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Nonlinear PI control for variable pitch wind turbine ☆

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ABSTRACT

Wind turbine uses a pitch angle controller to reduce the power captured above the rated wind speed and release the mechanical stress of the drive train. This paper investigates a nonlinear PI (N-PI) based pitch angle controller, by designing an extended-order state and perturbation observer to estimate and compensate unknown time-varying nonlinearities and disturbances. The proposed N-PI does not require the accurate model and uses only one set of PI parameters to provide a global optimal performance under wind speed changes. Simulation verification is based on a simplified two-mass wind turbine model and a detailed aero-elastic wind turbine simulator (FAST), respectively. Simulation results show that the N-PI controller can provide better dynamic performances of power regulation, load stress reduction and actuator usage, comparing with the conventional PI and gain-scheduled PI controller, and better robustness against of model uncertainties than feedback linearization control.

1. Introduction

Wind power is one of the most promising renewable energy sources and has received tremendous progress at the past decade. Most wind power generation system uses variable speed wind turbine with variable pitch to achieve an efficient and reliable conversion of wind power to electrical power. According to wind speed range, wind turbine has three operation modes and control objectives, as shown in Fig. 1 (Bianchi, De Battista, & Mantz, 2006). Region I starts from the cut-in wind speed to the wind speed when the rotor speed reaches its rated value and its' control objective is to capture the maximum available power from the wind flow, using variable speed operation of wind turbine (Boukhezzar & Siguerdidjane, 2010). In Region III, the wind speed is above its rated value and below the cut-out speed, in which the wind power forced on the blade is larger than the nominal power of the wind turbine and must be limited by pitch angle control, while minimizing the load stress on drive-train shaft at the same time. Between these two regions, the rotor speed can reach its rated value and must be kept constant until the generated power reaches the rated power. This buffer region is called Region II, whose control objective is to smoothly connect Regions I and III (Pao & Johnson, 2011).

Efficient and reliable operation of a WPGS heavily relies on the control systems applied on the WT operating at different regions. At the high speed Region III, pitch angle control is applied to limit the wind power captured by the wind turbine. Numerous control methods have been applied to design pitch angle controllers, such as PI-type controller (Bianchi et al., 2006; Hansen et al., 2005). The wind turbine is a highly non-linear system due to its nonlinear aerodynamics (Beltran, Ahmed-Ali, & Benbouzid, 2008; Kumar & Stol, 2010). As the wind turbine contains strong aerodynamic nonlinearities and operates under time-varying wind power inputs, the linear PI with fixed gains cannot provide consistently satisfactory performance in the whole wind speed region. Advanced control methods have been applied to tackle this problem, such as the gain scheduling PI (GSPI) (Bianchi et al., 2006; Hansen et al., 2005), digital robust control (Camblong, 2008), neural-network-based control (Yilmaz & Özer, 2009), model predictive control (Schlipf, Schlipf, & Kühn, 2013), and feedback linearization control (Kumar & Stol, 2010; Leith & Leithead, 1997). However, most control methods, such as the feedback linearization control, are designed based on the accurate wind turbine model, which is difficult to be obtained accurately in practical.

Extended-order state and perturbation (or disturbance)

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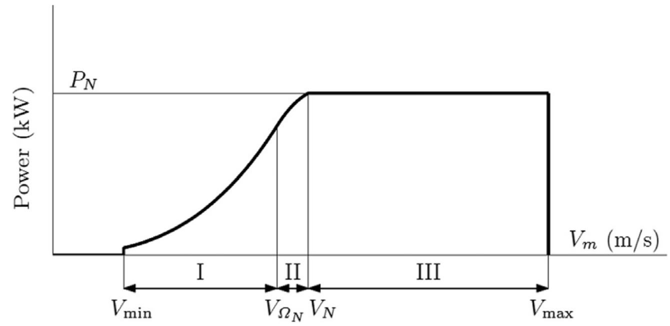

Fig. 1. Wind turbine operation modes versus wind speed (Bianchi et al., 2006).

observer (ESPO) has been proposed to estimate system state and perturbation term for nonlinear system which can be represented as a chained-integrator system and matched nonlinearities and disturbances. By defining perturbation as a lumped term to include all unknown nonlinearities, parameter uncertainties and external disturbance (Kim & Youn, 2002), ESPO can be implemented using a nonlinear observer (Chen, Komada, & Fukuda, 2000; Han, 2009; Zhou, Shao, & Gao, 2009), linear observers (Jiang, Wu, Wang, Zhang, & Zhou, 2001; Li & Liu, 2009), sliding mode observers (Jiang & Wu, 2002), fuzzy observers (Kim, 2002), and neural-network-based observers (Ko & Han, 2006). An ESPO-based controller uses the estimate of perturbation to compensate its real perturbation and achieve the adaptive feedback linearizing control, without requiring a detailed and accurate system model in conventional feedback linearization (FL) control (Kumar & Stol, 2010; Leith & Leithead, 1997). They have been applied in robotic systems (Chen, Ballance, Gawthrop, Gribble, & Reilly, 1999), power systems (Chen, Jiang, Yao, & Wu, 2014; Jiang et al., 2001), PMSM systems (Kim & Youn, 2002), induction motor (Gao, 2006), doubly-fed induction generator wind turbine (Patel & Zhao, 2010).

This paper designs a Nonlinear PI (N-PI) controller for wind turbine pitch angle control. It consists of an ESPO and a classic PI controller. The ESPO is used to estimate the unknown time-varying nonlinearities and disturbance, which are defined in a lumped perturbation term. The N-PI uses the estimated perturbation to compensate the real one for linearizing the nonlinear system. The procedure is similar to the feedback linearization (FL) method, which requires a detailed and accurate system model to calculate the nonlinearities (Leith & Leithead, 1997; Kumar & Stol, 2010). The N-PI is proposed to provide global and consistent optimal performance across the whole operation range only based on one set of PI gains tuned around the mean wind speed, and avoid the rapidly switching of gains of the gain-scheduled PI (GSPI) type controllers. Two types of gain scheduled PI controllers, wind speed switching and pitch-angle switching ones are compared using simulation tests based on a simplified two mass model and a detailed aero-elastic wind turbine simulator, FAST (Jonkman & Buhl, 2005).

2. Nonlinear wind turbine modeling

The configuration of a simplified two-mass model of wind turbine and its nonlinear power coefficient C_p is shown in Fig. 2.

The model is presented in a generalized nonlinear form as follows (Thomsen, 2006):

$$\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x}) + \mathbf{B}u = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ g_4 \end{bmatrix} u \tag{1}$$

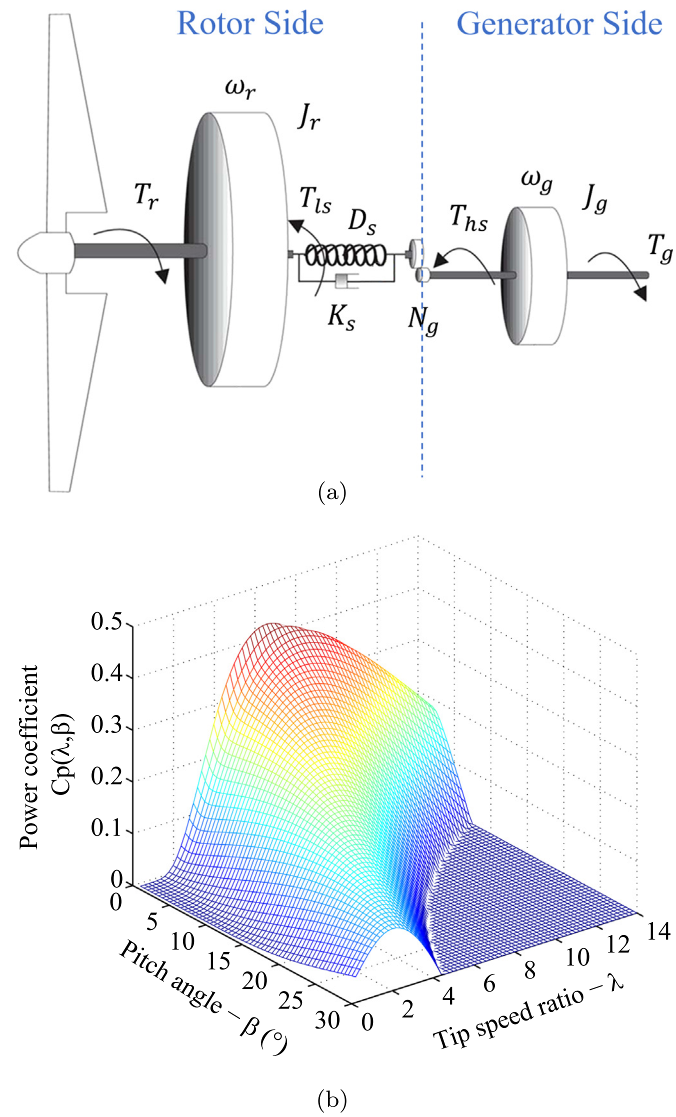

Fig. 2. Two-mass variable speed wind turbine model and nonlinear power coefficient Cp (Boukhezzar & Siguerdidjane, 2011).

The state vector $\mathbf{x}$, control input u and nonlinear vector $\mathbf{F}(\mathbf{x})$ are defined as

$$\mathbf{x} = \begin{bmatrix} \omega_r & \omega_g & \delta & \beta \end{bmatrix}^T$$
$$u = \beta_r \tag{2}$$

$$\mathbf{F}(\mathbf{x}) = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} = \begin{bmatrix} \dfrac{P_r(x_1, x_4, V)}{x_1 J_r} - \dfrac{x_1 D_s}{J_r} + \dfrac{x_2 D_s}{N_g J_r} - \dfrac{x_3 K_s}{J_r} \\ \dfrac{x_1 D_s}{N_g J_g} - \dfrac{x_2 D_s}{N_g^2 J_g} + \dfrac{x_3 K_s}{N_g J_g} - \dfrac{T_g}{J_g} \\ x_1 - \dfrac{x_2}{N_g} \\ -\dfrac{1}{\tau_\beta} x_4 \end{bmatrix} \tag{3}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & 0 & g_4 \end{bmatrix}^T$$