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Analysis and synthesis of sliding mode control for large scale variable speed wind turbine for power optimization

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ABSTRACT

The problem of designing a nonlinear feedback control scheme for variable speed wind turbines, without wind speed measurements, in below rated wind conditions was addressed. The objective is to operate the wind turbines in order to have maximum wind power extraction while also the mechanical loads are reduced. Two control strategies were proposed seeking a better performance. The first strategy uses a tracking controller that ensures the optimal angular velocity for the rotor. The second strategy uses a Maximum Power Point Tracking (MPPT) algorithm while a non-homogeneous quasi-continuous high-order sliding mode controller is applied to ensure the power tracking. Two algorithms were developed to solve the tracking control problem for the first strategy. The first one is a sliding mode output feedback torque controller combined with a wind speed estimator. The second algorithm is a quasi-continuous high-order sliding mode controller to ensure the speed tracking. The proposed controllers are compared with existing control strategies and their performance is validated using a FAST model based on the Controls Advanced Research Turbine (CART). The controllers show a good performance in terms of energy extraction and load reduction.

1. Introduction

1.1. Overview

As a result of population expansion and increased global integration, there has been a high growth in energy consumption. The high rates of electricity consumption supposes a risk for the depletion of natural resources, therefore the demand of renewable energy generation systems has increased [1]. Such demand is supported by social and environmental reasons: the debate on climate change, depletion of fossil resources and nuclear damage caused by the use of non-fossil fuels. All these factors have led to the global community, and national governments to set new policies in favor of renewable energy and drive future improvements in related technologies. Wind energy has been proved to be an important source of clean and renewable energy in order to produce electrical energy. Wind energy is currently one of the fastest growing renewable energy technologies in the world [2].

On the other hand, wind turbines present great challenges because they are complex nonlinear systems containing uncertain parameters, unmodeled dynamics, and unknown disturbances. Ongoing research is focused on increasing energy efficiency and reducing mechanical stress. One solution is to use advanced control strategies that enhance the performance of the turbine, which allows a better use of resources of the turbine, augmenting the lifetime of mechanical and electrical components, earning higher returns.

There are two primary types of horizontal-axis wind turbines: fixed speed and variable speed [3]. In this work, we choose the variable speed because although the fixed speed system is easy to build and operate, it does not have the ability that the variable speed system has in energy extraction, up to a 20–30% increase over fixed speed [3]. Wind turbine controller objectives depend on the operation area [4–7]. Variable speed wind turbine operation can be divided into three operating regions (Fig. 1):

- Region I: below cut-in wind speed.
- Region II: between cut-in wind speed and rated wind speed.
- Region III: between rated wind speed and cut out wind speed.

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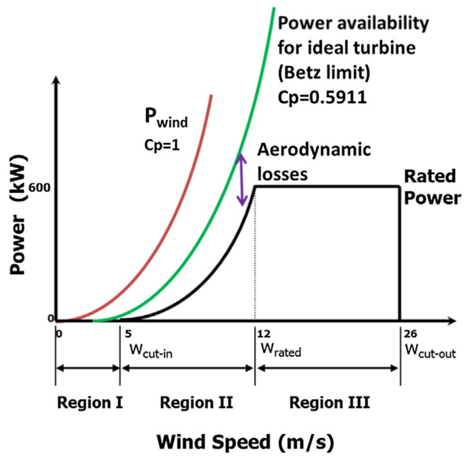

Fig. 1. Power curve for the CART.

In Region I, wind turbines do not move because power available in the wind is low compared to losses in the turbine system. Region II is an operational mode where it is desirable that the turbine captures as much power as possible from the wind, because wind energy extraction rates are low, and the structural loads are relatively small. Generator torque provides the control input to vary the rotor speed while the blade pitch is held constant. Region III occurs when the wind speed are high enough for the turbine, such that it must be limited the fraction of the wind power captured in order to guarantee that the safe electrical and mechanical loads limits are not exceeded.

The problem in Region II is considered in the present work. Classical controllers have been extensively used because linear control theory is a well-developed topic while nonlinear control theory is less developed and difficult to analyze and implement. PI and PID controllers are extensively used [8–10]. PID, gain scheduling, and LQR controllers are designed in Ref. [11]. LQR controllers reduce the pitch activity and power excursions compared to the PID controllers. In Ref. [12], a PI controller is used in conjunction with a gain-scheduled control to accommodate variations in the wind, while the gain-scheduled control allows better power regulation and load reduction. Although some of those classical methods have been successfully applied, they do not consider the nonlinearities on their controllers and do not take into account the dynamical aspect of the wind and the turbine [4,7,13,14]. To get a mathematical model that reflects accurately the wind dynamics and the mechanical behavior of the turbine, is a high difficult task because its complexity. That is the main reason to use a simplified model, mainly if it is pretended to perform a real implementation. One way of circumvent the modeling problem is through a control strategy that compensated the discrepancies between the real plant and the mathematical model.

1.2. Literature review

Recently, nonlinear controllers for wind turbines have been of interest to the scientific community; such as variable structure controllers. This approach is robust against parametric uncertainties, external disturbances, and unmodeled dynamics and presents the characteristic of finite-time reachability. A first-order sliding mode controller for power regulation is developed in Ref. [15], demonstrating the viability and effectiveness of the control strategy. Beltran et al. [16] extended the control to region II in conjunction with a Maximum Power Point Tracking algorithm, showing that the proposed control strategy is more efficient in terms of reduction of the drive-train mechanical stresses and output power fluctuations with respect to standard control. The main disadvantage of the proposed strategy by Beltran et al. [16] is that it uses a monotonic approximation of the signum function in order to avoid the chattering phenomena, losing robustness. An additional drawback of this strategy is that the rotor speed is not limited around its nominal value, allowing high mechanical loads over the drive-train. Four second-order sliding mode controllers are compared in Ref. [17] working in Region II concluding that the super-twisting algorithm is the best option for the studied case. Evangelista et al. [18] synthesized a super-twisting sliding mode control with variable gain, which is compared with a super-twisting algorithm with fixed gain showing a better performance in terms of chattering, mechanical loads, and power tracking. In Refs. [19], we developed a first-order sliding mode controller to solve the problem of power optimization assuming that all states can be measured. The strategy has a good capture of power, but presents chattering in generator torque. The chattering causes high torque variations increasing mechanical stress. The wind speed measurement is not an easy task, for that reason in Ref. [20] a wind speed estimator, using the wind turbine itself as a measuring device, was designed, the estimator is based on super-twisting observer and Newton–Raphson algorithm. A quasi-continuous second-order sliding mode controller was proposed in Ref. [21] to reduce the effects of chattering in the generated torque. The strategy provides a suitable compromise between conversion efficiency and mechanical loads, and there is no need for wind speed measured or estimated. The quasi-continuous second-order sliding mode controller was also used to solve the problem of power regulation and load reduction in Region III [22].

1.3. Contribution

The objective of this paper is to design controllers that in spite of nonlinear behavior, unmodeled dynamics, and unknown disturbances, maximize the capture of aerodynamic power and reduce the mechanics loads over the wind turbine. The contribution of this work consists in two proposing strategies using quasi-continuous sliding mode control [23,24]:

- The first approach uses a tracking algorithm with a wind speed estimator that ensures the optimal angular velocity for the rotor. The proposed controllers consist of two algorithms. The first one is a sliding mode state output feedback torque controller. The second proposed algorithm uses a quasi-continuous high-order sliding mode controller to ensure the speed tracking.
- The second strategy presents a non-homogeneous quasi-continuous high-order sliding mode controller [25] with MPPT algorithm to ensure the power tracking. This strategy only needs to measure the rotor speed and electric power.
- Effective improvements are brought regarding a previously proposed control strategies, such a better energy extraction and load alleviation without wind speed measurement.

The proposed controllers are validated using the high-order nonlinear aeroelastic model FAST (fatigue, aerodynamics, structures, and turbulence) of the CART [26–28].

1.4. Organization of the paper

The paper is organized as follows. In Section 2, the wind turbine model and problem formulation are presented. The design of the first strategy of control is covered in Section 3. In Section 4, the second strategy of control is given. Simulation results are provided and discussed in Section 5. Section 6 presents some conclusions.