L_{\rm m}\boldsymbol{I}^{\rm s}_{{\rm s}\alpha\beta} + L_{\rm r}\boldsymbol{I}^{\rm s}_{{\rm r}\alpha\beta} \end{aligned} \tag{1}$$

According to (1), the rotor flux linkage vector can be expressed in terms of stator current and stator flux linkage vector as

$$\psi^{\rm s}_{{\rm r}\alpha\beta} = -\boldsymbol{I}^{\rm s}_{{\rm s}\alpha\beta}/k_\sigma + L_{\rm r}\psi^{\rm s}_{{\rm s}\alpha\beta}/L_{\rm m} \tag{2}$$

where $k_\sigma = L_{\rm m}/(\sigma L_{\rm s}L_{\rm r})$ and $\sigma = 1 - L^2_{\rm m}/(L_{\rm s}L_{\rm r})$ is leakage factor.

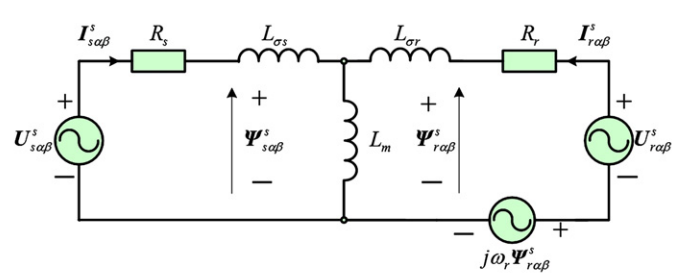

Fig. 1. Equivalent circuit of a DFIG in the stator stationary reference frame.