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# Innovative adaptive pitch control for small wind turbine fatigue load reduction[☆]

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ABSTRACT

As a renewable source of energy, wind is widely used to produce electrical power. The progress of wind turbine technology can greatly benefit from the improvement of control algorithms. The pitch angle control of a horizontal axis wind turbine above the rated wind speed is a challenging issue related to the nonlinear aerodynamic behavior of blades. The linearization of aerodynamic model around nominal operating condition, as well as manufacturing deficiencies, result in unknown parameter uncertainties in a wind turbine model. Therefore, the performance of controller, which is designed based on the mathematical model, defects in practice. In the current paper, an adaptive self-tuning regulator (STR) configuration is proposed for the pitch control, so that the parameters of wind turbine model are constantly estimated and the controller gains are updated based on the assessed parameters. The STR structure consists of a recursive least square estimator and a proportional-integral-derivative (PID) controller with adjustable gains, which are determined by the pole placement method in a real-time routine. The robustness of the closed loop system is investigated by implementation of the control structure on an aero-servo-elastic wind turbine simulator. For the sake of comparison, a baseline gain scheduling PID controller, which is well-accepted for wind turbine pitch control, is designed. A comparison between the simulations of two controllers confirms a significant improvement in the closed-loop performance including less fluctuation of rotor speed and power besides minor fatigue loads on the blades and main-shaft.

## 1. Introduction

Due to the higher demand for electrical energy and the limitation of fossil energy resources, renewable sources of energy are under serious consideration. The growth in the use of wind energy exceeds that of other renewables, because of cost effectiveness of wind turbines [1]. One of the most challenging issues in wind turbine technology is improving the control algorithms since it could significantly increase the efficiency. One of the most important control systems of a wind turbine is the pitch angle control, which regulates power above the rated wind speed and protects blades during a storm [2]. Over time, the benefits of this system have changed the wind turbine configuration from a fixed pitch to a variable pitch. In the following, the recent and most relevant papers in the application of pitch control above the rated wind speed in a power curve [3] are reviewed.

Hand and Balas [4] designed a PID pitch controller with the objectives of minimizing the deviation of the rotor speed error and the actuator motion. By means of a graphical approach, Wang et al. [5] analyzed and designed a classical proportional–integral (PI) pitch controller for a wind turbine generator. Camblong [6] proposed a discrete robust controller for pitch angle based on an average model representing wind turbine dynamics in all operating conditions. Hand and Balas [4], Wang et al. [5] and Camblong [6] as well as Moradi and Vossoughi [7] and Petrovic et al. [8] proposed fixed controllers for the pitch angle. However, the variations of wind speed considerably alter the assumed mathematical model of a wind turbine, consequently influences the controller performance.

Hansen et al. [9] tuned a gain scheduling PI for wind turbine pitch control based on an assumed second order mathematical model. By Sakamoto et al. [10], the minimum variance control was applied to an STR configuration to compensate the influence of parameter variations. Frost et al. [11] applied a direct model reference adaptive control method for the adaptive rejection of disturbances in wind turbine pitch control application. Hansen et al. [9], Sakamoto et al. [10] and Frost et al. [11] developed adaptive controllers in a way that the change of system parameters was not included in the control laws. Considering that the mathematical modeling errors are inevitable and the characteristics of wind turbine components vary slightly, tuning the pitch controller based

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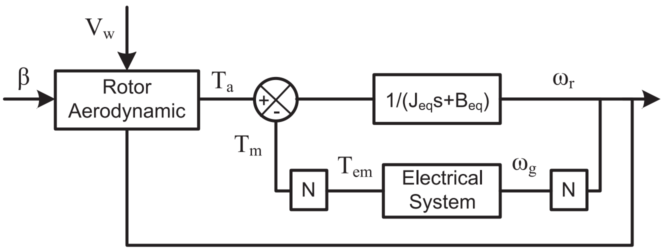

**Fig. 1.** Block diagram of the wind turbine power train.

on a real-time estimation of the system parameters improves the wind turbine performance.

The current paper proposes an innovative adaptive structure for pitch control to regulate rotor speed fluctuations above the rated wind speed. In the proposed control structure, the controller gains are adjusted in a real-time process based on the estimated parameters of model. Considering that parameter identification of complex model is time-consuming and hardly applicable in a real-time manner, based on [12], a simplified wind turbine model is proposed. The recursive least square (RLS) method is employed for estimation along with an adjustable PID which is tuned based on a pole placement method.

To investigate the applicability in wind turbines, the proposed STR controller is implemented on an aero-servo-elastic wind turbine simulator, named as FAST (Fatigue, Aerodynamics, Structures, and Turbulence) [13]. The stability, performance and robustness of the closed loop system is examined by simulations in which the coupled dynamic response of wind turbines are taken into consideration. Based on the simulation results obtained under turbulence wind conditions, the STR controller reveals significant improvement in closed-loop pitch control performance in comparison with a well-tuned gain-scheduled PID.

Henceforth, the current paper is organized as follows: In Section 2, the mathematical model of a wind turbine is presented. Based on the mathematical model, estimation of the plant parameters is then developed in Section 3. Afterward, the baseline and adaptive controllers are designed in Section 4. The simulation software is described in Section 5. The results of implementing the controllers on FAST code are discussed in Section 6. In the last section, benefits of the STR controller are summarized.

## 2. Modeling

The power train of a wind turbine extracts wind energy and converts it to electrical energy. Power train consists of rotor blades, gearbox and generator. The rotor blade drives rotating components by aerodynamic torque ($T_a$) as a function of wind speed ($V_w$), pitch angle ($\beta$) and rotor speed ($\omega_r$). The mechanical torque ($T_m$), which is a product of electromagnetic torque of generator ($T_{em}$) and gearbox ratio ($N$), acts against aerodynamic torque. Resultant torque applies on equivalent inertia ($J_{eq}$) and damping ($B_{eq}$) of rotary components and as a result, rotor speed is determined by Eq. (1), based on [14].

$$T_a - T_m = J_{eq}\frac{d\omega_r}{dt} + B_{eq}\omega_r \tag{1a}$$

$$J_{eq} = J_r + N^2 J_g \tag{1b}$$

$$B_{eq} = B_r + N^2 B_g \tag{1c}$$

$J_r$, $J_g$, $B_r$ and $B_g$ are rotor inertia, generator inertia, rotor damping and generator damping, respectively. The block diagram of wind turbine power train is presented in Fig. 1.

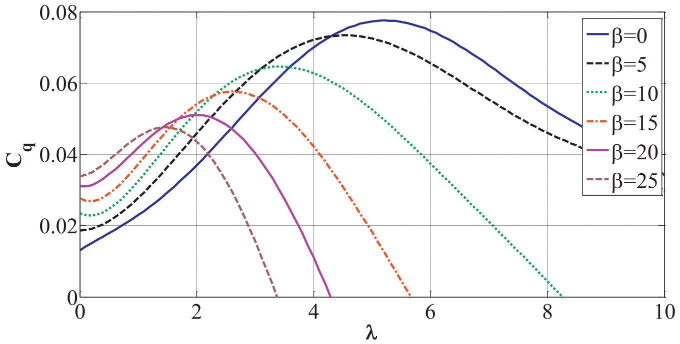

**Fig. 2.** Torque coefficient with respect to tip speed ratio for specified pitch angles.

**Table 1**
Nominal operating condition of a prototype wind turbine.

| Variable | Unit | Value | Variable | Unit | Value |
|---|---|---|---|---|---|
| No. of blades | – | 3 | Rated aero power ($P_a^*$) | W | 3600 |
| Rotor radius ($R$) | m | 3.3 | Rated rotor speed ($\omega_r^*$) | rpm | 145 |
| Tower height ($H$) | m | 12 | Rated wind speed ($V_w^*$) | m/s | 7.6 |
| Gear ratio ($N$) | – | 9.3 | Rated torque ($T_m^*$) | N m | 237 |

Using the momentum theory of an ideal wind turbine [15], the aerodynamic torque of rotor blade is expressed as

$$T_a(V_w, \beta, \omega_r) = C_q(\lambda, \beta)\frac{1}{2}\rho\pi R^3 V_w^2 \tag{2}$$

where $C_q$, $\lambda$, $\rho$ and $R$ are torque coefficient, tip speed ratio, air density and rotor radius, respectively. The tip speed ratio is calculated by

$$\lambda = \frac{R\omega_r}{V_w}. \tag{3}$$

Typical curves of $C_q$ as a function of $\lambda$ and $\beta$ corresponding to a prototype small wind turbine are plotted in Fig. 2.

Assuming the nominal rotor speed and the nominal power, the aerodynamic torque can be linearized and given by Eq. (4), further details could be found in [16]. The nominal operating conditions are presented in Table 1.

$$T_a = T_a^* + K_v\Delta V_w + K_\beta\Delta\beta + K_\omega\Delta\omega_r, \tag{4}$$

where $K_V = \partial T_a/\partial V_w$, $K_\beta = \partial T_a/\partial\beta$ and $K_\omega = \partial T_a/\partial\omega_r$.

The electrical system in this study, shown in Fig. 1, consists of an electrically exited synchronous generator which is connected to a 3-phase resistive load and its excitation voltage is set on the nominal value using a power supply. With consideration of wind turbine control concept above the rated wind speed, generator operates around its nominal working condition, as applied in [17–19]. Thus, the electromagnetic torque could be a linear function of generator speed as expressed in Eq. (5).

$$\Delta T_{em} = K_G\Delta\omega_g \tag{5}$$

Based on the linearized aerodynamic model and the assumed generator model, the updated block diagram of plant is illustrated in Fig. 3.

In the represented block diagram, the output, $\Delta\omega_r$, is a function of two inputs, $-\Delta\beta$ and $\Delta V_w$ which have relation

$$\Delta\omega_r = [\boldsymbol{G}]\begin{bmatrix}\Delta V_w \\ -\Delta\beta\end{bmatrix}, \tag{6}$$

where $\boldsymbol{G}$ is a transfer function matrix as

$$\boldsymbol{G} = [G_1 \quad G_2], \tag{7a}$$

$$G_1 = \frac{K_V}{J_{eq}s + B_{eq} + N^2K_G - K_\omega}, \tag{7b}$$

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