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Disturbance Tracking and Blade Load Control of Wind Turbines in Variable-Speed Operation

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DISTURBANCE TRACKING AND BLADE LOAD CONTROL OF WIND TURBINES IN VARIABLE-SPEED OPERATION*

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ABSTRACT

A composite state-space controller was developed for a multi-objective problem in the variable-speed operation of wind turbines. Disturbance Tracking Control theory was applied to the design of a torque controller to optimize energy capture under the influence of persistent wind disturbances. A limitation in the theory for common multi-state models is described, which led to the design of a complementary pitch controller. The goal of the independent blade pitch design was to minimize blade root fatigue loads. Simulation results indicate an 11% reduction in fatigue damage using the proposed controllers, compared to a conventional torque-only design. Meanwhile, energy capture is almost identical, partly because of nonlinear effects.

NOMENCLATURE

ρ	Air density
R	Rotor radius
C_{p0}	Peak rotor power coefficient
λ_0	Tip-speed ratio at C_{p0}
$\psi, \dot{\psi}$	Azimuth angle and rotor speed
β_i	Blade #*i* flap angle
T_g	Generator torque
$\boldsymbol{\theta}$	Full-span blade pitch angles
w	Hub-height wind speed
$\mathbf{x}$	Linear plant states
$\mathbf{u}$	Linear plant control inputs
$\mathbf{u_d}$	Linear plant disturbance input(s)
$\mathbf{y}$	Linear plant outputs
q_{op}	The value of q at the operating point
Δq	Perturbation of q about the operating point
s	Laplace operator

Bold denotes vector or matrix quantities

INTRODUCTION

Variable-speed wind turbine operation is an attractive configuration for large machines because it can increase energy capture over a wide range of wind speeds and reduce drive-train fatigue. Rotor speed must be regulated either to achieve maximum aerodynamic efficiency (often referred to as region 2) or to ensure mechanical limitations are not exceeded in above rated winds (region 3). (Region 1 is defined as startup, when there is insufficient wind to produce electrical power.) In region 2, the maximum power output occurs at a particular blade pitch angle and tip-speed ratio (tip speed divided by wind speed). Generally, power electronics are used to command generator torque to change the rotor speed as the wind speed fluctuates, thus tracking peak power. Using generator torque to influence the blade bending loads, however, is not practical because cyclic torque would be transmitted through the drive-train, which would compromise one of the main benefits of variable-speed operation. Also, only symmetric loads would be influenced. A more direct and effective method is individual blade pitch. The control design in this paper employs individual pitch and generator torque actuation simultaneously to meet both performance objectives: to maximize power and to mitigate cyclic blade loads in region 2.

State-space control uses a linearized turbine model to design feedback gains and estimate unmeasured states, such as tower and blade deflections or velocities. It is the ideal approach for this study because multivariable control designs are facilitated. Multiple actuators work in unison to meet multiple performance objectives. State-space control in region 2 has been investigated by Balas et al. [1] and Allen et al. [2] using a single-state turbine model. Disturbance Tracking Control (DTC) theory was developed for this purpose. Details of this approach are described later in this paper, but essentially it is used to control rotor speed via wind speed estimation tracking to maintain a constant tip-speed ratio. The present work investigates the application of DTC to multi-state turbine systems.

TURBINE MODEL

The turbine chosen for modeling is an operational test bed at the National Renewable Energy Laboratory, called the Controls Advanced Research Turbine (CART). It is a 600 kW upwind machine with a fixed tilt of 4°. The two-bladed, teetered rotor has a radius of R=21.3 m and zero precone. Control inputs include generator torque and individual blade pitch. A yaw drive is also present, but its response time is too slow to control transient behavior. From early performance models of the CART, the peak power coefficient, C_{p0}, occurs at a pitch angle of -1° and tip-speed ratio of approximately λ_0=7.5.

The nonlinear simulation plant in this study is a SymDyn [3] model of the CART, running in MATLAB® with Simulink® [4]. The structure has three degrees-of-freedom: rotor azimuth angle and flap angle for each blade $\{\psi, \beta_1, \beta_2\}$ (Figure 1). The blade pitch angles are not degrees-of-freedom, but they do rotate the blade flap hinges.

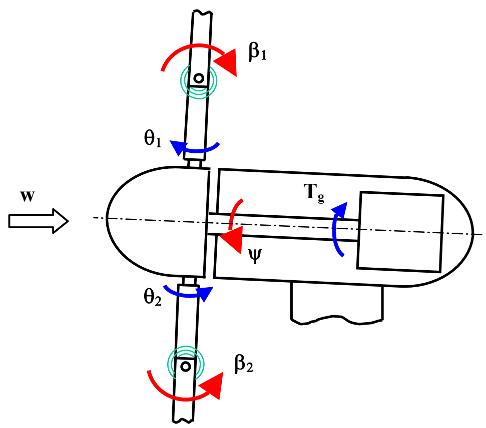

Figure 1: CART model degrees-of-freedom and control inputs.

The linear control model is given by

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\,\mathbf{u} + \mathbf{B_d}\,\mathbf{u_d} \\ \mathbf{y} = \mathbf{C}\mathbf{x} \end{cases} \tag{1}$$

where $\mathbf{x} = \begin{bmatrix}\Delta\psi & \Delta\beta_1 & \Delta\beta_2 & \Delta\dot{\psi} & \Delta\dot{\beta}_1 & \Delta\dot{\beta}_2\end{bmatrix}^T$,

$\mathbf{u} = \begin{bmatrix}\Delta T_g & \Delta\boldsymbol{\theta}^T\end{bmatrix}^T$, and

$\mathbf{u_d} = \Delta w$.

Linearization is performed about a steady-state solution of the nonlinear system. The chosen operating conditions in region 2 are:

w_{op} = 8 m/s (with vertical shear exponent 0.2)
T_{g_op} = 49 581 kNm
θ_{op} = [-1° -1°]^T
mean($\dot{\psi}_{op}(t)$) = 27 rpm

Nacelle tilt and vertical wind shear cause the linearization point to be periodic in time with period of 2.2 seconds. The state matrices (**A**, **B**, $\mathbf{B_d}$) are also periodic and would require periodic state-space feedback to guarantee stability. To simplify the controller in this study, time-invariant state matrices are calculated by averaging.

DISTURBANCE TRACKING CONTROL THEORY

This section briefly describes the theory of DTC as published in [1] and describes a limitation of its application to multi-state systems.

The persistent disturbance input $\mathbf{u_d}$ in (1) is produced by the following Disturbance Waveform Generator:

$$\begin{cases} \dot{\mathbf{z}}_\mathbf{d} = \mathbf{F}\,\dot{\mathbf{z}}_\mathbf{d} \\ \mathbf{u_d} = \Theta\,\dot{\mathbf{z}}_\mathbf{d} \end{cases} \tag{2}$$

where F and Θ are assumed to be known matrices.

Theorem: If

(a) (**A**, **B**) *controllable*

(b) ($\overline{\mathbf{A}} \equiv \begin{bmatrix} \mathbf{A} & \mathbf{B_d}\boldsymbol{\Theta} \\ \mathbf{0} & \mathbf{F} \end{bmatrix}$, $\overline{\mathbf{C}} \equiv \begin{bmatrix}\mathbf{C} & \mathbf{0}\end{bmatrix}$) *observable* (3)

(c) $\begin{cases} \mathbf{Q\Theta} = \mathbf{CL} \\ (\mathbf{A}+\mathbf{BG_x})\mathbf{L} - \mathbf{LF} + \mathbf{BG_T} + \mathbf{B_d}\Theta \end{cases}$

then $\mathbf{e_y}(t) \equiv \mathbf{y}(t) - \mathbf{Qu_d}(t) \xrightarrow[t\to\infty]{} \mathbf{0}$, *i.e., disturbance tracking occurs, with the following realizable DTC:*

$$\begin{aligned} &\mathbf{u} = \mathbf{G_x}\hat{\mathbf{x}} + \mathbf{G_T}\hat{\mathbf{u}}_\mathbf{d} \\ &\begin{cases} \dot{\hat{\mathbf{x}}} = \mathbf{A}\hat{\mathbf{x}} + \mathbf{Bu} + \mathbf{B_d}\hat{\mathbf{u}}_\mathbf{d} + \mathbf{K_x}(\mathbf{y} - \hat{\mathbf{y}}) \\ \hat{\mathbf{y}} = \mathbf{C}\hat{\mathbf{x}} \end{cases} \\ &\begin{cases} \dot{\hat{\mathbf{z}}}_\mathbf{d} = \mathbf{F}\,\hat{\mathbf{z}}_\mathbf{d} + \mathbf{K_d}(\mathbf{y} - \hat{\mathbf{y}}) \\ \hat{\mathbf{u}}_\mathbf{d} = \Theta\,\hat{\mathbf{z}}_\mathbf{d} \end{cases} \end{aligned} \tag{4}$$

where $\overline{\mathbf{K}} = \begin{bmatrix}\mathbf{K_x} \\ \mathbf{K_d}\end{bmatrix}$ *is chosen so that* $\overline{\mathbf{A}} - \overline{\mathbf{K}}\,\overline{\mathbf{C}}$ *has acceptable transient behavior.*

There is a limitation with DTC when the linear plant matrices have the form:

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{A}_{21} & \mathbf{A}_{22} \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ \mathbf{B}_2 \end{bmatrix}, \quad \mathbf{B_d} = \begin{bmatrix} \mathbf{0} \\ \mathbf{B}_{\mathbf{d}2} \end{bmatrix}, \quad \mathbf{x} = \begin{bmatrix} \mathbf{q} \\ \dot{\mathbf{q}} \end{bmatrix}, \tag{5}$$

which always occurs on transformation of a second order ordinary differential equation with physical coordinates $\mathbf{q}$. (In the SymDyn model, $\mathbf{q} = [\Delta\psi \quad \Delta\beta_1 \quad \Delta\beta_2]^T$.) If the desired disturbance tracking involves elements of $\dot{\mathbf{q}}$ (such as $\Delta\dot{\psi}$), DTC fails.

To prove this statement, assume that $\mathbf{C} = \mathbf{I}$, the identity matrix, and $\mathbf{Q} = \begin{bmatrix} \mathbf{0} \\ \mathbf{Q}_2 \end{bmatrix}$, so that

$$\mathbf{e_y} = \begin{bmatrix} \mathbf{q} \\ \dot{\mathbf{q}} - \mathbf{Q}_2\mathbf{u_d} \end{bmatrix}. \tag{6}$$

From (3c),

$$\mathbf{Q\Theta} = \mathbf{CL} \iff \mathbf{L} = \begin{bmatrix} \mathbf{0} \\ \mathbf{Q}_2\mathbf{\Theta} \end{bmatrix} \tag{7}$$

Let $\mathbf{e_T} = \mathbf{x} - \mathbf{Lz_d}$. The closed-loop dynamics of $\mathbf{e_y}$ are governed by:

$$\begin{cases} \dot{\mathbf{e}}_\mathbf{T} = (\mathbf{A} + \mathbf{BG_x})\mathbf{e_T} + ((\mathbf{A} + \mathbf{BG_x})\mathbf{L} - \mathbf{LF} + \mathbf{BG_T} + \mathbf{B_d\Theta})\mathbf{z_d} \\ \mathbf{e_y} = \mathbf{Ce_T} \end{cases} \tag{8}$$

The corresponding transfer matrix in the Laplace domain is

$$\frac{\mathbf{E_y}(s)}{\mathbf{Z_d}(s)} = \mathbf{C}(s\mathbf{I} - (\mathbf{A} + \mathbf{BG_x}))^{-1} \cdot ((\mathbf{A} + \mathbf{BG_x})\mathbf{L} - \mathbf{LF} + \mathbf{BG_T} + \mathbf{B_d\Theta}) \tag{9}$$

The steady-state value of $\mathbf{e_y}$ to a step input $\mathbf{z_d}$ is found from the final value theorem:

$$\lim_{t \to \infty} \mathbf{e_y}(t) = \lim_{s \to \infty} \mathbf{E_y}(s)$$

$$= -\mathbf{C}(\mathbf{A} + \mathbf{BG_x})^{-1}((\mathbf{A} + \mathbf{BG_x})\mathbf{L} - \mathbf{LF} + \mathbf{BG_T} + \mathbf{B_d\Theta})$$

Given (5), (6) and $\mathbf{G_x} = [\mathbf{G_{x1}}\ \mathbf{G_{x2}}]$,

$$\lim_{t \to \infty} \mathbf{e_y}(t) = -\begin{bmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{A_{21}} + \mathbf{B_2G_{x1}} & \mathbf{A_{22}} + \mathbf{B_2G_{x2}} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \mathbf{Q_2\Theta} \\ (\mathbf{A_{22}} + \mathbf{B_2G_{x2}})\mathbf{Q_2\Theta} - \mathbf{Q_2\Theta F} + \mathbf{B_2G_T} + \mathbf{B_{d2}\Theta} \end{bmatrix}$$

$$= \begin{bmatrix} (\mathbf{A_{21}} + \mathbf{B_2G_{x1}})^{-1}(-\mathbf{Q_2\Theta F} + \mathbf{B_2G_T} + \mathbf{B_{d2}\Theta}) \\ -\mathbf{Q_2\Theta} \end{bmatrix} \tag{10}$$

which does not equal zero. In fact, from (6) and (10), $\dot{\mathbf{q}} \xrightarrow[t\to\infty]{} \mathbf{0}$, instead of the desired value, $\mathbf{Q_2u_d}$.

The proof assumed that $\mathbf{C} = \mathbf{I}$, but the result is true for all other output matrices that extract an element of $\dot{\mathbf{q}}$ for tracking. If $\mathbf{Q}$ were full, i.e. $\mathbf{Q} = [\mathbf{Q_1}^T\ \mathbf{Q_2}^T]^T$, the lower half of (10) would be equal to $-(\mathbf{Q_2\Theta} + \mathbf{Q_1\Theta F})$. For the common disturbance waveforms attempted, this expression cannot be solved to zero.

Balas et al. [1] and Allen et al. [2] have illustrated acceptable performance of DTC when applied to single-state plant models. This was possible because in their cases, $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{B_d}$ were nonzero scalars. Owing to the DTC limitation just proven, a similar single-state approach is taken in the following control design.

CONTROL DESIGN

A composite torque plus pitch controller is developed in two steps. First, a torque controller is designed following DTC theory with a single-state representation of the linear plant. Its single objective is to track tip-speed ratio. Next, an individual blade pitch controller is designed, given the dynamics of the turbine plus torque controller, with the objective of reducing cyclic blade root bending moments.

The control input from (1) is first partitioned:

$$\mathbf{Bu} = [\mathbf{B_1} \quad \mathbf{B_2}]\begin{bmatrix} u_1 \\ \mathbf{u_2} \end{bmatrix} \tag{11}$$

where $u_1 = \Delta T_g$ and $\mathbf{u_2} = \Delta\boldsymbol{\theta}$. The rotor speed dynamics are extracted using $\Delta\dot{\psi} = \mathbf{Tx}$:

$$\Delta\ddot{\psi} = a\,\Delta\dot{\psi} + bu_1 + \mathbf{b_d u_d} \tag{12}$$

where $\mathbf{T}$ is a Boolean vector, $a = \mathbf{TAT}^T$, $b = \mathbf{T}B_1$, and $b_d = \mathbf{TB_d}$. The pitch input is ignored (discussed later). The single state DTC torque control law is

$$u_1 = G_1\,\Delta\dot{\psi} + \mathbf{G_T z_d} \tag{13}$$

with G_1 designed for desirable transient behavior of $a+bG_1$ and $\mathbf{G_T}$ calculated by the matching conditions (3c). Controllability of (a, b) is not an issue, since under these conditions $b\neq0$. From (1), (11) and (13), the intermediate closed-loop yields:

$$\dot{\mathbf{x}} = (\mathbf{A} + \mathbf{B_1}G_1\mathbf{T})\mathbf{x} + \mathbf{B_2 u} + (\mathbf{B_1G_T} + \mathbf{B_d\Theta})\mathbf{z_d} \tag{14}$$

Ignoring the disturbance term, the pitch control law

$$\mathbf{u_2} = \mathbf{G_2}\,\mathbf{x}$$

can provide the desired state regulation, given ($\mathbf{A}+\mathbf{B_1}G_1\mathbf{T}$, $\mathbf{B_2}$) controllable. Of particular interest is the regulation of the blade flap rate states ($\Delta\dot{\beta}_1, \Delta\dot{\beta}_2$), as this can minimize cyclic blade bending loads [3].

Success of the composite controller lies in the assumption that pitch commands are small in magnitude. Large pitch excursions would not only reduce the aerodynamic power, by decreasing the power coefficient, but also compromise the performance of the torque controller, which is designed assuming constant pitch. Therefore, the pitch controller must not be designed with weighting on the rotor speed state. If this were to happen, the torque and pitch controllers would essentially battle each other to meet different speed objectives.

A realizable controller is completed with the addition of an augmented state estimator, as described in (3) and (4). The implemented estimator form is

$$\begin{cases} \begin{bmatrix} \dot{\hat{\mathbf{x}}} \\ \dot{\hat{\mathbf{z}}}_\mathbf{d} \end{bmatrix} = (\overline{\mathbf{A}} + \overline{\mathbf{B}}\,\overline{\mathbf{G}} - \overline{\mathbf{K}}\,\overline{\mathbf{C}}) \begin{bmatrix} \hat{\mathbf{x}} \\ \hat{\mathbf{z}}_\mathbf{d} \end{bmatrix} + \overline{\mathbf{K}}\mathbf{y} \\ \mathbf{u} = \overline{\mathbf{G}} \begin{bmatrix} \hat{\mathbf{x}} \\ \hat{\mathbf{z}}_\mathbf{d} \end{bmatrix} \end{cases}$$

where $\overline{\mathbf{G}} = \begin{bmatrix} G_1 & \mathbf{G_T} \\ \mathbf{G_2} & \mathbf{0} \end{bmatrix}$.

The complete simulation block diagram is illustrated in Figure 2. The Nonlinear Plant block contains calls to SymDyn and AeroDyn for integration in time. The set point, subtracted from the position and velocity signals, is the mean of the periodic operating point.

For this study, all states are assumed measurable, i.e. $\mathbf{y} = \mathbf{x}$. Also, the disturbance waveform is assumed to be a step function, which gives F = 0, Θ = 1, and Q = $\dot{\psi}_{op} / w_{op}$ for tip-speed-ratio tracking. The torque control gain, G_1, is designed by closed-loop pole placement at s = -0.085 rad/s (originally at s = -0.023 rad/s). The pitch control gain, $\mathbf{G_2}$, and the estimator gain, $\overline{\mathbf{K}}$, are designed using LQR techniques [5]. With this method, particular states can be weighted for regulation and estimation performance. To tune the LQR weightings, short simulations were performed using a turbulent wind input with constant vertical shear exponent. The following design constraints were considered:

- Non-negative generator torques
- Maximum pitch rates less than 18 °/s
- High total energy output
- Low fatigue damage equivalent loads for flapwise blade bending.

RESULTS

A 10-minute simulation is performed using a full-field turbulent wind input. The mean hub-height wind speed is 8 m/s with a turbulence intensity of 19.5%, via the von Karman turbulence model [6]. The trace of hub-height wind speed is shown in Figure 3 (dark line). Dynamic stall and generalized dynamic wake effects are included in the aerodynamics.

The DTC with pitch design is compared to a conventional torque controller for variable-speed [7]. It has the form:

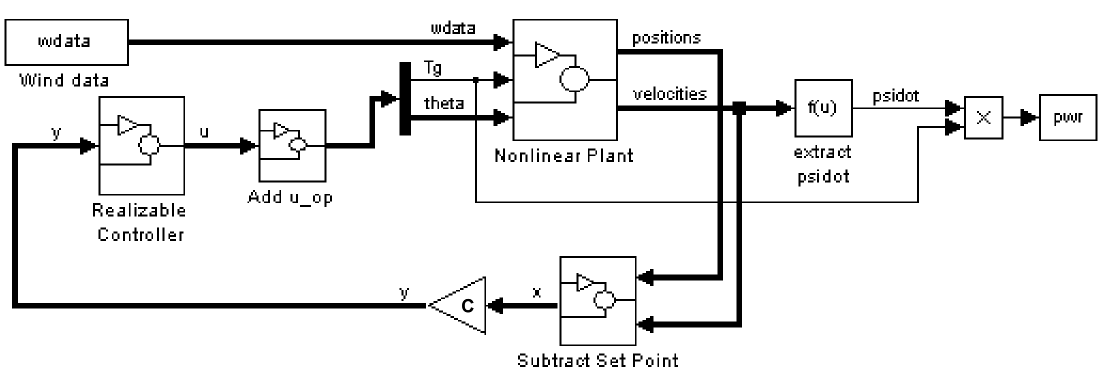

Figure 2: Simulink block diagram for the closed-loop system.

$$T_g = k\,\dot{\psi}^2$$

where $k = \dfrac{\rho\pi R^5 C_{p0}}{2\lambda_0^3} =$ 6389 for the CART model. Pitch is held constant at -1°.

A summary of results is given in Table 1. Damage equivalent load is calculated using the blade moment at the flap hinge, rainflow counting [8], and a reference frequency of 1.0 Hz. The blade edge load response is not considered.

	Conventional Controller	DTC with Pitch
Mean Power [kW]	168	167
Damage Equiv. Load [kNm]	98.7	87.7
Max. Pitch Rate [°/s]	0	11.1

Table 1: Results from the controller comparison

Although DTC is designed for optimal energy capture, the mean power from the simulation is almost identical to that from the conventional controller. Increasing the feedback gains does little to improve the performance and only produces higher frequency torque commands, which would reduce the life of the drive-train. Figure 4 illustrates the higher frequency torque commands using the present gains, compared to the conventional controller response.

Nonlinearity effects play a role in the power capture performance of DTC. The controller is designed at a single operating point, but is expected to operate over a range of conditions, where the linear assumption fails to hold. Deterioration of performance can be seen in the wind speed estimator plot, Figure 3(light line), at speeds furthest away from w_{op} = 8 m/s. The result is unsuitable high and low torque commands. Common gain-scheduling techniques could be employed to minimize the effects of this problem. One favorable observation seen in Figure 3 is that the general trend of mean wind speed is being estimated well.

The pitch controller reduces damage equivalent loads very well. Table 1 suggests that an 11% reduction is possible. Figure 5 illustrates the load response from blade #1 over a typical 20-second interval of the simulation. Clearly, the conventional controller produces higher amplitude cyclic loads. The phase differences that are evident in the figure are a result of speed (and therefore, azimuth) differences between the simulations of each controller. Consequently, the same wind event has a different effect in each case.

The plot of blade pitch angles in Figure 6 illustrates the action of each independent blade over a 10-second interval. The times when the blades appear to pitch in phase would correspond to a gust event acting over the entire rotor, e.g. at 215 seconds. Note that the magnitude of the pitch adjustments is small and that the pitch angles remain close to the desired mean of -1° (±0.9°). This means that the pitch controller has little effect on energy capture and does not interfere with the torque controller – a desirable situation. The maximum pitch rate of 11°/s is within the performance envelope of the CART pitch actuators.

CONCLUSIONS

Disturbance Tracking Control theory fails to apply to multi-state systems of a particular form; a form that is common in structural dynamic problems. The simplest work-around is to apply the theory to single-state systems only. In wind turbines, where the objective is constant tip-speed ratio in region 2, the state must be rotor speed and one of the persistent disturbances must be wind speed.

A composite controller is designed for region 2 operations using the limited DTC theory for a torque control element and state feedback for individual blade pitch. Successful operation is illustrated on a turbine model with three degrees-of-freedom (six states). The most important design consideration is that the pitch controller should not attempt to regulate rotor speed, or energy capture will be reduced and undesirable interaction with the torque controller may result.

Simulation results using full-field turbulent wind indicates that DTC with individual pitch control can reduce fatigue damage equivalent loads in the blades by 11%. Meanwhile, mean power output is comparable to that from a conventional variable-speed torque controller. As expected, performance is best when operating within in the vicinity of the operating point, used in the design of the linear model. At high and low wind speeds, disturbance estimation is degraded by nonlinearities in aerodynamics.

Future research will focus on the following areas:

- Gain scheduling of DTC over the operating range of wind speeds. Disturbance estimation and torque controller performance is likely to improve using this technique. It is unclear whether energy capture will significantly increase.
- Conventional torque control augmented by state-space pitch control. This approach would marry the clean torque command benefits of a conventional

torque controller with the fatigue reduction capabilities of individual blade pitch.

- Alternative torque control. It would be advantageous to utilize generator torque to control states other than just rotor speed, e.g., drive-train compliance or resonance. This approach would require that we develop an entirely different strategy.
- Testing on a fully flexible turbine model. Here one could investigate the influences of unmodeled flexibilities on performance. Most likely, additional degrees-of-freedom would need to be included in the control model to avoid undesirable resonance, particularly in the tower and drive-train.

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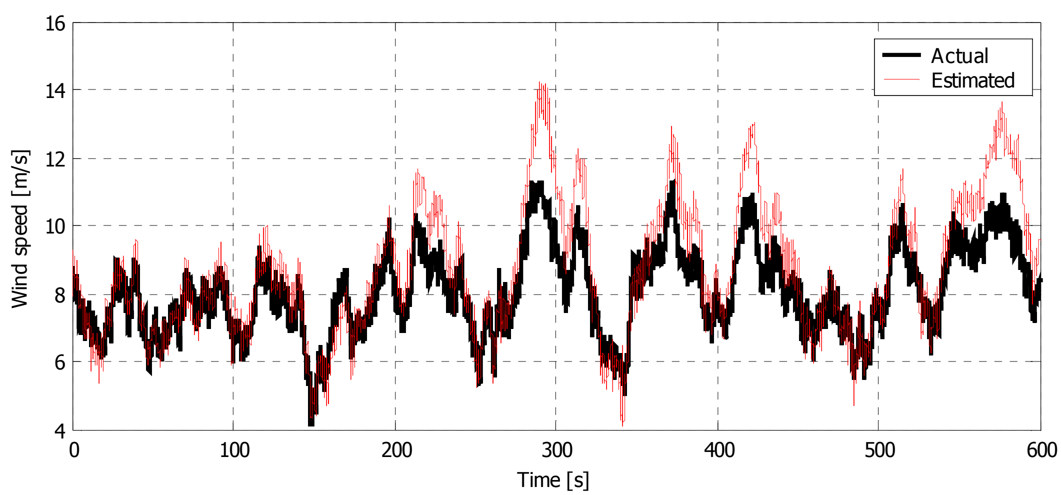

Figure 3: Hub-height wind speed for the 10-minute simulation.

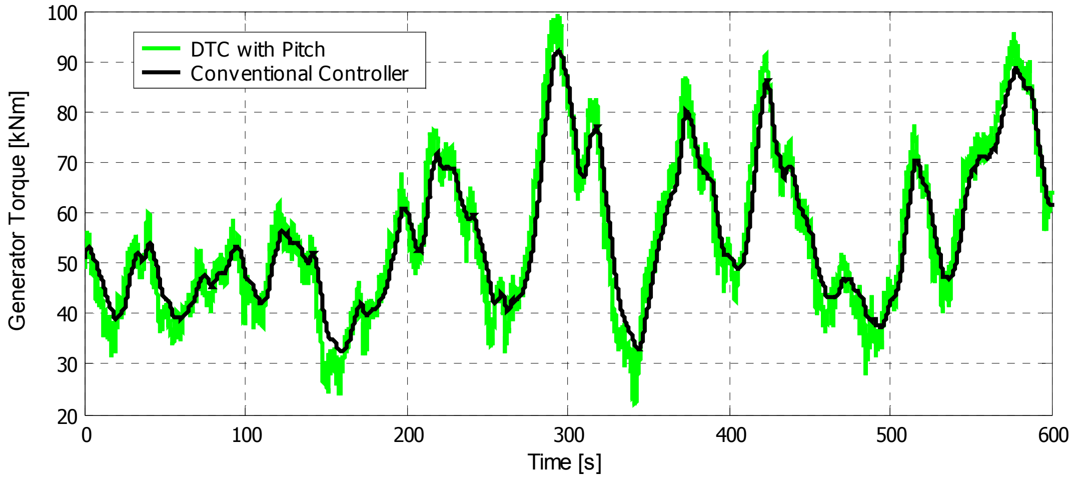

Figure 4: Generator torque commands.

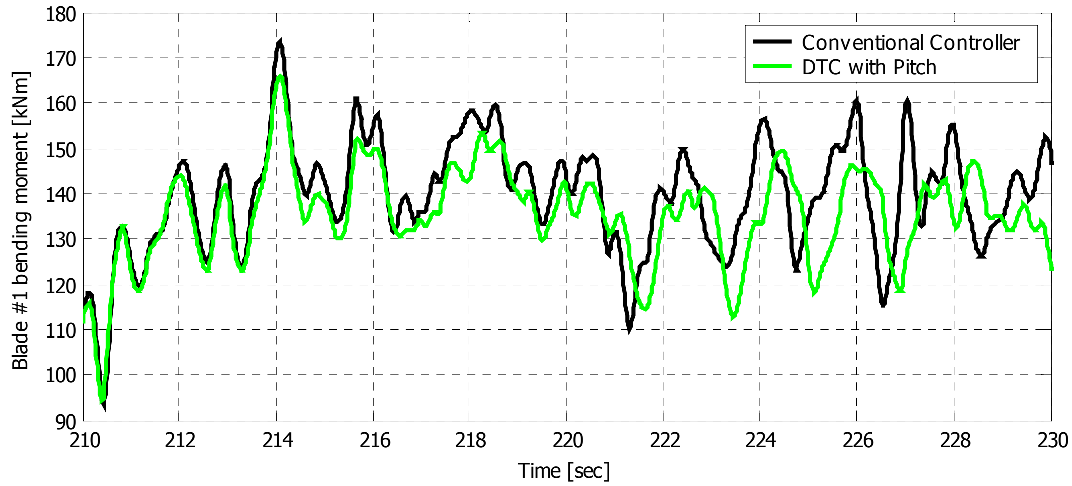

Figure 5: Blade #1 flap bending moment response.

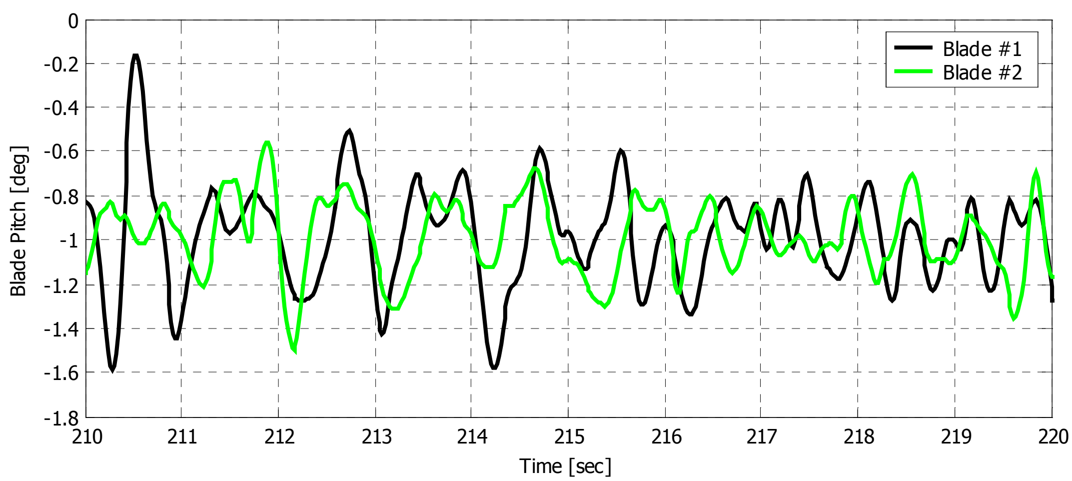

Figure 6: Individual blade pitch commands for the composite controller.

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