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Nonlinear control with wind estimation of a DFIG variable speed wind turbine for power capture optimization

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ABSTRACT

A cascaded nonlinear controller is designed for a variable speed wind turbine equipped with a Doubly Fed Induction Generator (DFIG). The main objective of the controller is wind energy capture optimization while avoiding strong transients in the turbine components and specially in the drive train. The inner loop controller ensures an efficient tracking of both generator torque and stator flux, while the outer loop controller achieves a close tracking of the optimal blade rotor speed to optimize wind energy capture. It is combined to a wind speed estimator that provides an estimation of the wind speed and the aerodynamic torque involved in the controller. The global controller is firstly tested with a simplified mathematical model of the aeroturbine and DFIG for a high-turbulence wind speed profile. Secondly, the aeroturbine controller is validated upon a flexible wind turbine simulator. These new control strategies are compared to other existing controllers based on tests upon an aeroelastic wind turbine simulator. The obtained results show better performance in comparison with the existing controllers.
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1. Introduction

Wind energy conversion systems have quickly evolved over the last decades, therefore, an efficient and reliable exploitation tools are necessary to make these installations more profitable [1]. It was shown that the control strategies have a major effect on the wind turbine and the electric grid loads [2], and whatever the kind of the wind turbine, the control strategy remains a key factor [3]. Modern high-power wind turbines (WT) are equipped with adjustable speed generators [4]. The doubly fed induction generator (DFIG) with a power converter is a common and efficient configuration to transfer the mechanical energy from the variable speed rotor to a constant frequency electrical grid [5]. Many contributions have been devoted to the control of the aeroturbine mechanical as well as the electrical components. The global control objective mainly consists in optimizing the extracted aerodynamic power in partial load area.

The contribution of this paper consists on proposing a new control structures even for the DFIG and the mechanical part (aeroturbine) that overcomes some of the drawbacks of existing control methods. The global controller is organized in two cascaded controllers. The first one concerns the aeroturbine, while the second one is devoted to the DFIG. These controllers are designed using the dynamical features of the wind speed, the aeroturbine and the DFIG together with their nonlinear characteristics.

Many approaches have been proposed for DFIG torque and flux control [6,7]. They are generally based on simplifying assumptions that allow the use of a vector control techniques similar to those employed with an induction machine control [8]. In order to achieve high-performance control during the transient period, a new DFIG controller is proposed. It consists on using a field oriented technic without any simplifications in the DFIG model.

For the aeroturbine mechanical part control, the control design is generally based on a local linearized model of the WT around its operating points [9]. Some nonlinear controllers were proposed assuming that the wind turbine operates in steady state conditions [10,11]. The dynamical aspect of the wind and the turbine is then not taken into consideration. The second contribution of this work then consists then on proposing an aeroturbine controller that is based directly on the nonlinearity and dynamics of the mathematical model without any need of wind speed measurement. The controller is also able to reject the effect of an additive disturbance on the control input.

The linearization by feedback is well known in the theory of nonlinear control systems, but in renewable energy domain, the classical controllers are mainly implemented only. In our previous works, we have proposed the use of the linearization by feedback based approach and also the use of LQG controller described in [12], with no consideration of DFIG.

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This paper is organized as follows: the aeroturbine and DFIG mathematical models are presented in Section 2. Section 3 starts with a description of the global control structure including the aeroturbine control and the DFIG control loops. The control objectives are then detailed. After a short review of some existing controllers, the proposed DFIG controlled is exposed in Section 4. The designed nonlinear static state feedback linearization with asymptotic rotor speed reference tracking and PI action are described in Section 5 in order to reach the required specifications for aeroturbine control. In Section 6, a brief description of the used aeroturbine simulator and the experimental wind turbine characteristics are given. After what, the validation results show quite good performance of the proposed approach upon the whole wind energy system.

2. Wind turbine modelling

2.1. Aeroturbine modelling

The aerodynamic torque expression is given by

$$T_a = \frac{1}{2}\rho\pi R^3 C_q(\lambda,\beta)v^2 \tag{1}$$

The torque coefficient C_q depends on the blade pitch angle β and the tip-speed ratio λ which is defined as follows:

$$\lambda = \frac{\omega_t R}{v} \tag{2}$$

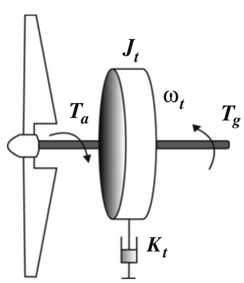

Fig. 1. One mass wind turbine model dynamics.

where ω_t is the rotor speed, R is the rotor radius and ρ is the air density.

If a perfectly rigid low-speed shaft is assumed, a single mass model of the turbine may then be considered [13]

$$J_t\dot{\omega}_t = T_a - K_t\omega_t - T_g \tag{3}$$

where

$$J_t = J_r + n_g^2 J_g$$
$$K_t = K_r + n_g^2 K_g$$
$$T_g = n_g T_{em}$$

The one mass wind turbine model is shown in Fig. 1.

2.2. DFIG modelling

A scheme of a DFIG-based wind turbine is shown in Fig. 2. This kind of wound-rotor machine can be fed from both stator and rotor side [14]. The most significant feature of the DFIG is that the stator is directly connected to the grid while the rotor winding is interfaced through a back-to-back variable frequency, voltage source converters [4]. By decoupling the power system electrical frequency and the rotor mechanical frequency, the converter system allows a variable speed operation of the wind turbine. As commonly done in the literature [15], the DFIG is described in the *Park* *d–q* frame by the well known following set of equations:

$$v_{sd} = R_s \cdot i_{sd} + \frac{d\Phi_{sd}}{dt} - \omega_s \cdot \Phi_{sq} \tag{4}$$
$$v_{sq} = R_s \cdot i_{sq} + \frac{d\Phi_{sq}}{dt} + \omega_s \cdot \Phi_{sd} \tag{5}$$
$$v_{rd} = R_r \cdot i_{rd} + \frac{d\Phi_{rd}}{dt} - \omega_r \cdot \Phi_{rq} \tag{6}$$
$$v_{rq} = R_r \cdot i_{rq} + \frac{d\Phi_{rq}}{dt} + \omega_r \cdot \Phi_{rd} \tag{7}$$

As the d and q axis are magnetically decoupled, the flux are given by

$$\Phi_{sd} = L_s \cdot i_{sd} + M \cdot i_{rd} \tag{8}$$
$$\Phi_{sq} = L_s \cdot i_{sq} + M \cdot i_{rq} \tag{9}$$
$$\Phi_{rd} = L_r \cdot i_{rd} + M \cdot i_{sd} \tag{10}$$
$$\Phi_{rq} = L_r \cdot i_{rq} + M \cdot i_{sq} \tag{11}$$

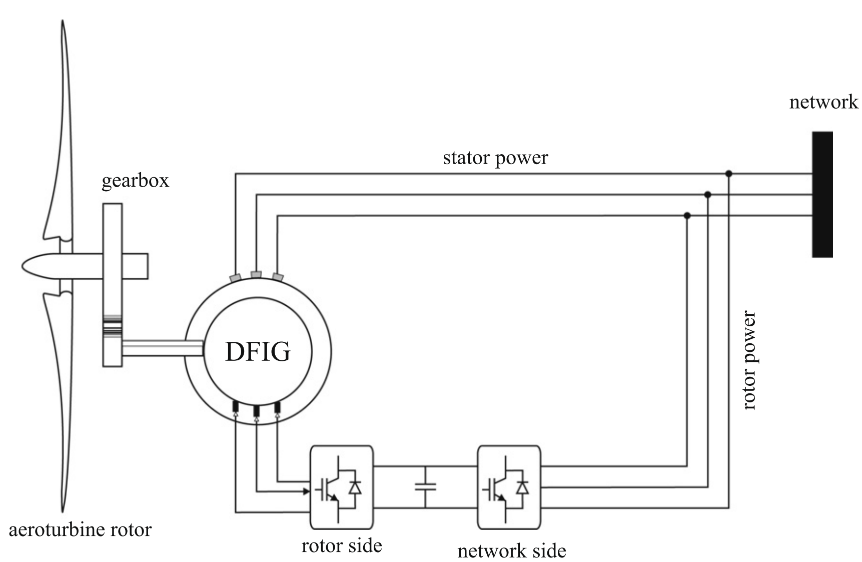

Fig. 2. Configuration scheme of a DFIG-based wind turbine.

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