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Sliding mode control of DFIG powers in the case of unknown flux and rotor currents with reduced switching frequency

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ABSTRACT

This paper aims to implement a stator power control for a doubly fed induction generator (DFIG) with unknown flux and rotor currents. This goal is achieved based on a high-gain sliding mode control (HG-SMC) and by exploiting the fact that the flux remains near the nominal value. A new implementation scheme has been developed to achieve low switching frequency compared to the conventional method. The advantages of the new scheme over the old one are presented. Some interesting features of the new scheme are: (1) elimination of rotor's current sensor, which leads to lower cost and failure rate in the drive system; (2) simpler implementation because it does not require any modern method for the flux estimation; (3) longer lifetime of the rotor side-converter. The proposed control scheme is verified by simulations results and experiments on a 7.5 kW DFIG power prototype.

1. Introduction

Doubly fed induction generators (DFIGs) are mostly used in high-power wind energy conversion systems (WECSs) due to their salient features [1,2] and they can be employed in other power generation systems like hydropower [3]. Several ways of driving a grid connected DFIG-based WECS have been proposed in literature which includes controlling the electromagnetic torque [4–10], controlling the rotating speed [11–13], and controlling the stator active power [2,14–20]. The main goal of all these three control methods is to track the maximum attainable power of the wind turbine as long as the wind speed is below a certain upper limit. These goals are also valid for other grid connected DFIG-based renewable energy conversion systems.

The main drawback of the torque control is that the electromagnetic torque is estimated and is not measured. Moreover, the estimated value changes with the variation of DFIG inductances. On the other side, the speed control needs the knowledge of some quantities, such as system inertia, electromagnetic torque, and aerodynamic torque, which are difficult to estimate. If these quantities are not estimated correctly, mechanical oscillations may be formed and affect the wind turbine. Stator active power control is the most studied approach in the literature [2,14–20] since it has interesting features compared to two other methods. In this approach, the active power is measured easily. Moreover, it does not dependent on DFIG parameters or on mechanical quantities, such as total inertia and aerodynamic torque.

One common weakness of the above mentioned approaches [1–20] is their sensitivity to various errors [21] resulting from the employment of classical flux estimation or simple integral method. These errors include DFIG resistance variations, measurement noises, digital approximation errors, DC offset, and initial conditions errors. In addition, these methods require rotor current sensors, which increase the system cost and may cause system malfunction under sensor faults.

The sensitivity of classical flux estimation, i.e., voltage model flux, can be reduced by employing a low-pass (LP) filter instead of a pure integrator [22,23]. This modification reduces the performance of the drive system due to insertion of phase and magnitude errors in the control loops. Refs. [24,25] have proposed two methods to diminish the effect of this weakness. These methods, however, are not straightforward and increase the implementation cost. Another solution is based on the current model flux [26], which depends heavily on the accuracy of rotor time constant. This technique is difficult to implement, needs a large set of machine parameters and requires rotor current sensors.

The authors of [21] have proposed a method for stator power control, without using flux or rotor current measurements. In this

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approach, however, the control law requires a high switching frequency for the implementation. This will cause high switching losses in the rotor-side converter and will reduce the converter efficiency and its lifetime. Moreover, the robustness and feasibility of this control method has not been verified practically.

This paper proposes the sliding mode control (SMC) of stator active and reactive powers for unknown rotor currents and flux with new implementation scheme. The target of proposed approach is achieving a reduced switching frequency compared to the classical method, even in the case of applying a high sliding mode gain control. The rest of this paper is categorized as follows. The DFIG model is presented in Section 2. Sections 3 and 4 present the SMC for unknown rotor currents and flux, and the proposed scheme, respectively. In Section 5, simulation results are presented to verify the viability of new method. Section 6 presents the experimental results and conclusions are given in Section 7.

2. Model of doubly fed induction generator

In the rotational reference frame (or (d,q) reference frame) and based on the usual assumptions [27], the DFIG model can be given by the following equations

$$\begin{cases} v_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_s \varphi_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_s \varphi_{ds} \\ v_{dr} = R_r i_{dr} + \frac{d\varphi_{dr}}{dt} - (\omega_s - \omega)\varphi_{qr} \\ v_{qr} = R_r i_{qr} + \frac{d\varphi_{qr}}{dt} + (\omega_s - \omega)\varphi_{dr} \end{cases} \tag{1}$$

$$\begin{cases} \varphi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \varphi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \varphi_{dr} = L_r i_{dr} + L_m i_{ds} \\ \varphi_{qr} = L_r i_{qr} + L_m i_{qs} \end{cases} \tag{2}$$

where

$(i_{ds,r}, i_{qs,r})$ are the stator-rotor current components;
$(\varphi_{ds,r}, \varphi_{qs,r})$ are the stator-rotor flux components;
$(v_{ds,r}, v_{qs,r})$ are the stator-rotor voltage components;
R_r, R_s are the rotor and stator resistances;
L_r, L_s, L_m are the rotor, stator, and mutual inductances; and
ω, ω_s are the rotor and stator angular frequencies, respectively.

3. High-gain SMC for control of stator's active and reactive powers

This section presents an SMC that allows the drive of DFIG by the active and reactive stator powers in the case of unknown rotor currents and flux.

According to (1) and (2), the dynamics of the stator current components can be obtained as follows (see Appendix A).

$$\begin{cases} \frac{di_{ds}}{dt} = -a_1 i_{ds} + \omega_s i_{qs} + a_2 \varphi_{ds} - a_3 \omega \varphi_{qs} - a_4 v_{dr} + a_3 v_{ds} \\ \frac{di_{qs}}{dt} = -\omega_s i_{ds} - a_1 i_{qs} + a_2 \varphi_{qs} + a_3 \omega \varphi_{ds} - a_4 v_{qr} + a_3 v_{qs} \end{cases} \tag{3}$$

where

$$a_1 = \left(\frac{1}{\sigma T_s} + \frac{1}{\sigma T_r}\right), \quad a_2 = \frac{1}{\sigma L_r T_s}, \quad a_3 = \frac{1}{\sigma L_r}, \quad a_4 = \frac{(1-\sigma)}{\sigma L_m};$$

and $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ is the dispersion coefficient.

If it is assumed that the q axis of the rotating reference frame coincides along the stator voltage vector, the direct component of the stator voltage will be zero. Then, the expression of stator active and reactive powers, i.e., P_s, Q_s can be given by (4)

$$P_s = v_{qs} i_{qs}, \quad Q_s = v_{qs} i_{ds} \tag{4}$$

From (3) and (4), the dynamics of active and reactive powers are obtained as

$$\begin{cases} \frac{dQ_s}{dt} = -a_1 i_{ds} v_{qs} + \omega_s i_{qs} v_{qs} + a_2 \varphi_{ds} v_{qs} + \\ \qquad - a_3 \omega \varphi_{qs} v_{qs} - a_4 v_{dr} v_{qs} \\ \frac{dP_s}{dt} = -\omega_s i_{ds} v_{qs} - a_1 i_{qs} v_{qs} + a_2 \varphi_{qs} v_{qs} + \\ \qquad + a_3 \omega \varphi_{ds} v_{qs} - a_4 v_{qr} v_{qs} + a_3 v_{qs}^2 \end{cases} \tag{5}$$

The sliding surfaces S_P, S_Q relative to stator active and reactive powers are defined as

$$\begin{cases} S_P = P_s - P_{ref} \\ S_Q = Q_s - Q_{ref} \end{cases} \tag{6}$$

where P_{ref} and Q_{ref} are reference values of P_s, Q_s, respectively.

In the sequel, it is assumed that P_{ref} and Q_{ref} and their derivatives $\dot{P}_{ref}$ and $\dot{Q}_{ref}$ are bounded and available.

According to (5) and (6), the dynamics of sliding surfaces S_P and S_Q are given by

$$\begin{cases} \frac{dS_Q}{dt} = Y_1 - a_4 v_{dr} v_{qs} \\ \frac{dS_P}{dt} = Y_2 - a_4 v_{qr} v_{qs} \end{cases} \tag{7}$$

With

$$\begin{cases} Y_1 = -a_1 i_{ds} v_{qs} + \omega_s i_{qs} v_{qs} + a_2 \varphi_{ds} v_{qs} - a_3 \omega \varphi_{qs} v_{qs} - \dot{Q}_{ref} \\ Y_2 = -\omega_s i_{ds} v_{qs} - a_1 i_{qs} v_{qs} + a_2 \varphi_{qs} v_{qs} + a_3 \omega \varphi_{ds} v_{qs} + \\ \qquad + a_3 v_{qs}^2 - \dot{P}_{ref} \end{cases} \tag{8}$$

Now, the dynamics of sliding surfaces are chosen as

$$\begin{cases} \frac{dS_Q}{dt} = -K\ sign(S_Q) - GS_Q \\ \frac{dS_P}{dt} = -K\ sign(S_P) - GS_P \end{cases}; \quad K, G > 0 \tag{9}$$

where the gains K and G are positive values.

The terms $-GS_Q$ and $-GS_P$ are added in (9) to improve the convergence speed of active and reactive powers to their references P_{ref} and Q_{ref}, respectively.

According to (8) and (9), the (dq) components of rotor voltages (v_{dr}, v_{qr}) are calculated to satisfy the relation (9):

$$\begin{cases} v_{dr} = (K\ sign(S_Q) + GS_Q + Y_1)/(a_4 v_{qs}) \\ v_{qr} = (K\ sign(S_P) + GS_P + Y_2)/(a_4 v_{qs}) \end{cases}; \quad a_4, v_{qs} \neq 0 \tag{10}$$

When rotor voltage components take the form (10), the quantities $S_Q \frac{dS_Q}{dt}$, $S_P \frac{dS_P}{dt}$ would be negative. In this case, $S_Q \to 0$ and $S_P \to 0$. In other words, the SMC law or (10) ensures the regulation of P_s and Q_s to the reference values P_{ref} and Q_{ref}, respectively.

Unfortunately, the values of v_{dr}, v_{qr} in (10) cannot be calculated easily due to several reasons, including DFIG parameters variations, modeling errors, and stator flux estimation difficulties. For this reason, the gain K in (10) must be chosen high to ensure the convergence.

To overcome the problems related to estimation methods and to reach the SMC robustness, the control law in (10) is modified as

$$\begin{cases} v_{dr} = (K\ sign(S_Q) + GS_Q + \overline{Y}_1)/(\overline{a}_4 v_{qs}) \\ v_{qr} = (K\ sign(S_P) + GS_P + \overline{Y}_2)/(\overline{a}_4 v_{qs}) \end{cases} \tag{11}$$

where

$$\begin{cases} \overline{Y}_1 = -\overline{a}_1 i_{ds} v_{qs} + \omega_s i_{qs} v_{qs} + \overline{a}_2 \overline{\varphi}_{ds} v_{qs} + \\ \qquad - \overline{a}_3 \omega \overline{\varphi}_{qs} v_{qs} - \dot{Q}_{ref} \\ \overline{Y}_2 = -\omega_s i_{ds} v_{qs} - \overline{a}_1 i_{qs} v_{qs} + \overline{a}_2 \overline{\varphi}_{qs} v_{qs} + \overline{a}_3 \omega \overline{\varphi}_{ds} v_{qs} + \\ \qquad + \overline{a}_3 v_{qs}^2 - \dot{P}_{ref} \end{cases} \tag{12}$$