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Power capture optimization of variable-speed wind turbines using an output feedback controller

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ABSTRACT

One of the major factors that can increase the efficiency of wind turbines is through control of the rotor speed to track the optimal value. A high performance controller can significantly increase the amount of energy that can be captured from wind. The main problem associated with controller design is the presence of uncertainties in the dynamic model of the system, which can be associated with unknown constant parameters and/or unmodeled dynamics such as external disturbances. several adaptive and robust control approaches have been developed to account for these uncertainties. In this paper, a robust controller is presented that compensates for both types of uncertainties; the full mechanical and electrical dynamics of the turbine are considered. These dynamics require acceleration of the rotor to provide feedback information which is not available in sufficiently accurate form during practice. Therefore, in this approach, an observer estimates this information using the speed of the rotor as the output, with the estimation error considered during the stability analysis. This presents one of the main advantages of the approach; the simulation results illustrate the effectiveness of the controller.

1. Introduction

There has been growing interest in wind energy in the past two decades because it is a potential source of electricity associated with minimal environmental impact. Commensurate with advancements in this industry, wind turbines are now available, at low cost and over large scales, which can produce considerable amounts of power [19]. Currently, approximately 6% of total electrical consumption in the US and Europe is provided by wind, although the wind industry intends to produce more than 20% of the electrical energy in these countries within the next two decades [33]. To achieve this goal, a number of improvements are required in the areas of aerodynamic, electronic and control design.

Among the different types of wind turbines, variable-speed wind turbines (VSWTs) have received a considerable attention within the industry due to their advantages over fixed-speed wind turbines. VSWTs can track changes in wind speed by adapting the shaft speed. It is known that, at every wind speed, there is an operating point for the turbine that provides the highest efficiency. This property confers a constant optimal value for the tip-speed ratio of the wind turbine. Therefore, using VSWTs it is possible to maintain this optimal value, and hence achieve maximum turbine efficiency by controlling the speed of rotation at different wind speeds. Another advantage of VSWTs is that the effects of wind power fluctuations can be attenuated, since the blades absorb wind torque peaks during changes in rotation speed [9,18].

Studies on the improved performance and reliability of VSWTs show that their behavior is significantly affected by the control strategy used [11]. The major challenge in this regard concerns tracking control of the rotor speed. However, some research has also focused on controlling the blade pitch angle [7,27]. Generally, control of the blade pitch is undertaken during high-wind periods and is fixed to a constant optimal value [9,27].

Linear controllers have been used extensively for rotor speed tracking. These approaches include classic PI controllers, optimal LQ and LQG controllers [13,25,32] and linear robust controllers [16]. However, since the wind turbine model is generally nonlinear, using a linear controller comes at the price of poor system performance and reduced reliability [22]. Therefore, several studies have been concerned with designing a nonlinear controller. Ref. [7] proposes a combination of a linear and a nonlinear controller. In Ref. [12] a nonlinear controller using the Lyapunov method was designed. A feedback linearization method was exploited in Ref. [17], while in [26], a nonlinear optimal controller was developed. Intelligent approaches, such as those using fuzzy methods and

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artificial neural networks, are described in [10,30,36]. Finally, a variable structure controller has also been considered, in [35,34].

Although a nonlinear controller would provide markedly superior performance compared to linear controllers, in practice obtaining an exact nonlinear model of the wind turbine, for use in controller design, is almost impossible. Generally, a nonlinear dynamic model includes certain parameters that may vary over time or cannot be identified exactly. Furthermore, the model may include certain unmodeled dynamics, which may be related to external disturbances or neglected terms in the course of modeling. In Ref. [31], an adaptive controller was designed to compensate for the parametric uncertainty of the system. However, the existence of external disturbances was overlooked. To deal with unstructured uncertainty [3], proposed a sliding mode controller. An extended version of this work is presented in Ref. [4], in which a second-order sliding mode controller is designed to address the chattering phenomenon and provide a smooth input for the turbine. However, this approach uses the parameters of the dynamic model as the known data at the design stage. A nonlinear adaptive control approach is also utilized in Refs. [24,23], where the dynamic of the electrical part is not considered during controller design. It is mentioned in Ref. [28] that performance can be improved when the electrical component is also taken into account at the design stage. However, the controller makes use of the acceleration of the rotor, for which highly accurate data is not available.

This paper presents an output feedback rotor speed tracking controller allowing VSWTs to capture maximum wind energy. Unlike several other published methods, in which the electrical dynamic is not considered, or an inner-loop controller is used without taking into account its interaction with the mechanical dynamic, the approach presented herein considers the full dynamic of the turbine and also improves the performance and reliability of the system by using a linear observer to estimate the acceleration of the rotor. The controller is robust with respect to both the parametric and unstructured uncertainties of the system. Stability analysis guarantees that system errors remain uniformly ultimately bounded (UUB). Simulation results are provided to validate the performance of the proposed approach.

The remainder of the paper is organized as follows. Sec. 2 presents a model of the wind turbine; the proposed robust output feedback controller is detailed in Sec. 3; the simulation results are presented in Sec. 4; and the conclusions are given in Sec. 5.

2. Wind turbine modeling

This section describes the mathematical model of the VSWT. The turbine is assumed to be fixed-pitch and the model draws from those described in the literature, for example in Refs. [31] and [8].

The wind turbine model represents the conversion of kinetic energy from wind into electrical power. Generally, a wind turbine consists of an aeroturbine, which converts wind energy into mechanical energy, a gearbox, which serves to increase speed and decrease torque, and a generator to convert mechanical energy into electrical energy. A typical two-mass model of such a system is shown in Fig. 1.

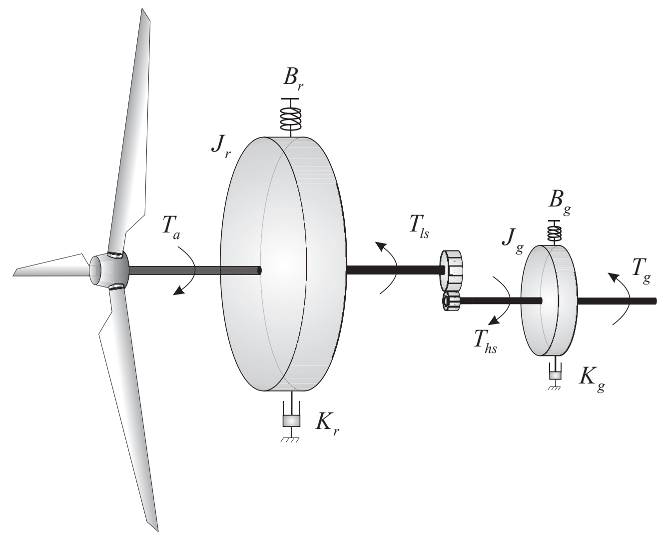

Fig. 1. Two mass model of the VSWT.

The aerodynamic power captured by the wind turbine is given by the following nonlinear relation:

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

where ρ is the air density, R is the rotor radius, v is wind speed, λ is the well-known tip-speed ratio and $C_p(\lambda,\beta)$ denotes the power coefficient of the wind turbine, which describes the capacity of the turbine to obtain energy from wind. This coefficient is a function of the blade pitch angle β and λ which is generally determined experimentally and provided by the manufacturer. This can also be approximated by a nonlinear function [5]. The following is an example model [29]:

$$C_p(\lambda,\beta) = 0.22\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{12.5}{\lambda_i}} \tag{2}$$

with

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}. \tag{3}$$

From a theoretical point of view, a maximum can be considered for C_p, which is referred to as Betz's limit [14]. This is derived according to the reason that, if all the energy coming from wind movement through a turbine was extracted as useful energy, the wind speed thereafter would drop to zero. Generally, the maximum value of C_p for modern turbines is less than 0.5. For the model described by (2) and (3), C_p characteristic for different values of λ and β is shown in Figs. 2 and 3, which indicate that, firstly, C_p is high for small values

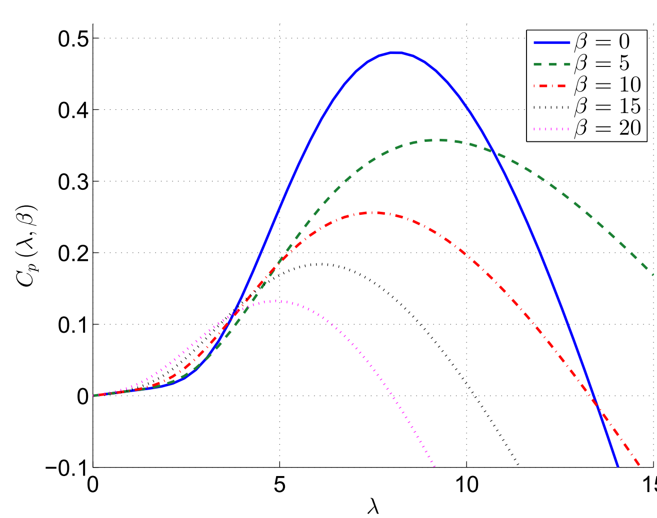

Fig. 2. Wind turbine power coefficient curve.