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Multivariable control algorithm for laboratory experiments in wind energy conversion

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ABSTRACT

Advanced experimentation with wind energy conversion systems is described. The real time multivariable control of a wind turbine is designed for investigation of theoretical concepts and their physical implementation. The control system includes a speed controller and a disturbance estimator for enhanced robustness of the control system. In order to provide students with deeper understanding of wind energy and energy extraction, a maximum power point tracking algorithm is developed and integrated into the control system. The multivariable control system is implemented in a small wind turbine laboratory system. A power electronic interface is based on two DC–DC converters: a buck converter for control of the speed and a boost converter controlling the load voltage. Experimental results demonstrate effectiveness of the multivariable control system for a wind turbine providing maximum power extraction. The experiment can be reconfigured for teaching various control concepts to both undergraduate and graduate students.

1. Introduction

In modern power systems, the power generation based on wind energy enjoys significant interest, which has caused considerable increase in the related education and research [1–4]. Because it is difficult to use a real wind turbine in laboratory environment, a small turbine that can be used indoors is the best tool for implementation and demonstration of control strategies [5,6]. Wind turbine emulators, involving motor-generator set, variable load, and control system, which operate with the power-speed characteristics of a wind turbine are frequently used for research and teaching purposes due to their simplicity, low power, and low cost design [5]. However, neglecting the real wind effects represents an important flaw, especially when dealing with control strategies whose robustness need to be verified under realistic operating conditions [7].

Laboratory experiments in the wind energy area including hardware-in-the loop (HIL) and advanced control systems are important for education of future engineers and researchers. Developing a control system from the model of the wind turbine, and its practical realization would bridge the gap between theory and practice. It would allow the students to implement theories of advanced control by analysing the major components of a wind turbine system and extracting mathematical models needed for the design of a model-based control system. One major requirement in the considered wind energy conversion system (WECS) is controlling the generator speed and the load voltage in order to maximize wind energy extraction. As well known, the optimum turbine speed is a function of wind speed [1–3]. Variable speed WECS are increasingly common. Typically, at high wind speeds, the WECS use aerodynamic control in combination with power electronics to regulate torque, speed, and power, and prevent the turbine from damage. However, the aerodynamic control using variable pitch blades is usually expensive and complex. It ca also cause an unnecessarily high activity of the pitch actuator due to small fluctuations of power during the steady state operation [7].

Control systems implemented in the power electronic interface represent an efficient means to operate a wind turbine at the maximum power extraction. The control is not always aimed at capturing as much energy as possible. Power generation is limited during high wind speeds or when the load demand in an isolated system is low. Model based control strategies, such as feedback,

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predictive, and sliding mode, can be employed for speed control in WECS. Quality of control strategies depends on the accuracy of mathematical model of the system, which is usually not high [8,9]. For accurate speed tracking, the controller must maintain high performance when facing parameter variations and uncertainties of the system [10–15].

In this paper, a feedback speed control strategy is developed from the mathematical model of a generator connected to a wind turbine. Information about the turbine and wind speeds is assumed to be unavailable and their variations will be compensated using a torque estimator integrated in the controller. Performance of the proposed controller will be tested under multivariable control conditions with a maximum power point tracking (MPPT) algorithm and load voltage control. A Quanser's five-blade wind turbine is employed in an experimental setup equipped with a power electronic interface. The setup allows to verify efficacy of the proposed control system and to investigate its behaviour with real wind [16].

The rest of the paper is organized as follows: In Section 2, a description of the experimental system of wind turbine system is given. The proposed feedback control method for speed tracking is detailed in Section 3 followed by the robustness and stability analysis in Section 4. The MPPT algorithm, generating the speed reference needed for maximum extraction of power from wind, is described in Section 5. The experimental setup is described in details in Section 6 and experimental results and their discussion are given in Section 7.

2. Wind turbine experimental system

2.1. Wind turbine

The wind turbine, manufactured by Quanser Inc., is installed in a wind tunnel. It has five blades and drives a DC generator through a gearbox of ratio 1:1. The gearbox converts rotation of the horizontal-axis turbine to that of the vertical-axis generator. The generator is connected to the load via a power electronic interface allowing control of the shaft speed and load voltage.

The power delivered by the turbine shaft (neglecting losses in the drive train) is given by

$$P_t = 0.5\pi\rho C_p(\lambda) r^2 v_w^3 \tag{1}$$

where ρ denotes the air density, r is the length of the turbine blade, v_w is the wind speed, and λ is the ratio of blade tip speed to wind speed, that is

$$\lambda = \frac{\omega r}{v_w} \tag{2}$$

where ω is the angular velocity of the turbine.

The power coefficient C_p depends on speeds of the turbine and wind, and its relation to λ is shown in Fig. 1. The power coefficient reaches maximum at a specific optimum value λ_{opt}. In order to extract maximum power from wind, the turbine speed should be so controlled as to maintain λ at the optimum level.

In some wind turbines, the optimum tip speed ratio may be unknown or not well defined and subject to change. Therefore, instant locating of the maximum C_p during the operation of wind turbine is very important. An MPPT algorithm based on the variation of the generated power and the shaft speed is proposed, in Section 3.

The torque at the turbine shaft produced by the wind is given by

$$T_t = 0.5\pi\rho C_t r^3 v_w^2 \tag{3}$$

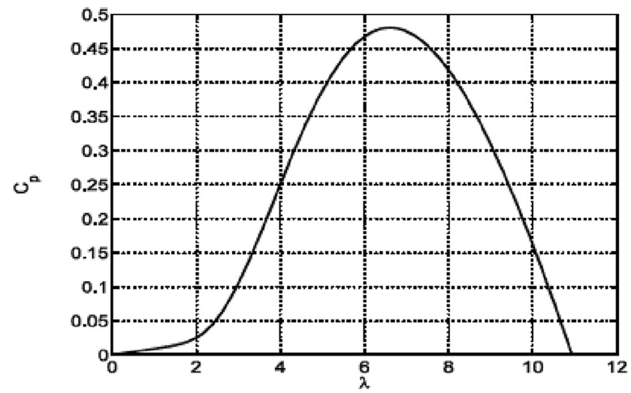

Fig. 1. Power coefficient of the wind turbine versus tip-speed ratio.

where $C_t = C_p/\lambda$ is the torque coefficient. Here, the mathematical model of the mechanical structure of wind turbine system is assumed to be unknown. This uncertainty is dealt with in the proposed control system.

2.2. DC generator

The armature of the DC generator is modeled as an RLE circuit, with E representing the back emf (speed voltage). Denoting the generated voltage as V, the electrical and mechanical equations of the generator can be written as

$$\frac{di}{dt} = -\frac{R}{L}i + \frac{K_b}{L}\omega - \frac{1}{L}V \tag{4a}$$

$$\frac{d\omega}{dt} = -\frac{K_i}{J}i - \frac{B}{J}\omega + \frac{1}{J}T_t \tag{4b}$$

where i is the armature current, K_b is the machine constant, ω is the rotational speed of the generator, V is the generator voltage, J is the rotor inertia, B is the viscous-friction coefficient, and T_t is the unknown turbine torque.

3. Feedback control for speed tracking

3.1. Feedback controller development

From the electrical and mechanical Equation (4) of the DC machine, a linear state-space equation can be derived as

$$\dot{x} = Fx + g_1 V + g_2 T_t \tag{5}$$

where,

$$x = [i \quad \omega]^T; \quad F = \begin{bmatrix} -\frac{R}{L} & \frac{K_b}{L} \\ -\frac{K_i}{J} & -\frac{B}{J} \end{bmatrix}; \quad g_1 = \begin{bmatrix} -\frac{1}{L} \\ 0 \end{bmatrix}; \quad g_2 = \begin{bmatrix} 0 \\ \frac{1}{J} \end{bmatrix}$$

The controlled output is the rotational speed ω, the input is the voltage V and the disturbance is the turbine torque T_t.

In order to find a relationship between the output ω and the input V, the mechanical Equation (4b) is differentiated, using Equation (4a), which yields