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An observer-based blade-pitch controller of wind turbines in high wind speeds

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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. Coupled design is described of an observer-based blade-pitch control input and a generator torque controller, both of which not requiring the availability of wind speed measurements. Closed loop convergence of the overall control system is proved. The proposed control solution has been validated on a 5-MW three-blade wind turbine using the National Renewable Energy Laboratory (NREL) wind turbine simulator FAST (Fatigue, Aerodynamics, Structures, and Turbulence) code.

1. Introduction

The extraction of wind power by a Wind Energy Conversion System (WECS) can be divided into different operating regions associated with wind speed, maximum allowable rotor speed and rated power (Beltran, Ahmed-Ali, & Benbouzid, 2009; Liserre, Cardenas, Molinas, & Rodriguez, 2011). In practice, variable-rotor-speed/variable-blade-pitch wind turbines have three main regions of operation with respect to wind speed (Cirrincione, Pucci, & Vitale, 2013; Johnson, Pao, Balas, & Fingersh, 2006; Liserre et al., 2011; Senjyu et al., 2006). A stopped turbine or a turbine that is just starting up is considered to be operating in region 1. Region 2 is an operational mode with the objective of maximizing wind energy capture. In region 3, which encompasses 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 (Corradini, Ippoliti, & Orlando, 2013a, 2013b, 2015; Huang, Li, & Jin, 2015; Kim, Van, Lee, Song, & Kim, 2013; Pao & Johnson, 2011), while control of blade pitch is typically used to limit power for turbines operating in region 3 (Bossanyi, Fleming, & Wright, 2013; 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, Mantz, & Christiansen, 2004b, 2007; Muljadi & Butterfield, 2001; Petru & Thiringer, 2002). 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 (Jafarnejadsani, Pieper, & Ehlers, 2013; Tang, Guo, & Jiang, 2011). The presented control strategy specifically addresses the case of full load operation in the so-called Regime 3 (high wind speeds), 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 (Bossanyi et al., 2013; Jafarnejadsani et al., 2013; Peng, 2010; Tang et al., 2011) suggests that a coupled control design of pitch actuator input and electrical torque of the Wind Turbine (WT) should be pursued to achieve effective results. Nonlinear optimal control approaches have been proposed (Saravanakumar & Jena, 2015, 2016) also adopting sliding mode control techniques. PI controllers have been also used for regulating the pitch angle (Hansen et al., 2005; Jonkman, Butterfield, Musial, & Scott, 2009; Semrau, Rimkus, & Das, 2015). In Jonkman et al. (2009) a gain scheduled PI control for blade pitch is coupled to a baseline torque control, the latter ensuring tracking of the reference power while the former being used for speed control. In Semrau et al. (2015) a framework is proposed to visualize and analyze the equilibria of the wind turbine as its operating regimes and controllers change. A method for blade pitch modulation to control rotor speed at high wind speeds is also proposed, based on rotor speed and working in parallel with the generator torque control loop of Jonkman et al. (2009). In Hansen

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et al. (2005) a PI controller has been proposed with the generator speed (low pass filtered) as input and the pitch servo set-point as output. A selection of the regulator parameters is also suggested based on empirical considerations about the expected pitch sensitivity, i.e. on tests performed to determine the pitch angle that produces the rated mechanical power at different wind speeds at the reference rotor speed. The calculated pitch sensitivity shows a large variation with wind speed so constant control parameters cannot produce a satisfactory closed loop behavior. Nonetheless, pitch sensitivity shows a nearly linear dependence on the pitch angle, and a gain correction factor (dependent on the pitch angle) is proposed for the PI controller parameters. 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 previously discussed approach does indeed suggest that the availability of reliable wind speed measurements, or its estimates, is a key factor for improving closed-loop control performances. In the cited case, it could potentially improve the closed loop response in terms of pitch sensitivity due to its dependence on wind speed. It is worth also to recall that, in the design procedure of a model-based wind turbine controller, wind speed is both the input for the system and the parameterizing variable for the dynamics that determine the operating point of the WECS (Soltani et al., 2013). To compensate for variations in parameters or dynamic behavior adaptive or gain-scheduled controllers have been used, in which the control gains are adapted/scheduled based on the measured or calculated varying parameters (Bianchi, Mantz, & Christiansen, 2004a; Leith & Leithead, 1996), such as the generator velocity in region 2 and the pitch angle in region 3 (Bianchi et al., 2007). Using the wind speed as scheduling parameter would have an advantage of keeping a single parameter for the whole operation region (Ohtsubo & Kajiwara, 2004) but 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 (Abo-Khalil & Lee, 2008; Huang et al., 2015; Ioakimidis, Oliveira, & Genikomsakis, 2014) and a good comprehensive analysis of these techniques is given in Soltani et al. (2013). Indeed, recent advances in light detection and ranging (LIDAR) systems have shown promise for providing real-time measurements of wind speed (Mikkelsen et al., 2013), opening a new area of research in feedforward wind turbine control (Wang, Johnson, & Wright, 2012, 2013) and receding horizon control for load reduction (Soltani, Wisniewski, Brath, & Boyd, 2011).

In this paper, a coupled blade pitch/generator torque controller (in region 3) will be presented 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 (https://nwtc.nrel.gov/FAST). The paper is organized as follows. The WECS dynamics are presented in Section 2. In Section 3 the problem statement is given, and details on the considered observer-based coupled blade pitch/generator torque controller are discussed in Section 4. Results on numerical tests are reported in Section 5. The paper ends with comments about the proposed control policy.

2. WECS dynamics

The system model here reported is inspired by the studies (Bianchi et al., 2007; Zaragoza et al., 2011) 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 (Bianchi et al., 2007; Zaragoza et al., 2011):

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

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, Qu, & Harley, 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 & 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:

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

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

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 Eq. (4) to the C_p tables for the NREL 5-MW wind turbine generated using the NREL code WT_perf (https://wind.nrel.gov/forum/wind/viewtopic.php?f=2&t=582).

Following Georg, Schulte, and Aschemann (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 https://wind.nrel.gov/forum/wind/viewtopic.php?f=2&t=582 for the NREL 5-MW reference wind turbine.

The mechanical equation governing the turbine can be simplified as follows (Jonkman & 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: