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Observer Based Blade-Pitch Control of Wind Turbines operating above rated: a preliminary study

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Abstract: The paper focuses on variable-rotor-speed/variable-blade-pitch wind turbines operating in the region of high wind speeds, where blade pitch and generator torque controllers are aimed at limiting the turbine's energy capture to the rated power value. Preliminary results are presented about a coupled design technique of an observer based blade pitch control input and a generator torque controller, neither of which requiring the availability of wind speed measurements. Closed loop convergence of the overall control system can be proved. Preliminary results about the validation of the control solution using the $5-MW$ three-blade wind turbine using the National Renewable Energy Laboratory (NREL) wind turbine simulator FAST (Fatigue, Aerodynamics, Structures, and Turbulence) code.

Keywords: Wind Energy Conversion Systems, Pitch Control, High Wind Speeds, Nonlinear Observers, Generator Torque Control, NREL-FAST code.

1. INTRODUCTION

The extraction of wind power by a Wind Energy Conversion System (WECS) can be divided in different operating regions associated with wind speed, maximum allowable rotor speed and rated power. In general, variable-rotor-speed/variable-blade-pitch Wind Turbines (WT) have three main regions of operation with respect to wind speed [Johnson et al., 2006]: *i*) a turbine that is just starting up is considered to be operating in region 1; *ii*) Region 2 is an operational mode with the objective of maximizing wind energy capture; *iii*) in region 3 (high wind speeds) the turbine must limit the captured wind power so that safe electrical and mechanical loads are not exceeded. Generator torque control, keeping the blade pitch constant at an optimal value for peak energy extraction, is usually adopted in region 2 [Pao and Johnson, 2011, Corradini et al., 2013], while control of blade pitch is typically used to limit power for turbines operating in region 3 [Peng, 2010]. In particular, power regulation in region 3 using only pitch angle control exhibits some limitations, which are due to constraints on the amplitude and speed of response of the pitch servos [Bianchi et al., 2004]. Nowadays there is an increasing interest to reduce the effects of pitch actuators limitations by combining pitch angle and generator torque control to shed excess power and limit the turbine's energy capture to the rated power value in region 3 [Tang et al., 2011]. The presented control strategy specifically addresses the case of full load operation in the so-called Regime 3, therefore it should be intended as a solution of this part of the WECS control problem.

The most common blade pitch control strategy is a feedback policy based on the error between the rated power and the actual output power, but the strongly nonlinear relationship between pitch angle, wind speed and rotor speed [Peng, 2010] suggests that a coupled control design of pitch actuator input and electrical torque of the WT should be pursued to achieve effective results. Nonlinear optimal control approaches have been proposed [Saravanakumar and Jena, 2015], also adopting sliding mode control techniques. PI controllers have been also used for regulating the pitch angle citepJonkman:09, [Semrau et al., 2015]. Though effective and easy to implement, PI-based controllers rely on loosely defined theoretical rules, require a careful setting and often need corrective actions, usually based on heuristics as well. Also, anti-windup mechanisms have to be added to achieve satisfactory performances.

The previous discussion do indeed suggest that the availability of reliable wind speed measurements, or its estimates, is a key factor for improving closed-loop control performances, since wind speed is both the input for the control system and the parameterizing variable for the dynamics that determine the operating point of the WECS. The measured wind speed on the nacelle is unfortunately imprecise and not a good representative of the rotor effective wind speed [Soltani et al., 2013]. To solve this problem, a number of algorithms present dedicated estimators of the wind speed affecting the entire rotor, and a good comprehensive analysis of these techniques in given in [Soltani et al., 2013].

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In this paper, some preliminary results will be presented about a coupled blade pitch/generator torque controller (in region 3) avoiding the need of wind speed measurements. An observer-based blade pitch actuator input will be designed such that the minimum of the error between rated and actual power is achieved, without any feedback measurements of wind speed. Closed loop convergence of the overall control system is proved. The theoretical development is supported by simulations using the three-blade NREL $5-MW$ wind turbine using the FAST code simulator [NWTC, a].

2. WECS DYNAMICS

The system model here reported is inspired by the studies [Zaragoza et al., 2011, Bianchi et al., 2007] and references therein. As well known, wind energy is transformed first into mechanical energy through the WT blades and, ultimately, into electrical energy through the generator. The aerodynamic (mechanical) power that the wind turbine extracts from the wind is expressed by the following equation [Zaragoza et al., 2011, Bianchi et al., 2007]:

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

where ρ is the air density, r is the wind turbine rotor radius, V is the wind speed and the power coefficient $C_p(\lambda,\beta)$ represents the turbine efficiency to convert the kinetic energy of the wind into mechanical energy [Bianchi et al., 2007]. This coefficient is a function of both the blade pitch angle β and the tip speed ratio λ which is defined as [Qiao et al., 2009] $\lambda = \frac{\omega}{V}r$, where ω is the WT angular shaft speed. The introduction of the expression of λ in Eq. (1) gives:

$$P_a = \frac{K_a r\omega C_p(\lambda,\beta)}{\lambda} V(t)^2 \tag{2}$$

with $K_a \stackrel{\text{def}}{=} \rho\frac{\pi}{2}r^2$. As a consequence, the torque that the wind turbine extracts from the wind is given by:

$$T_a(t) = \frac{K_a r C_p(\lambda,\beta)}{\lambda} V(t)^2. \tag{3}$$

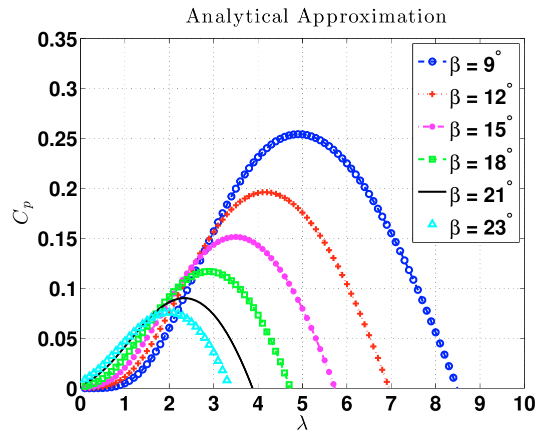
The power coefficient $C_p(\lambda,\beta)$ is a nonlinear function [Monroy and Alvarez-Icaza, 2006, Siegfried, 1998], and depends on blade aerodynamic design and WT operating conditions. In [Zaragoza et al., 2011], the following equation is proposed to approximate the power coefficient:

$$C_p(\lambda,\beta) = c_1\left(k_1\gamma + k_2\beta + \bar{k}_3\right)\exp(k_4\gamma) \tag{4}$$

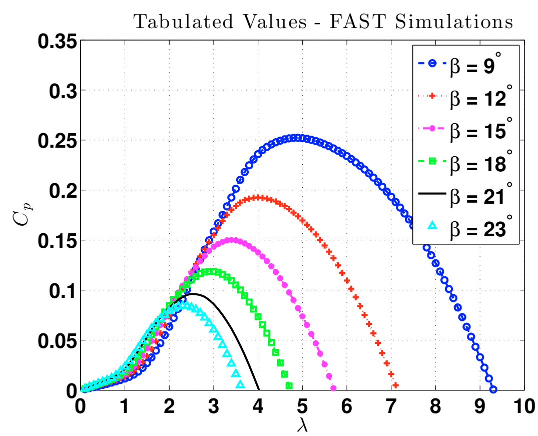
$$\gamma = \left(\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3+1}\right) \tag{5}$$

The coefficients c_1, $k_1, k_2, \bar{k}_3, k_4$ depend on the shape of the blade and its aerodynamic performance [Beltran et al., 2009, Zaragoza et al., 2011]. The following coefficient values have been considered in this work: $c_1 = 6.909$; $k_1 = 7.022$; $k_2 = -0.04176$; $\bar{k}_3 = -0.3863$; $k_4 = -14.52$. These coefficients have been obtained fitting the Eq. (4) to the C_p tables for the NREL $5-MW$ wind turbine generated using the NREL code.

Following [Georg et al., 2012], the behavior of the function (4) with the proposed coefficients has been reported in Fig. 1(a) for different pitch angles, compared to the corresponding plots (see Fig. 1(b)) of the curves based on the tables in [NWTC, b] for the NREL $5-MW$ reference wind turbine.



(a)



(b)

Fig. 1. (a) Analytical approximation with function (4) ; (b) Tabulated values obtained from FAST simulations [NWTC, b]. β is in degrees.

The mechanical equation governing the turbine can be simplified as follows [J.M. Jonkman and M.L. Buhl , 2005]:

$$J\dot{\omega}(t) = -K\omega(t) + T_a(t) - N_g\tilde{T}_e(t) \tag{6}$$

where $\omega(t)$ is the rotor angular speed, K is the coefficients of viscous friction of the low-speed shaft, N_g is the gearbox ratio, $\tilde{T}_e(t)$ is the electrical torque of the generator, which can be imposed designing currents and voltages of the generator stage. For convenience the following definition is introduced, to be used hereafter $T_e(t) \stackrel{\text{def}}{=} N_g\tilde{T}_e(t)$.

3. VARIABLE ROTOR SPEED AND VARIABLE BLADE PITCH WT REGIME

In the paper, operation in the region of high wind speed will be considered, and the objective of the control system will be defined as that of maintaining the captured wind power at the rated value $\bar{P}_a$.

3.1 Problem statement

As pointed out, the control objective in high wind speeds is to maintain the captured wind power at the rated value $\bar{P}_a$, i.e. to minimize the following squared error: