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Mixed-Sensitivity Robust Disturbance Accommodating Control for Load Mitigation and Speed Regulation of Wind Turbines

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Abstract— **To meet ever-growing global demand of renewable energy, wind turbines have seen an exponential growth in size over the past few decades to capture more energy from wind. This has led to a growing concern of increased loading of wind turbine components as a result of additional weight and flexibility, hence, affecting operational and power reliability. To tackle this challenge, this contribution proposes a robust observer-based control strategy for mitigating structural loads as well as regulating power production of utility-scale wind turbines. Variation of the rotor effective wind profile, which is responsible for fatigue loading of turbine components, acts as a disturbance to the wind energy conversion system. Additionally, linear models used to design most wind turbine control systems have inherent modeling errors and do not capture nonlinearities caused by changing operating conditions. Although robust controllers address this challenge, they do not incorporate wind disturbance models. A few robust disturbance accommodating controllers have been proposed before to mitigate modeling errors and nonlinearities due to wind disturbances. However, these have been tested on smaller wind turbines. Their performance have also not been benchmarked against the latest baseline controllers. Therefore, this contribution proposes to extend this control strategy to an onshore 5 MW National Renewable Energy Laboratory (NREL) reference wind turbine (RWT) and compares its performance against the recently developed proportional-integral (PI)-based baseline controller from NREL, the reference open-source controller (ROSCO). Based on simulations results for various wind profiles, the proposed control scheme improves tower load mitigation and generator speed regulation performance.**

I. INTRODUCTION

In the past few decades wind energy has grown to become mainstream renewable energy resource, and will play an important role in the transition to a net-zero energy system [1]. This has been supported by sustained improvements in wind turbine design and control technologies [2]. To capture as much wind energy, wind turbines have grown in size, with its rotors and towers getting larger, highly flexible, and heavier. Due to the stochastic nature of wind flow, this has led to increased structural loading of these components. This can potentially cause early fatigue failures, reducing reliability and increasing operation and maintenance (O&M) costs of wind turbines.

Advanced wind turbine control schemes have been developed to meet different objectives including power maximization, speed/power regulation, and structural load reduction. For the above-rated operation, multi-objective advanced control schemes are required for regulating generator speed and reducing loads especially in rotor blades and tower. Although these controllers are typically designed for specific operating points, they are affected by modeling errors and nonlinearities resulting from wind disturbances. These multi-objective control requirements can be met by robust controllers. In [3] a robust H_∞ controller is proposed for regulating generator speed and reducing tower and drive-train loads in above-rated power production. In [4], [5] robust H_∞ controllers designed via μ-synthesis based on *D*-*K*-iteration algorithm are used for regulating rotational speed and power output of a wind turbine. Although in [3], [4], [5], the proposed controllers are robust against model uncertainties, they do not incorporate models for wind disturbance rejection. In [6], [7], disturbance accommodating controllers (s) are designed for reducing blade loads and regulating rotor speed. However, these DAC controllers are not robust. In [8], [9], observer-based controllers, which are robust against modeling errors and nonlinearities, are proposed to regulate rotor speed and mitigate tower loads of the 1.5 MW WindPACT reference wind turbine (RWT)

This contribution extends the robust disturbance accommodating controller (RDAC) first proposed in [9] by designing a robust observer-based controller applied to the 5 MW national renewable energy laboratory (NREL) RWT for tower load mitigation and generator speed regulation. The proposed control scheme is robust against modeling errors and wind disturbances. Unlike previous work [9], the proposed controller is applied to a larger RWT. It is benchmarked against the latest baseline proportional integral PI controller [10] for the 5 MW NREL RWT, both reflecting the current state-of-the-art in the wind industry. Compared with the baseline controller, the proposed control strategy provides significant load mitigation performance without compromise on generator speed regulation, while being robust against modeling errors and system nonlinearities.

This paper is organized as follows. In section II, the wind turbine model used in this work as well as the baseline reference open-source controller (ROSCO) [10], used to evaluate the performance of the proposed control strategy are described. In section III, the robust disturbance accommodat-

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ing control design and implementation is outlined. In section IV, results obtained from closed loop dynamic simulation of the NREL 5MW reference wind turbine are presented and discussed. Finally, conclusions are drawn in section V.

II. WIND TURBINE MODEL AND BASELINE CONTROLLER SPECIFICATION

An overview of the 5 MW NREL RWT model used for controller design and performance evaluation of the proposed control scheme is given. The ROSCO baseline controller is briefly described.

A. Wind turbine model specifications

Reference wind turbines have been used in the recent past to study state-of-the-art technologies for enhancing performance of future wind turbines [11]. The multi-physics, high fidelity open-source fatigue, aerodynamics, structures, and turbulence (OpenFAST) software [12], designed for simulating coupled dynamic response of onshore and offshore wind turbines is used in this work. OpenFAST is build on a previous release of FAST.

The onshore NREL 5 MW RWT [13], which domicile in OpenFAST is chosen for designing and evaluating performance of the proposed control scheme. Specifications of the 3-bladed, upwind RWT are summarized in Table I. To describe the tower, blades, drive-train, gearbox, and nacelle motions, the land-based full-order 5 MW wind turbine model has 16 degrees of freedom (DoFs). However, to obtain a linear model for control design, selected DOFs are enabled before linearization process.

TABLE I

5 MW NREL REFERENCE WIND TURBINE SPECIFICATIONS

Parameter	**Value**	**Unit**
Rated power	5	MW
Hub height	90	m
Cut-in, Rated, Cut-out wind speed	3, 11.4, 25	m/s
Cut-in, Rated rotor speed	6.9, 12.1	rpm
Gearbox ratio	97	-
Rotor, Hub radius	63, 1.5	m
Blade pitch range	0-90	^{o}
Blade pitch rate	8	^{o}/sec
Optimum pitch angle (β_{opt})	0	^{o}
Optimum Tip-Speed Ratio (λ_{opt})	7.55	-
Maximum power coefficient ($C_{p_{max}}$)	0.482	-

The generalized equation of motion used to describe the nonlinear behavior of the wind turbine system modeled in OpenFAST is expressed as

$$M(q,u,t)\ddot{q} + f(q,\dot{q},u,u_d,t) = 0, \qquad (1)$$

where M denotes the mass matrix, f a nonlinear forcing function vector of the enabled DoFs q and their first derivatives $\dot{q}$, as well as the vectors of control input u and wind disturbance input u_d, and t denotes time.

To obtain a reduced order model used for control design the nonlinear model (1) is linearized about a stead-state operating point (OP) in above-rated operation defined by a constant wind speed, blade pitch angle, and rotor speed. Linearization is then carried out numerically in OpenFAST after a steady-state condition is achieved, by linearizing the input-output coupling relations between modules in the OpenFAST glue-code about the specified OP. All the linearized matrices are combined to form a full-system linear state-space model [14].

B. Baseline controller description

With the evolution of RWTs over the past few decades, a growing need for RWT controllers to meet the changing needs is observed. The ROSCO controller [10] is a modularized RWT controller that can be adapted to work with a range of RWTs including the 5 MW NREL and International Energy Agency (IEA) 15 MW RWTs. It performs comparably with existing reference controllers including the 5 MW NREL and technical university of Denmark (DTU) 10 MW controllers.

The ROSCO controller has additional control features similar to those found in many industry controllers. These include, tip speed ratio (TSR) tracking generator torque control suitable for highly flexible rotors, minimum pitch saturation for limiting rotor thrusts near-rated wind speeds and power maximization in low wind speeds, and a set-point smoother applied near-rated operation to avoid unwanted blade pitch and generator torque control interactions. A wind speed estimator realizes TSR tracking generator torque control and pitch saturation. The block diagram for ROSCO controller logic is shown in Fig. 1. For brevity the control features implemented for the above-rated operation relevant to this work are briefly described. More details are given in [10].

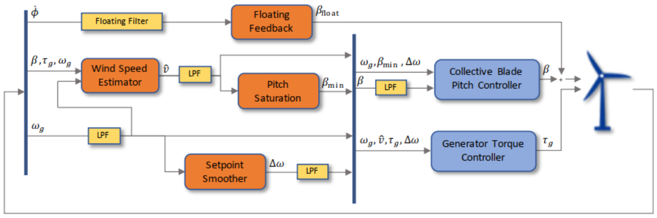

Fig. 1. Block diagram of the general controller logic in ROSCO [10]

In ROSCO, a gain-scheduled PI controller is used in above-rated operation to improve performance of the blade pitch controller. By assuming that the generator speed is constant in the steady-state above-rated operation, hence TSR is only a function of wind speed, the wind speed-dependent optimal pitch angle $\beta_{opt}(v)$ can be defined. Therefore, gains of the PI blade pitch controller are scheduled based on the blade pitch angle obtained from the power coefficient C_p curve of the wind turbine. This is slightly different from the 5 MW NREL reference controller in which the linear relationship between pitch sensitivity and rotor collective pitch angle is used to implement gain-scheduling [13]. Although gain-scheduling greatly improves performance of these reference controllers, they are not robust to changing operating points resulting from wind disturbance.

In the 5 MW NREL reference controller, generator torque is held constant in above-rated operation. However, in ROSCO controller either constant torque (2), with power output directly relating to changes in generator speed or constant power (3), in which slight and consistent changes in output power occurs, is used to actuate the generator torque controller. The set-point smoother shifts the reference generator speed to achieve either constant torque or power expressed as

$$\tau_{g,ar} = \frac{P_{rated}}{\omega_{g,rated}}, \tag{2}$$

$$\tau_{g,ar} = \frac{P_{rated}}{\omega_g(t)}. \tag{3}$$

Here, $\tau_{g,ar}$ denotes the above-rated generator torque, P_{rated} the rated power, and $\omega_{g,rated}$ the rated generator speed.

III. ROBUST DISTURBANCE ACCOMMODATING CONTROLLER

The design of RDAC controller used for tower load mitigation and generator speed regulation of the 5 MW NREL RWT in above-rated operation is outlined. The control strategy was proposed in [9] for control of the 1.5 MW WindPACT RWT.

A. *Observer-based Disturbance Accommodating Control*

A reduced order model used to design the proposed controller is obtained by linearizing the nonlinear wind turbine model (1) in OpenFAST about an operating point in the above-rated wind speed regime, defined by 18 m/s hub-height wind speed, 12.1 rpm rated rotor speed, and related blade pitch angle of 14.6^o. To capture relevant dynamics in the linear model for control design used to achieve desired closed-loop performance related to speed regulation and load reduction, six DoFs are enabled including first tower fore-aft bending mode, first blade flap-wise bending modes, drive-train rotational flexibility, and generator motion. The obtained linear state-space model is expressed as

$$\dot{x} = Ax + Bu + B_d d, \; y = Cx, \tag{4}$$

where $A \in \mathbb{R}^{11x11}$ denotes the system matrix, $B \in \mathbb{R}^{11x1}$ the control input matrix, $B_d \in \mathbb{R}^{11x1}$ the disturbance matrix, $C \in \mathbb{R}^{2x11}$ the output matrix, $u \in \mathbb{R}^{1x1}$ the perturbed collective pitch angle $\Delta\beta$, and $d \in \mathbb{R}^{1x1}$ the perturbed hub-height wind speed Δv. The measurements $y \in \mathbb{R}^{2x1}$ include generator speed ω_g and tower-base fore-aft bending moment ζ. The dynamic states x include the enabled DoF displacements and velocities besides the generator displacement.

Spatio-temporal variations in the rotor effective wind speed influences the power output quality as well as structural loading of wind turbine components. To counteract these effects, an assumed wind disturbance model is augmented to the linear model (4) to design a DAC controller, which estimates the wind disturbance state x_d and cancels its effects through its gain [15]. The assumed linear disturbance waveform model is expressed as

$$d = \theta x_d, \; \dot{x}_d = F x_d, \tag{5}$$

where θ and F denote the disturbance state-space model. Sudden uniform rotor effective wind speed fluctuations used to describe the disturbance can be approximated using a step disturbance waveform with $\theta = 1$ and $F = 0$ [16]. Therefore, the extended linear model becomes

$$\begin{aligned} \underbrace{\begin{bmatrix} \dot{x} \\ \dot{x}_d \end{bmatrix}}_{\dot{x}_a} &= \underbrace{\begin{bmatrix} A & B_d\theta \\ 0 & F \end{bmatrix}}_{A_a} \underbrace{\begin{bmatrix} x \\ x_d \end{bmatrix}}_{x_a} + \underbrace{\begin{bmatrix} B \\ 0 \end{bmatrix}}_{B_a} u, \\ y &= \underbrace{\begin{bmatrix} C & 0 \end{bmatrix}}_{C_a} \begin{bmatrix} x \\ x_d \end{bmatrix}. \end{aligned} \tag{6}$$

Assuming full observability of (6), an extended observer for estimating system and disturbance states is used for full-state feedback control. The observer is expressed as

$$\dot{\hat{x}}_a = (A_a + B_a u - L_a C_a)\hat{x}_a + L_a y, \tag{7}$$

where L_a denotes the observer gain matrix while $u = -K_a \hat{x}_a$ is the control input signal in which the full-state feedback controller K_a is used for disturbance rejection, generator speed regulation, and load mitigation. To avoid steady-state tracking error in generator speed regulation, the observer-based DAC model (7) is extended with a partial integral state $x_i = \int \omega_g dt$. Therefore, the integral action becomes $\dot{x}_i = C_i y$, where C_i denotes the location of generator speed measurement ω_g. The observer-based DAC model with partial integral action becomes

$$\begin{aligned} \underbrace{\begin{bmatrix} \dot{\hat{x}}_a \\ \dot{x}_i \end{bmatrix}}_{\dot{x}_r} &= \underbrace{\begin{bmatrix} A_a - B_a K_a - L_a C_a & -B_a K_i \\ 0 & 0 \end{bmatrix}}_{A_r} \underbrace{\begin{bmatrix} \hat{x}_a \\ x_i \end{bmatrix}}_{x_r} + \underbrace{\begin{bmatrix} L_a \\ C_i \end{bmatrix}}_{B_r} y, \\ u &= \underbrace{-\begin{bmatrix} K_a & K_i \end{bmatrix}}_{C_r} \begin{bmatrix} \hat{x}_a \\ x_i \end{bmatrix}, \end{aligned} \tag{8}$$

where K_i denotes integral gain. Existing approaches for designing DAC including linear quadratic regulator (LQR) and pole placement, calculate the controller gains L_a, K_a, and K_i separately without consideration closed-loop stability, system robustness, and optimality. In this work, a robust control method for designing these gains simultaneously to meet desired robustness and performance requirements is used.

B. *Background on Mixed-Sensitivity H_∞ Control*

The standard H_∞ control problem for designing an optimized controller R^* to minimize the H_∞ norm $\|.\|_\infty$ i.e. the peak gain of the transfer function G_{zd} from the exogenous disturbances d to the controlled outputs z is expressed as

$$R^* = \underset{R \in \mathscr{R}}{argmin} \parallel G_{zd}(P,R) \parallel_\infty, \tag{9}$$

where $\mathscr{R}$ denotes a set of controllers R that stabilize the plant P. However, this can not be applied to control systems with structural constraints like the observer-based DAC model (8) having control design parameters L_a, K_a, and K_i. For such systems, weighting functions W1, W2, and W3 are introduced to the original plant O as shown in Fig. 2 to provide the required trade-off between performance and robustness against uncertainties.

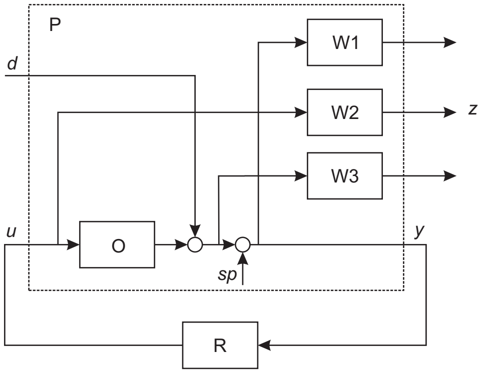

Fig. 2. Mixed sensitivity H∞ control

The mixed-sensitivity H∞ synthesis problem is expressed as

$$R^* = \underset{R \in \mathscr{R}}{argmin} \left\| \begin{matrix} W_1 S \\ W_2 RS \\ W_3 T \end{matrix} \right\|_\infty , \tag{10}$$

where S, RS, and T denote the sensitivity, control sensitivity, and complementary sensitivity functions, respectively. W_1, W_2, and W_3 specify the target closed loop shapes of S, RS, and T. The mixed-sensitivity H∞ approach is used to design of RDAC controller for load mitigation and speed regulation of the 5 MW NREL RWT.

C. Robust Disturbance Accommodating Controller applied to the 5 MW NREL Reference Wind Turbine

The mixed-sensitivity H∞ norm approach (10) is used as a cost function for optimizing parameters of the structured DAC control system (8) to obtain an optimal RDAC controller $RDAC^*(L,K)$ defining the optimal gains $K = [K_a \; K_i]$ and $L = [L_a \; C_i]^T$. The control problem is formulated as

$$RDAC^* = \underset{RDAC \in \mathscr{RDAC}}{argmin} \; \| G_{zd}(P, RDAC) \|_\infty , \tag{11}$$

where $\mathscr{RDAC}$ denotes a set of controllers $RDAC$ that stabilize the generalized plant P. To guarantee closed-loop asymptotic stability, the optimization problem (11) is subjected to the Lyapunov stability constraint $\| C_r(sI - \mathscr{A}(RDAC))^{-1} B_r \|_\infty < +\infty$, where $\mathscr{A}(RDAC)$ denotes the closed-loop system matrix A_r.

Since (11) is non-convex, it can not be solved using algebraic Riccati equations (AREs). Therefore, non-smooth H∞ synthesis [17], [18], used for tuning structured controllers subject to stability constraints is used to find an optimal controller $RDAC^*$. The H∞ norms are calculated from the closed-loop system using a bisection algorithm

The proposed RDAC controller, is applied to the 5 MW NREL RWT as shown in Fig. 3. The wind disturbance d excites the wind turbine dynamics in above-rated operation. The controller relies on measured outputs including generator speed ω_g and tower fore-aft bending moment ζ, to generate a collective pitch angle u used for regulating ω_g at the rated value $\omega_{g,rated}$ and damping the first tower fore-aft vibration mode.

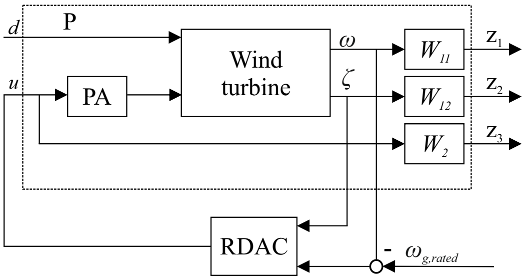

Fig. 3. RDAC applied to the 5 MW NREL reference wind turbine

The weighting functions W_{11}, W_{12}, and W_2 are designed as transfer functions to achieve the desired performance related to the closed-loop frequency response. To shape the desired profile of generator speed response and ensure robustness against wind disturbances, W_{11} is designed as an inverted high-pass filter. To reduce tower fore-aft oscillation in the first mode $Tfa_1 = 2.06$ rad/s, W_{12} is designed as an inverted notch filter centred at this frequency. Finally, W_2 is designed as an inverted low-pass filter to reduce controller activity in high frequencies thereby increasing robustness. Figure 4 shows a Bode diagram of the open-loop transfer functions from wind speed to measurement outputs and the related weighting functions. As illustrated, $1/W_{11}$ and $1/W_{12}$ shape the respective open-loop responses to achieve desired closed-loop frequency response.

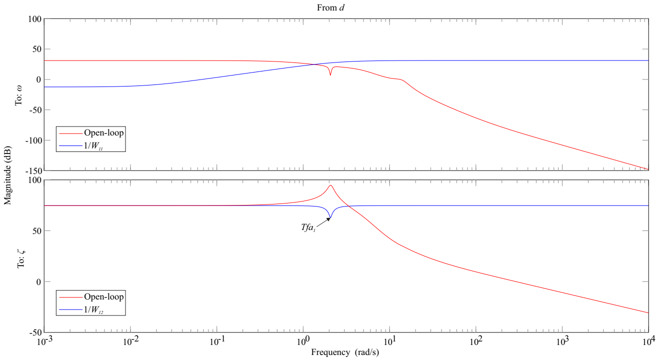

Fig. 4. Bode plot of open-loop response and weighting functions for RDAC control design

To account for the slow pitch actuator dynamics relative to other turbine dynamics, the wind turbine model is supplemented with a pitch actuator PA modeled as a second order transfer function from the commanded pitch signal β_{com} to the actual pitch angle β expressed as

$$\beta = \frac{\omega_{PA}^2}{s^2 + 2\zeta \omega_{PA} s + \omega_{PA}^2} \beta_{com}, \tag{12}$$

where the natural frequency ω_{PA} is taken to be five times the turbine's rated rotor speed $\omega_r = 1.267$ rad/s, and damping ratio ζ is 80% critical as recommended by NREL [19]. In [9], [20], [21], the actuator dynamics is modeled as a first-order lag filter simulating the time delay between β_{com} and β.

In this contribution, a second order system is considered to improve response to transients resulting from a stochastically varying wind field.

The generalized state-space system made up of the generalized plant P shown in Fig. 3 interconnected with the observer-based system (8) is implemented using lower linear fraction transformation (LFT). Plant P contains fixed elements of the control architecture including the wind turbine model, weighting functions, and pitch actuator. The observer-based system carries the tunable elements K_a, K_i, and L_a. Using non-smooth H_∞ optimization, which minimizes the maximum singular value of the closed-loop transfer function from d to controlled outputs $[z_1 \; z_2 \; z_3]^T$, the RDAC controller is obtained. This controller is robust against modeling errors and disturbances and is used to regulate generator speed and reduce the amplitude of the first tower fore-aft vibration mode of the NREL 5 MW RWT using a CPC signal u. A detailed explanation on RDAC control design is given in [9].

IV. RESULTS AND DISCUSSION

The results obtained from simulation of 5 MW NREL RWT with ROSCO and RDAC controllers are discussed. Stochastic and step wind profiles are used to excite the wind turbine dynamics in above-rated operation.

A. *Step wind profile results*

The step wind profile shown in Fig. 5 is used to evaluate control performance outside its design operating point. Hub-height wind speed varies in steps from 14-22 m/s, which covers the wind turbine's above-rated operation. To evaluate performance of the proposed RDAC controller in tower load mitigation, tower fore-aft bending moment is measured. As shown in Fig. 6, RDAC controller realizes significant reduction in tower fore-aft bending moment compared with the baseline ROSCO controller. This is attributed to reduction of wind effect on the first tower fore-aft mode. To ascertain that this improvement does not compromise speed regulation performance, generator speed is evaluated. The proposed RDAC controller provides better performance expressed by improved transient response in changing wind speeds shown in Fig. 7.

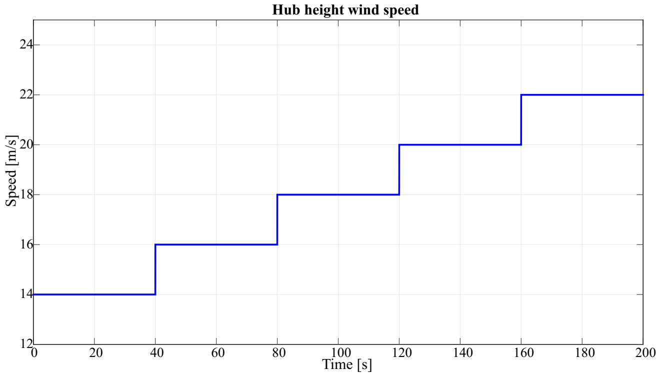

Fig. 5. Step wind profile

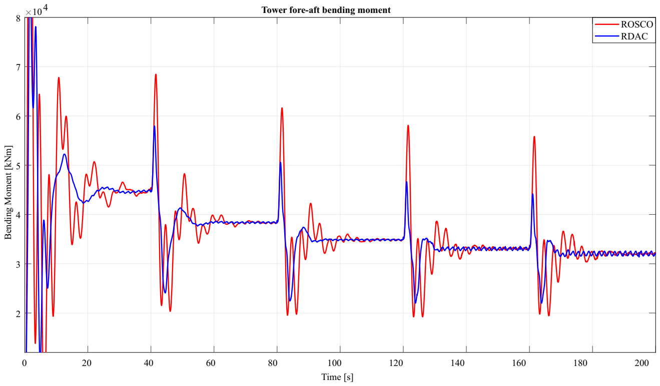

Fig. 6. Tower load mitigation response to step wind profile

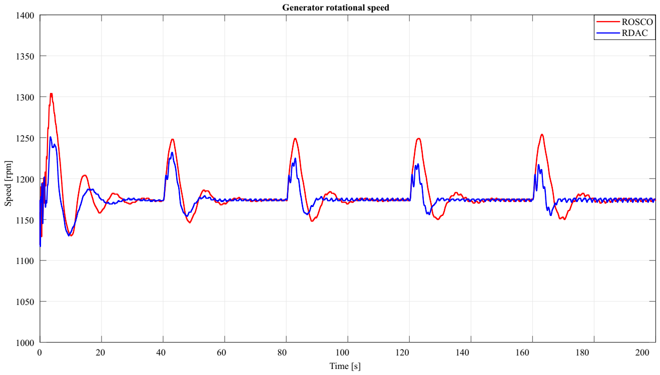

Fig. 7. Generator speed regulation response to step wind profile

B. *Stochastic wind profile results*

To evaluate the disturbance rejection performance of RDAC controller under more realistic wind conditions, a stochastic wind profile shown in Fig. 8 is used. The full-field IEC von Karman type B wind profile has a turbulence intensity of 14.9 % and a mean hub-height speed of 18 m/s. In this scenario, the proposed controller shows better tower load mitigation response expressed by reduction in tower fore-aft bending moment variation in Fig. 9. The standard deviation is reduced by 34.6 %. Additionally, RDAC controller shows improved generator speed regulation performance compared with ROSCO controller as illustrated in Fig. 10. A 41.7 % reduction in standard deviation is realized. This is attributed to robustness of RDAC controller to wind disturbances. However, this improvement comes with increased pitching activity leading to steady-state speed variations especially in high wind speeds.

V. CONCLUSIONS

In this contribution, a robust disturbance accommodating controller designed for speed regulation and structural load mitigation of the 5 MW NREL onshore reference wind turbine is presented. The RDAC controller designed by minimizing the mixed-sensitivity H_∞ norm of the generalized wind turbine system, is robust to modeling errors and nonlinearities caused by wind disturbances. The proposed controller is applied for the first time to the 5 MW NREL RWT.

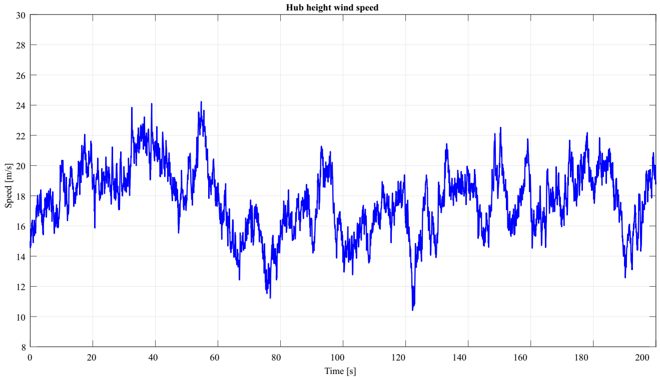

Fig. 8. Stochastic wind profile

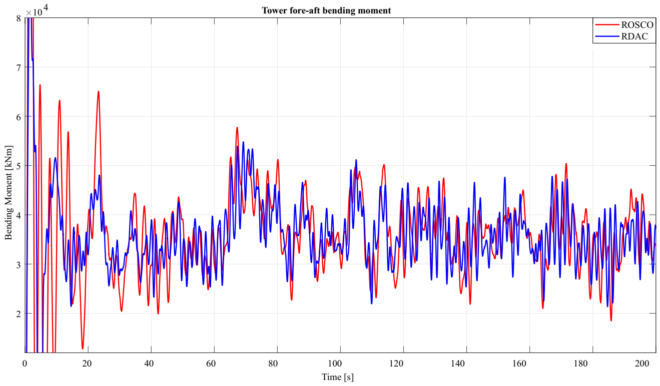

Fig. 9. Tower load mitigation response to stochastic wind profile

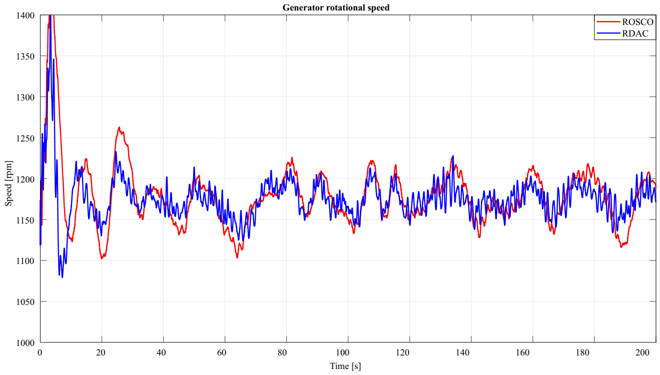

Fig. 10. Generator speed regulation response to stochastic wind profile

Compared with the baseline gain-scheduling PI ROSCO controller, simulation results show that the proposed control strategy reduces the first tower fore-aft vibration amplitude without significant compromise on generator speed regulation performance. This work can be extended by designing RDAC controller based on independent pitch control for additional load mitigation in the rotor blades.

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