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A novel adaptive control scheme for dynamic performance improvement of DFIG-Based wind turbines

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ABSTRACT

A novel adaptive current controller for DFIG-based wind turbines is introduced in this paper. The attractiveness of the proposed strategy results from its ability to actively estimate and actively compensate for the plant dynamics and external disturbances in real time. Thus, the control strategy can successfully drive the rotor current to track the reference value, ensuring that the performance degradation caused by grid disturbances, cross-coupling terms and parameter uncertainties can be successfully suppressed. Besides, the two-parameter tuning feature makes the control strategy practical and easy to implement in commercial wind turbines. To quantify the controller performances, the transfer function description of the controller is derived. General disturbance rejection, robustness against parameter uncertainties, bandwidth and stability are also addressed. Simulation results, together with the time-domain responses, proved the stability and the strong robustness of the control system against parameter uncertainties and grid disturbances. Significant tracking and disturbance rejection performances are achieved.

1. Introduction

Wind energy today is becoming a global business [1–6]. This leads to increasing wind power penetration. Accordingly, wind turbine modeling and system control become research focus, resulting in rapid development of wind turbine technology [7–16]. Recently, the concern about the stability and reliability of power systems results in continuous reformulation of the grid connection requirements for wind turbines. This demands high-performance of connected plants with respect to power control ability [17–20], as well as the capability of remaining connected and providing necessary support to the grid during grid faults [21], leading industry to explore new high-performance control strategies.

Wind turbines based on DFIGs (doubly-fed induction generators) with converters rated at around 30% of the generator rating dominate the world market. Compared with the wind turbines using fixed speed induction generators or fully-fed synchronous generators with full-sized converters, DFIG-based wind turbines offer not only the advantages of variable-speed operation and four-quadrant active and reactive power capabilities, but also lower converter cost and power losses [22]. Thus, design and control of DFIG-based wind turbines gain attentive focus.

Dealing with control of DFIG-based wind turbines, a common way is to control the rotor current with stator flux orientation [23], or with stator voltage orientation [24], or with air-gap-flux orientation [25]. However, this technique is designed assuming the stator voltage to be ideal and the derivative of stator flux neglectable [26]. During grid disturbances which mean stator flux is not constant, conventional control methods usually cannot react directly and fast to reject these disturbances, although these control methods can finally suppress them through feedback regulation in a relatively slow way. This results in a degradation of system performance during grid disturbances. Moreover, the effect of the controller is dependent on accuracy information on system parameters, especially the rotor time constant. However, DFIG machine parameters are affected by temperature, saturation, and skin effects, which can deteriorate the controller performance when designed with nominal parameter values. Besides, DFIG-based wind turbines operate in a wide operating range during its whole life. Therefore, another concern regarding DFIG rotor current control is the robustness against variations in plant parameters. If the feed-forward terms do not entirely cancel the extra dynamics, the closed-loop poles are slower than intended and the damping factor deteriorates. The same effect was reported in [27], pointing out that variations of the system parameters compromise both the decoupling and the desired pole-zero cancellation.

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Recently, with the rapid progress in power electronics, digital signal processors and modern control theories, nonlinear control methods gain attentive focus, and various algorithms have been proposed [28]. These algorithms have improved the control performance of DFIG systems from different aspects.

In this paper, an adaptive disturbance rejection controller (ADRC) is developed for the rotor current control of DFIG-based wind turbines in which the grid disturbances, parameter variations, coupling terms and flux compensation are considered and compensated in real time. ADRC is a novel and unique design concept, proposed by Han [29] and further developed by Gao [30]. This method has achieved much success in some industrial control problems, e.g., electro-mechanical systems [31], machining processes [32], flexible-joint systems [33], robotic systems [34], manipulator systems [35], motor control systems [36,37] and power converters [38].

The principle of proposed control strategy for the DFIG-based wind turbines uses an extended state observer (ESO) to build a solid base for better performance and disturbances compensation via the provision of output and the real action component of internal dynamics and external disturbances. With accurate estimation of DFIG internal dynamics and external disturbances, the control strategy can successfully drive the rotor current to track the reference value, ensuring that the performance degradation caused by the grid disturbances and parameter uncertainties can be suppressed. More importantly, the two-parameter tuning feature makes the control strategy practical and easy to implement in commercial wind turbines.

This paper is organized as follows. The dynamics of DFIG-based wind turbines is explained in Section 2. The control problems are described in Section 3. The proposed strategy design and its stability analysis are presented in Section 4 and Section 5, respectively. Performance tests, discussion, and results are shown in Section 6. Finally, concluding remarks are made in Section 7.

2. DFIG-based wind turbine system dynamics and modeling

A DFIG-based wind turbine consists of a pitch controlled wind turbine and a DFIG. The DFIG is a wound-rotor induction machine with the stator windings directly connected to the three-phase grid and with the rotor windings connected to a partial scale frequency converter [1]. Direct control of the rotor currents allows for variable-speed operation and reactive power control. Consequently, DFIG-based wind turbines can operate at a higher efficiency over a wide range of wind speeds and help provide voltage support for the grid.

2.1. Generator model

Dealing with the modeling of DFIG is not a trivial task and different levels of detail may be achieved doing some assumptions. In this work, it is assumed the stator and rotor windings to be placed sinusoidally and symmetrical, the magnetical saturation effects and the capacitance of all the windings neglectable. Using the motor convention, the relation between the voltages on the machine windings and the currents and its first derivative may be written in terms of a synchronous reference dq frame representation as

$$u_{sd} = R_s i_{sd} + L_s \frac{\mathrm{d}i_{sd}}{\mathrm{d}t} - \omega_s L_s i_{sq} + L_m \frac{\mathrm{d}i_{rd}}{\mathrm{d}t} - \omega_s L_m i_{rq} \quad (1)$$

$$u_{sq} = R_s i_{sq} + L_s \cdot \frac{\mathrm{d}i_{sq}}{\mathrm{d}t} + \omega_s L_s i_{sd} + L_m \frac{\mathrm{d}i_{rq}}{\mathrm{d}t} + \omega_s L_m i_{rd} \quad (2)$$

$$u_{rd} = L_m \frac{\mathrm{d}i_{sd}}{\mathrm{d}t} - (\omega_s - \omega_r) L_m i_{sq} + R_r i_{rd} + L_r \frac{\mathrm{d}i_{rd}}{\mathrm{d}t} - (\omega_s - \omega_r) L_r i_{rq} \quad (3)$$

$$u_{rq} = L_m \frac{\mathrm{d}i_{sq}}{\mathrm{d}t} + (\omega_s - \omega_r) L_m i_{sd} + R_r i_{rq} + L_r \frac{\mathrm{d}i_{rq}}{\mathrm{d}t} + (\omega_s - \omega_r) L_r i_{rd} \quad (4)$$

where L_s and L_r are the stator and rotor windings self-inductance, L_m is the mutual inductance between the stator and the rotor, ω_s is the synchronous angular frequency and ω_r is the generator angular frequency. This model is able to represent rotor and stator transients correctly.

The electromagnetic torque can be written in terms of stator flux linkages and currents as

$$T_e = 1.5p\left(\psi_{sd} i_{sq} - \psi_{sq} i_{sd}\right) \quad (5)$$

where p represents the number of pole pairs, and ψ_{sd}, ψ_{sq} denote the d- and q-axis flux component, respectively.

The stator reactive power expression, which is also the control objective of the rotor-side converter control as well as the electromagnetic torque, has the following form

$$Q_s = 1.5\left(u_{sq} i_{sd} - u_{sd} i_{sq}\right) \quad (6)$$

The equivalent circuit of DFIG is shown in Fig. 1.

2.2. Wind turbine and mechanical drive train model

The turbine is made up of the three-bladed rotor and the hub. Through the turbine, wind energy is transformed into mechanical energy that turns the main shaft of the generator. The aerodynamic torque T_m captured by the wind turbine is given by

$$T_m = \frac{\pi \rho r^2 C_p v^3}{2\omega_t} \quad (7)$$

where ρ is the air density, r the radius of the turbine disk, v the wind speed, ω_t the turbine angular frequency and C_p represents the wind turbine power coefficient.

The power coefficient C_p is a function of the tip speed ratio λ as well as the blade pitch angle β in a DFIG-based wind turbine. The accurate computation of the power coefficient requires the use of Blade-Element Theory and the knowledge of the blade geometry. These complex issues are normally empirically considered. In this paper, the power coefficient is given by

$$C_p(\lambda, \beta) = 0.22\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) e^{\frac{-12.5}{\lambda_i}} \quad (8)$$

where

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (9)$$

The tip speed ratio λ is defined as

$$\lambda = \frac{\omega_m r}{V} \quad (10)$$

The mechanical drive train of a DFIG-based wind turbine comprises the turbine shaft, the gearbox, and the generator's rotor shaft. A common way to model the mechanical drive train is to treat it as a series of equivalent discrete masses connected together by springs and dampers with a multiplication ratio between them. When applications are limited to the impact of wind fluctuations, it is usually sufficient to consider the mechanical drive train as a single-mass shaft model because shaft oscillations of the wind turbines are not reflected to the grid due to the fast active power