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A robust LMI-based pitch controller for large wind turbines

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ABSTRACT

This paper utilizes the linear matrix inequalities' techniques (LMI) for designing a robust collective pitch controller (CPC) for large wind turbines. CPC operates during up rated wind speeds to regulate the generator speed in order to harvest the rated electrical power. The proposed design takes into account model uncertainties by designing a controller based on a polytopic model. The LMI-based approach allows additional constraints to be included in the design (e.g. H_∞ problem, H_2 problem, H_∞/H_2 trade-off criteria, and pole clustering). These constraints are exploited to include requirements for perfect regulation, efficient disturbance rejection, and permissible actuator usage. The proposed controller is combined with individual pitch controller (IPC) that reduces the periodic blade's load by alleviating once per revolution (1P) frequency fatigue loads. FAST (Fatigue, Aero-dynamics, Structures, and Turbulence) software code developed at the US National Renewable Energy Laboratory (NREL) is used to verify the results.

1. Introduction

The use of wind power is increasing rapidly. At the same time the need for better cost effectiveness of wind power plants has stimulated growth in wind turbines' size and power. In above-rated wind conditions, the goals for turbine operation change from control of generator torque for maximum power tracking to those of regulating power at rated levels with mitigating fatigue loading on the turbine structure. An ordinary PI pitch controller regulates the generator speed without taking into consideration the unstructured dynamics of the blades, the drivetrain nor the tower. The nonlinear variation of rotor torque with wind speed and the pitch angle are typically not considered in design. Further, the pitch actuator also has restricted limits on pitch angle and pitch rate [1]. Other challenging problems are the presence of nonlinearities in the system dynamics, and the continuous change of the operating points during operation. All previous reasons motivate the need for robust pitch controller that provides an accepted performance, and disturbance rejection at different operating points within the allowed actuator constrains. In this paper, a multi-objective collective pitch controller will be designed using LMI techniques for generator speed regulation.

Another objective is to reduce the structural mechanical loads by using IPC. This should be fulfilled within the permissible range and rate of the pitch angle of the actuator. The importance of load reduction becomes vital as turbines become larger and more flexible. When the turbine blade sweeps, it experiences changes in wind speed due to wind shear, tower shadow, yaw misalignment and turbulence. These variations lead to (1P) large component in the blade loads, it's essential to design (IPC) to cancel this component [2].

Pitch controller is designed using H_∞ technique in [3,4]. In these papers, the controller main objective is to regulate the speed by improving disturbance rejection. The required control effort isn't considered in the design. In [5], it is proposed to design gain scheduled feedback/feed forward CPC for speed regulation combined with IPC for load reduction. Also in [6], optimal LQG feedback/feed forward CPC is proposed for speed regulation combined with IPC for load reduction. Combined CPC with IPC is proposed in [7] both as PI controllers. In [5–7], all the proposed controllers is based on a single linearized model, which only reflects one single operating point. A multi-objective (H_2/H_∞) pitch controller is proposed in [8], but it doesn't provide (H_2/H_∞) trade-off criteria. It also doesn't consider improving the transient response at different operating points. In our proposed work in this paper, an LMI-based CPC is considered. The controller design constraints include H_∞ problem for better speed regulation, and H_2 problem for optimizing control action with performance. The design also addresses H_∞/H_2 trade-off criteria for the optimization of the two previous problems. Pole clustering for improving transient response is also considered. The controller is based on a polytopic model to overcome model uncertainty at different operating points. CPC is combined with IPC to mitigate mechanical fatigue loads.

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Table 1
Wind turbine specifications.

Hub height	90 m
Rotor diameter	126 m
Cut in, rated, cut out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut in, rated rotor speed	6.9 rpm, 12.1 rpm
Gear box ratio	97
Rated generator speed	1173.7 rpm
Rotor, Tower, nacelle mass	110 ton, 347.4 ton, 240 ton

In Section 2, the turbine model specifications plus the turbine linearized models are discussed. In Section 3, the proposed CPC design, and the controller objectives are shown. The design considers two cases; single operating point-based model, and a polytopic-based model. In Section 4, IPC design is discussed. The simulation results showing a comparison between the proposed controller and a conventional PI controller are shown in Section 5. Finally the conclusions are stated in Section 6.

2. Model description

Simulations are performed on a full nonlinear turbine model provided by the FAST (Fatigue, Aero-dynamics, Structures, and Turbulence) software code developed at the US National Renewable Energy Laboratory (NREL) [9]. The model used is a 3-bladed, variable-speed 5 MW wind turbine model with the specifications given in Table 1.

More specifications could be found in [10, pp. 26]. The pitch actuator, represented as a second order model, has a pitch angle range from 0 to 90° with maximum rate of 8°/s.

FAST provides many degrees of freedom reflecting whether or not different turbine parts' dynamics are considered. The following degrees of freedom (DOF) are considered in our study:

(a) Generator DOF (q_1).
(b) Drivetrain rotational-flexibility DOF (q_2).
(c) First fore-aft tower bending-mode DOF (q_3).
(d) First flapwise blade mode for each blade DOF (q_4, q_5, q_6).

where (q_I) denotes the displacement of the Ith DOF. Each DOF could be presented as a linearized model around certain operating point according to:

$$M\Delta\ddot{q}_I + C\Delta\dot{q}_I + K\Delta q_I = F^{*}u + F_d{}^{*}u_d \tag{1}$$

where M, C, K, F F_d, u, *and* u_d denote mass matrix, stiffness matrix, damping matrix, control input matrix, wind input disturbance matrix, control input vector, and disturbance input vector, respectively. Assume $\Delta x = [\Delta q_I, \Delta\dot{q}_I]^T$, the linearized model takes the form:

$$P(S):\begin{cases}\Delta\dot{x} = A\Delta x + B\Delta u + B_d\Delta u_d\\ \Delta y = C\Delta x + D\Delta u + D_d\Delta u_d\end{cases} \tag{2}$$

where Δx, Δu, Δu_d, and Δy are the state vector perturbation, perturbation in the control action, perturbation in input disturbance, and perturbation in the output, respectively. Fig. 1 shows the synthesis of FAST model used in simulation.

The generator torque has four control regions: 1, 2, 2.5, and 3. Region 1 is a control region before cut in wind speed (v_{ci}) with zero generator torque so no power is extracted from the wind. Instead, the wind is used to accelerate the rotor for start-up. The main task in Region 2 is optimizing power capture by maintaining a constant (optimal) tip-speed ratio; ($\lambda = \lambda_0$), while the pitch angle is kept zero. In Region 3, the wind speed is above-rated speed. In this region, the generator controller task is to hold the generator torque constant. In the same time, the pitch controller regulates the generator speed at the rated value in order to capture the rated power. Region 2½ is a linear transition between Regions 2 and 3 used to limit tip speed (for less noise emissions) at rated power. The torque speed response of the model is shown in Fig. 2.

3. Designing an LMI-based collective pitch controller

The proposed technique is to design state feedback, LMI-based collective pitch controller (CPC) to regulate the generator speed in region 3. This controller is combined with IPC that mitigates the flapwise moment by canceling (1P) frequency. The proposed control strategy is shown in Fig. 3.

$M_{1,2,3}$ are the blade tip flapwise moments of each blade. ω_{gen} is the generator speed. The total control action (β) is calculated as follows:

$$\beta = \beta_{ipc} + \beta_{cpc} + \overline{\beta} \tag{3}$$

where ($\overline{\beta}$) is the pitch angle operating point. It is calculated by changing operating point with wind speed through a look up table. The generator speed is regulated by the control action (β_{cpc}), and the flapwise moment is reduced by the control action (β_{ipc}).

In this design, we are looking for a solution that addresses the combination of the following objectives:

1. Efficient disturbance rejection for better speed regulation (H_∞ problem) [11]. This could be achieved by keeping the RMS gain of $T(s)_\infty$ (H_∞ norm) below a predefined value γ_0: ($\gamma_0 > 0$). $T(s)_\infty$ is the closed loop transfer function from W to Z_∞, where $Z_\infty = [\Delta\omega_{gen}]$ represents the regulation error due to disturbance (W).
2. To minimize a cost function (J) that reflects a weighted sum of the control effort and states' perturbations. Trade-off between the control effort and the performance is represented as a H_2 problem. [11]. The minimization is carried by keeping the H_2

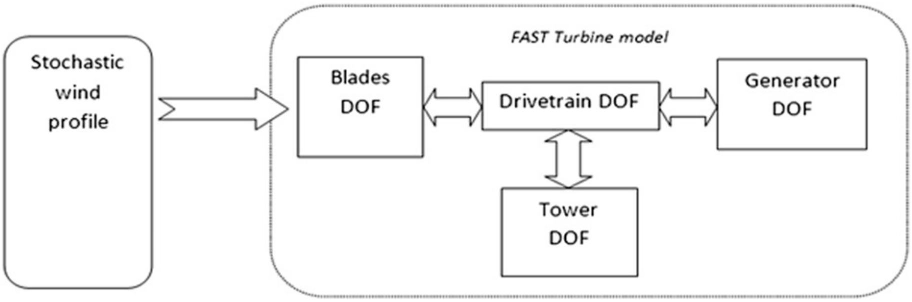

Fig. 1. FAST model components.