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Pitch control for wind turbine systems using optimization, estimation and compensation

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ABSTRACT

Delays caused by hydraulic pressure driven units in wind turbines may degrade and even destabilize pitch control system, leading to the performance degradation or collapse of the whole wind turbine energy conversion system. As a result, there is a strong motivation to improve pitch control technique to overcome the adverse effects from the unknown delays caused by the hydraulic driven units. In this study, a novel pitch control approach is developed by integrating optimization, delay-perturbation estimation, and signal compensation techniques. Specifically, an optimal PI controller is designed by applying direct search optimization to ideal delay-free pitch model. A delay estimator is next designed to estimate the perturbation caused by the delay. The signal compensation technique is then implemented to remove the effect from the delay-perturbation to the turbine output so that the actual output is consistent with the optimal output of the ideal delay-free model. Furthermore, the technique is extended to PID-based pitch control systems. The blade-tower dynamics models of three wind turbines, respectively with rated powers 1.5 MW, 275 kW and 50 kW, are investigated and the effectiveness of the proposed techniques are demonstrated by detailed simulation studies. It is worthy to point out a priori on the delay is not necessary in this design, which much meets the situations in practical wind turbine systems. Finally, a 4.8 MW benchmark wind turbine energy conversion system is investigated via the proposed pitch control technique, which has shown that delay perturbation estimate based compensation can effectively improve the pitch control performance in the real-time wind turbine energy conversion system.

1. Introduction

Benefited from the rapid progress in wind turbine technology, wind energy has become the fastest growing power industry around the world. For instance in EU (European Union) in 2014, wind power has the highest installation rate accounting for 43.7% of all new power installations and 55.3% of all new renewable power installations. Over the last 14 years, the wind power installation has a compound annual growth rate of 9.8% in EU leading to a total of 128.8 MW installation up to 2014 [1].

The architecture of a wind turbine system can be depicted by Fig. 1, which is composed of turbine, gearbox, generator, AC/DC/AC converter and grid. Therefore, wind power can be converted to mechanic power, and then electric power with the aid of control units embedded in the wind turbine system.

With the enhancement of wind turbine generating capability, it is vital to develop effective and reliable control strategies in wind energy conversion systems to achieve optimal power harvesting performance [2–5]. Most wind turbines support variable-speed operation with the aid of pitch control so that the desired power output can be achieved [6–11]. Pitch control is capable of regulating the pitch angle of the wind turbine blades so that a steady output power can be obtained when the wind speed is above the rated value. As a result, pitch control is critical for variable-speed wind turbine conversion systems. During the last decades, numerous results were reported for pitch control in wind turbines utilizing a variety of techniques such as fuzzy logic [12,13], LQR (linear quadratic regulator) control [14,15] and PI (proportional and integral) or PID (proportional, integral and derivative) control [16–18] and so forth.

PID control was initialized in 1940s [19], which has proven a powerful control tool in industrial processes owing to its robust

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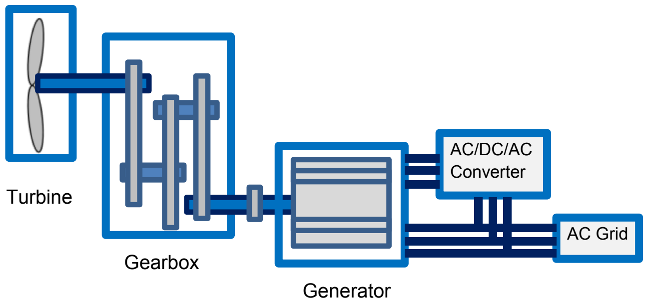

Fig. 1. Architecture of wind turbine systems.

performance and simplicity for implementation. Up to date, more than 90% of the control loops in process industries are employing PID or PI controllers. It is a key to tune PI or PID control parameters to stabilize processes. During the last decades, there were various methods reported on how to tune PI or PID parameters, e.g., see Refs. [20–23]. In Ref. [20], a complete analytical solution was developed for computing all stabilizing controllers on the basis of generalized Hermite-Biehler theorem. However, the computation time of the analytical method increases in an exponential manner. An alternative approach for fast computation of PI or PID stabilizing controllers were addressed in Ref. [21] by using Nyquist plot. Recently, the stability boundary locus approach and Kronecker summation method were respectively proposed in Refs. [22,23] for determining the parameters of all the stabilizing PI or PID controllers.

Hydraulic pressure driven units introduce delays to wind turbine conversion systems, which is particularly true for large wind turbines. Very recently, a graphic approach was proposed in Ref. [24] to characterize the stabilizing region of PI-based pitch controllers for wind turbine systems subjected to delays caused by hydraulic driven units. Motived by Ref. [24], an optimal PID controller design approach was developed in Ref. [25] for wind turbine systems subjected to delays by combing particle swam optimization (PSO) and radial basis function neural network (RBFNN) algorithms. It is noticed that [24,25] both assume the induced delays in wind turbines are known constant numbers. Unfortunately, in practical wind turbine systems, the induced delays by hydraulic pressure driven units are challenging to identify, which are usually unknown, and even time-varying. Therefore, the approaches addressed in Refs. [24,25] would become invalid when the assumed constant delays significantly departure from the real unknown delays. As a result, there is a strong incline to develop a novel PI or PID based pitch control approach for wind turbines subjected to unknown delays caused by hydraulic press driven units.

In Refs. [26,27], interesting descriptor estimators were developed to estimate sensor noises and sensor faults, which provide us a clue on how to estimate the unexpected delays in wind turbines and how to remove the effects from the delays. In addition, direct search optimization [28,29] is a powerful tool to seek optimal solutions without the need of calculation for gradients, which may facilitate to seek optimal PI or PID control parameters. In this study, motivated by Refs. [26–29], a novel PI-based pitch controller design method is proposed by integrating estimation, compensation and optimization.

The contribution of this paper is as follows:

i) Novel PI-based pitch control technique is to be addressed by integrating direct search optimization, delay perturbation estimation and delay perturbation compensation. Specifically, direct search optimization algorithm is to be utilized to optimize the PI parameters for delay-free wind turbine models so that the desired performance can be obtained. Delay perturbation estimator is to be addressed to estimate unknown delay perturbations induced by hydraulic driven units in wind turbine system. Signal compensation is to be implemented to remove the effect from the delay-perturbation to the wind turbine output.
ii) Novel PID-based pitch control technique is to be presented by extending the work above.
iii) The blade-tower dynamics of three wind turbines respectively with rated power of 1.5 MW, 275 kW and 50 kW are to be investigated with details to demonstrate the effectiveness of the proposed methods.
iv) A 4.8 MW benchmark wind turbine energy conversion system is to be further analyzed to show the effectiveness of the proposed pitch control technique in a real-time wind turbine system.
v) No priori of delay is necessary for the proposed control design; therefore, the proposed pitch control is applicable for wind turbine systems under practical real-time operation conditions.

2. System description of three wind turbine systems

The linearized model representing the blade-tower dynamics in a horizontal-axis wind turbine is given by Ref. [24], which can be described as:

$$G_{\beta\to\gamma_t} = G_{p0}(s)e^{-\tau s} \tag{1}$$

where γ_t is the tower fore-aft modal deflection, β corresponds to the deviation of the pitch angle from its value at the operation point, τ is the time delay parameter caused by hydraulic pressure driven units, and

$$G_{p0}(s) = \frac{a_2s^2 + a_1s + a_0}{b_4s^4 + b_3s^3 + b_2s^2 + b_0}, \tag{2}$$

a_2, a_1, a_0, b_4, b_3, b_2 and b_0 are known constant coefficients of the wind turbine model, whose values depend on the configuration of wind turbine systems.

It is noticed that in Ref. [24], the time delay τ is assumed to be known and constant. However, in practical wind turbine systems, the induced delay is unknown and even time-varying. Therefore, the system model can be re-expressed in a more general form, depicted by Fig. 2.

In Fig. 2, $C(s)$ is a PI or PID controller, $G_{p0}(s)$ is the transfer function defined in (2), and the delay block represents an unknown delay (either constant or time-varying delay) caused by hydraulic pressure driven units, r is the reference input, β is the input of the controlled system (the deviation of the pitch angle from its value at the operating point) and γ is the system output (the tower for-aft modal deflection). Considering various turbine configurations and operating conditions, three wind turbines, named WT1, WT2 and

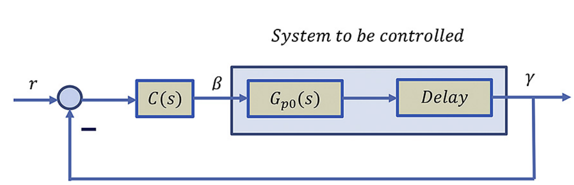

Fig. 2. Schematic of pitch control in wind turbine systems.