Direct Active and Reactive Power Regulation of DFIG Using Sliding-Mode Control Approach

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***Abstract*—This paper presents a new direct active and reactive power control (DPC) of grid-connected doubly fed induction generator (DFIG)-based wind turbine systems. The proposed DPC strategy employs a nonlinear sliding-mode control scheme to directly calculate the required rotor control voltage so as to eliminate the instantaneous errors of active and reactive powers without involving any synchronous coordinate transformations. Thus, no extra current control loops are required, thereby simplifying the system design and enhancing the transient performance. Constant converter switching frequency is achieved by using space vector modulation, which eases the designs of the power converter and the ac harmonic filter. Simulation results on a 2-MW grid-connected DFIG system are provided and compared with those of classic voltage-oriented vector control (VC) and conventional lookup table (LUT) DPC. The proposed DPC provides enhanced transient performance similar to the LUT DPC and keeps the steady-state harmonic spectra at the same level as the VC strategy.**

***Index Terms*—Constant switching frequency, direct power control (DPC), doubly fed induction generators (DFIGs), sliding-mode control (SMC), wind power.**

NOMENCLATURE

$\boldsymbol{I}_s$, $\boldsymbol{I}_r$	Stator, rotor current vectors.
L_m	Mutual inductance.
L_s, L_r	Stator, rotor self-inductances.
$L_{\sigma s}$, $L_{\sigma r}$	Stator, rotor leakage inductances.
P_s, Q_s	Stator output active and reactive powers.
R_s, R_r	Stator, rotor resistances.
$\boldsymbol{U}_s$, $\boldsymbol{U}_r$	Stator, rotor voltage vectors.
θ_r	Rotor angle.
$\boldsymbol{\psi}_s$, $\boldsymbol{\psi}_r$	Stator, rotor flux linkage vectors.
ω_1, ω_r, ω_{slip}	Stator, rotor, and slip angular frequencies.

Subscripts

α_s, β_s	Stationary $\alpha_s\beta_s$ axis.
α_r, β_r	Rotor $\alpha_r\beta_r$ axis.
s, r	Stator, rotor.

Superscripts

s, r	Stator $\alpha_s\beta_s$, rotor $\alpha_r\beta_r$ reference frames.
$*$	Reference value for controller.
$\wedge$	Conjugate complex.

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I. INTRODUCTION

DOUBLY fed induction generators (DFIGs) are extendedly used in modern wind power generation systems due to their variable speed operation, four-quadrant active and reactive power capability, low-converter cost, and reduced power losses compared with other solutions such as fixed speed induction generators or fully fed synchronous generators with fully sized converters.

Classic control of grid-connected DFIGs is usually based on either stator voltage oriented [1], [2] or stator-flux-oriented (SFO) [3], [4] vector control (VC). The scheme decouples the rotor current into active and reactive power components in the synchronous reference frame. Control of instantaneous stator active and reactive powers is then achieved by regulating the decoupled rotor currents, using proportional-integral (PI) controllers. One main drawback for this control scheme is that the performance highly relies on the tuning of the PI parameters and accurate machine parameters such as stator and rotor inductances and resistances. Thus, performance may degrade when actual machine parameters deviate from values used in the control system.

Considering discrete operation of voltage source inverters, direct torque control (DTC), as an alternative to the VC control for induction machines, was proposed in [5] and [6]. The DTC strategy provides direct torque regulation of the machine's torque, reduces the complexity of the VC strategy and minimizes the use of machine parameters. Initially, the basic DTC method directly controls the torque and flux by selecting voltage vectors from a predefined lookup table (LUT) based on the stator flux and torque information. One main problem [7] is that the converter switching frequency varies with operating conditions and torque/flux hysteresis controllers' bandwidth, which significantly complicates power circuit designs and results in obvious torque pulsations. Several efforts have been addressed to solve this problem by incorporating space vector modulation (SVM) technique, and meanwhile constant switching frequency was achieved [8]–[10]. In [8] and [9], inverter switching duty cycles were generated from torque and flux PI controllers, whereas in [10], they were calculated based on the instantaneous errors of torque and flux within each sampling period. In [11], 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.

Recently, based on the principles of DTC, similar DTC or direct power control (DPC) strategies have also been developed to control DFIG systems [12]–[16]. In [12] and [13], 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 significantly with active and reactive power variations, the power controllers' hysteresis bandwidth as well as the machine operating velocity. As a result, the stator side ac filter preventing switching harmonics from injecting the connected grid needs to be designed to absorb broad-band harmonics, and the filter's efficiency is reduced with increased size and power losses. To solve this issue highlighted, in [14] and [15], 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 or active power and flux or reactive power. Although a constant switching frequency was achieved, it required complicated online calculations and had oscillating problems when the generator operates around its synchronous speed. A simple constant switching frequency DPC strategy based on a predictive power model was developed in [16] and [17]. The method, however, was implemented in the synchronous reference frame, which necessitates the angular information of network voltage and the synchronous coordinate transformations.

Variable structure control or sliding-mode control (SMC) strategy is an effective and high-frequency switching control for nonlinear systems with uncertainties [18]–[20]. The design principles of SMC and its applications to electrical drive systems were initially proposed in [18]. It features simple implementation, disturbance rejection, strong robustness, and fast responses, but the controlled state may exhibit undesired chattering. Thus, a SMC-based DTC drive for induction machine was proposed in [19] and [20] with SFO and regulated. It is named linear and variable structure control, which employs a switching component and a linear one, and has dual behaviors.

Owing to the robustness with respect to external disturbance and unmodeled dynamics of wind turbines and generators, a few second-order SMC approaches have been introduced for renewable energy applications in terms of aerodynamic control [21], [22] and power converters control [23], [24]. In [21], a robust sliding-mode controller was proposed for the purpose of regulating power generation in variable-speed wind turbines. As a result, the stability in two operation regions, namely, low-speed and high-speed regions, is guaranteed, and the ideal feedback control solution despite mode uncertainties is imposed as well. The power reference is generated by a maximum power point tracking (MPPT) algorithm that searches for the peak power on the power–speed curve, but much of the time wind speed fluctuations force the turbine to operate off the peak of the MPPT curve. On the other hand, tight tracing of the MPPT curve would lead to significant mechanical stress and transfer aerodynamic fluctuations into the power system. This, as a consequence, will result in less energy capture. In order to improve the performance, a high-order SMC strategy was presented in [22] for variable-speed wind turbines, which combines a second-order sliding-mode observer for the estimation of the aerodynamic torque together with a second-order sliding-mode controller for tracking the optimal torque. While for the rotor side converter of DFIG driven by marine current turbine [23] and wind turbine [24], respectively, second-order SMC schemes were proposed to regulate the d- and q-axis rotor currents or d-axis rotor current and electromagnetic torque with SFO in the synchronous reference frame. Apparently, similar to VC [1]–[4] and predictive DPC [13], [14] schemes, these converter's control strategies [23], [24] based on SMC approach, also require synchronous coordinate transformation associated with the angular information of stator flux. Besides, identical to classic VC scheme, additional outer control loop for active and reactive powers is required to generate the reference values of d- and q-axis rotor currents as well.

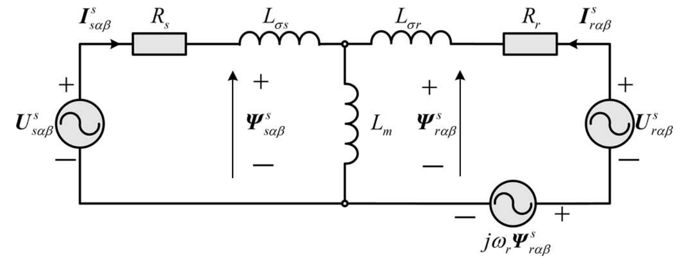

Fig. 1. Equivalent circuit of a DFIG in the stator stationary reference frame.

In order to tackle the drawback highlighted earlier, this paper presents a new direct active and reactive power regulation schemes for grid-connected DFIGs, using nonlinear SMC approach. The proposed SMC-based DPC is capable of simply regulating the instantaneous 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. As a result, enhanced transient performance similar to the conventional LUT DPC is obtained and steady-state stator and rotor current harmonic spectra are kept at the same level as the classic VC strategy due to the use of SVM module. The rest part of the paper is organized as follows. Section II gives dynamic behavior of grid-connected DFIG in the stationary reference frame and the associated instantaneous stator active and reactive power flows. With conventional LUT DPC briefly described, SMC-based DPC strategy is proposed, designed, and analyzed in Section III. Section IV presents the simulation results to demonstrate the performance of the proposed DPC strategy. Finally, the conclusions are made in Section V.

II. 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 it is shown, in the stator stationary reference frame, the stator and rotor flux linkage vectors can be given as

$$\begin{aligned}\psi^s_{s\alpha\beta} &= L_s \boldsymbol{I}^s_{s\alpha\beta} + L_m \boldsymbol{I}^s_{r\alpha\beta}\\ \psi^s_{r\alpha\beta} &= L_m \boldsymbol{I}^s_{s\alpha\beta} + L_r \boldsymbol{I}^s_{r\alpha\beta}.\end{aligned} \tag{1}$$