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ORIGINAL ARTICLE

Sliding mode direct power control of RSC for DFIGs driven by variable speed wind turbines

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Abstract In spite of its several advantages, a classic direct power control (DPC) of doubly fed induction generators (DFIGs) driven by variable speed wind turbines has some drawbacks. In this paper, a simple and robust total sliding mode controller (TSMC) is designed to improve the classical DPC performance without complicating the overall scheme. The TSMC is designed to regulate the DFIG stator active and reactive powers. Two integral switching functions are selected for describing the switching surfaces of the active and reactive powers. Reaching phase stability problem of the classical sliding mode controller is avoided in the proposed TSMC. Neither current control loops nor accurate values of machine parameters are required in the proposed scheme. In addition, axes transformation of the stator voltage and current are eliminated. The grid side converter is controlled based on DPC principle to regulate both DC-link voltage and total reactive power. The feasibility of the proposed DPC scheme is validated through simulation studies on a 1.5 MW wind power generation system. The performance of the proposed and conventional DPC schemes is compared under different operating conditions.

1. Introduction

Doubly Fed induction generators have been widely used for large scale wind generation systems. Control and operation of DFIGs have been the subject of intense research during last few years. Wind farms based on the DFIGs with converters rated at 25–30% of the generator rating are becoming increasingly popular. Compared with wind turbines using fixed speed, the DFIGs based wind turbines offer not only advantages of variable speed operation and four-quadrant active and reactive power capabilities, but also lower converter cost and power losses [1]. Various control algorithms have been proposed for studying the behavior of DFIG based wind-turbine system during normal operation. Most existing models widely used a conventional vector control based on a stator flux orientation (SFO) [2] or a stator voltage orientation (SVO) [3]. A decoupled control of the instantaneous stator active and reactive powers has been achieved by regulating the decomposed rotor currents using proportional–integral (PI) controllers. However, PI-controllers performance is highly dependence on tuning of parameters and accurate tracking of angular information of stator flux/voltage. Moreover, the vector or field oriented control schemes need accurate values of machine parameters and rotor speed.

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Alternative approaches to field oriented control such as a direct self control (DSC) [4] and a direct torque control (DTC) [5] have been proposed for cage rotor induction machines. In these strategies, two hysteresis controllers, namely torque and flux controllers are selected to determine the inverter instantaneous switching state [6]. Similar to the DTC, a direct power control (DPC) of DFIG based wind turbine systems has proposed recently [6–15]. The instantaneous switching state of the rotor side converter is determined based on the stator active and reactive power errors. Thus, unlike existing DTC techniques, measurements are carried out at one terminal of the machine whereas the switching action is carried out at another terminal [6]. Since the rotor supply frequency may be very low, the rotor flux estimation can be significantly affected by the machine parameter variations. In [7], DPC strategy based on an estimated stator flux has been proposed. As the stator voltage is relatively harmonics free, the accuracy of the stator flux estimation can be guaranteed. However, an unfixed switching frequency is considered the main drawback of classical DPC. In [8], a modified DPC strategy was proposed based on SFO control with a constant switching frequency, where a reference rotor voltage was calculated based on the estimated stator flux, active and reactive powers and their errors. In [9], an active and reactive power proportional–integral controllers and space vector modulation technique (SVM) were combined to replace the conventional hysteresis controllers. For operation under unbalanced and harmonically grid voltage, different DPC algorithms were designed to overcome the bad effects under these conditions and improve the overall performance [10–15]. In [10], two resonant controllers were designed to regulate the active and reactive power without sequential decomposition involved. In [11], the electromagnetic torque oscillations at double supply frequency under unbalanced stator supply were eliminated. In [15], an improved DPC strategy of a wind turbine driven DFIGs connected to distorted grid voltage conditions was presented.

For robust and high performance DPC, a sliding mode controller (SMC) was studied in the literature [16–23]. It is an effective, high frequency switching control strategy for nonlinear systems with uncertainties. It can offer many good properties such as good performance against unmodeled dynamics, insensitivity to parameters variation, external disturbance rejection and fast dynamic response. A SMC was designed to control the RSC under normal abnormal grid voltage conditions [16–23]. In [16], an integral sliding mode controller was designed to regulate the electromagnetic torque and stator reactive power. SMC and fuzzy logic controller are combined to control doubly fed induction machines [17]. A discrete SMC is designed to regulate the real and reactive stator power of DFIG [18]. Sliding mode controller is proposed to regulate the stator active and reactive power under unbalanced and harmonically distorted grid voltage [20–23]. In [22], two sliding mode controllers are designed to determine directly the switching state of RSC and GSC under harmonically and unbalanced grid voltage conditions. However, the switching frequency of the two converters is variable and high chattering appears in the electromagnetic torque, DC-link voltage, stator and total powers waveforms. However, the reaching phase stability and chattering problem were not taken into account in the previous research.

In this paper, a coordinated direct power control of the RSC and grid side converter (GSC) is presented. The GSC is controlled based on DPC principle to regulate the DC-link voltage, total active and reactive power. Meanwhile, the RSC is controlled to regulate the stator active and reactive powers. To obtain high performance DPC, a simple and robust sliding mode controller is designed to control the RSC and regulate the stator active and reactive power. Two integral functions are selected to describe the switching surfaces for stator active and reactive power control. The total sliding mode controller is designed to avoid the reaching phase stability problem. The proposed scheme preserves the advantages of the classical DPC such as simplicity, less parameters dependence and fast response. In addition, axes transformation of the stator voltage or current is not required. The stability of the total sliding mode controller is proven using Lyapunov stability theorem. Finally, the proposed and conventional DPC [11] schemes performance is verified by the simulation study on 1.5 MW DFIG system under variation of wind speed, machine parameters and unbalanced grid voltage.

2. Maximum Power Point Tracking (MPPT) strategy

The output power of a wind turbine is given [24]:

$$P_m = c_P(\lambda,\beta)\frac{\rho A}{2}v_t^3 \tag{1}$$

where P_m is a mechanical output power of the turbine (W), c_P is a power coefficient, ρ is an air density (kg/m^3), A is a turbine swept area (m^2), v_t is a wind speed (m/s), λ is a tip speed ratio of the rotor blade tip speed to wind speed, and β is a blade pitch angle (°). A generic equation is used to model c_p (λ, β), based on the modeling turbine characteristics is:

$$c_P(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \tag{2}$$

The coefficients c_1 to c_6 of 1.5 MW wind turbine are [24]: $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$ and $c_6 = 0.0068$. The maximum value of c_p ($c_{p\max} = 0.48$) is achieved for $\beta = 0°$ and for $\lambda = 8.1$. This particular value of λ is defined as the nominal value ($\lambda_{\_\text{nom}}$). The mechanical power P_m as a function of generator speed, for different wind speeds and blade pitch angle $\beta = 0°$, is illustrated in Fig. 1.

3. Dynamic model of DFIG

Fig. 2 shows the generalized equivalent circuit of a DFIG in a synchronous reference frame (d-q) rotating at an angular speed of ω_e [1]. The stator and rotor voltages are given, respectively, as follows:

$$\begin{aligned} V_s &= R_s I_s + \frac{d}{dt}\lambda_s + j\omega_e\lambda_s \\ V_r &= R_r I_r + \frac{d}{dt}\lambda_r + j\omega_s\lambda_r \end{aligned} \tag{3}$$

where ω_s is the slip angular speed ($\omega_s = \omega_e - \omega_r$), ω_r is the rotor angular speed, R_s and R_r are the stator and rotor resistances, respectively, I_s and I_r are the stator and rotor currents, respectively. The stator and rotor flux can be expressed as follows: