

Generator Speed Regulation in the Presence of Structural Modes through Adaptive Control using Residual Mode Filters

Susan A. Frost^a, Mark J. Balas^b, and Alan D. Wright^c

^aCorresponding author, NASA Ames Research Center, Intelligent Systems Division, M/S 269-3, Moffet Field, CA 94035, USA, 01-650-604-0828, fax: 01-650-604-3594, susan.a.frost@nasa.gov

^bUniversity of Wyoming, Department of Electrical and Computer Engineering, 1000 E. University Ave., Laramie, WY 82071, USA, mbalas@uwyo.edu

^cNational Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401, USA, alan.wright@nrel.gov

Abstract—Wind turbines operate in highly turbulent environments resulting in aerodynamic loads that can easily excite turbine structural modes, potentially causing component fatigue and failure. Two key technology drivers for turbine manufacturers are increasing turbine up time and reducing maintenance costs. Since the trend in wind turbine design is towards larger, more flexible turbines with lower frequency structural modes, manufacturers will want to develop control paradigms that properly account for the presence of these modes. Accurate models of the dynamic characteristics of new wind turbines are often not available due to the complexity and expense of the modeling task, making wind turbines ideally suited to adaptive control approaches. In this paper, we develop theory for adaptive control with rejection of disturbances in the presence of modes that inhibit the controller. A residual mode filter is introduced to accommodate these modes and restore important properties to the adaptively controlled plant. This theory is then applied to design an adaptive collective pitch controller for a high-fidelity simulation of a utility-scale, variable-speed wind turbine. The adaptive pitch controller is compared in simulations with a baseline classical Proportional Integrator (PI) collective pitch controller.

Keywords: wind turbine, pitch control, adaptive control, flexible structure control, residual mode filter, disturbance rejection

I. INTRODUCTION

Rated wind speed is the velocity at which maximum power output, or rated power, of a wind turbine is achieved. The power output of a wind turbine increases in proportion to the cube of the wind speed. A turbine operating at or above the rated wind speed needs a method to maintain the rated generator speed, otherwise the generator and power electronics system could overheat and the aerodynamic forces on the machine could lead to component fatigue or system failure. Region 3 is the name of the wind speed operation area where power output is regulated to the turbine's rated value [1].

The control objective for region 3 operation is to maintain power output at rated power and reduce aerodynamic loads on the turbine. Conventional utility-scale variable-speed turbines use active control in region 3 to achieve the control objectives. In its simplest form, the controller applies a constant torque at the generator and actively pitches the turbine blades to vary the aerodynamic lift, thereby maintaining the turbine's rated rotational speed and reducing aerodynamic loads. Collective blade pitch control is a well-accepted approach to regulating turbine speed and responding to changes in wind speed [2].

Wind turbine control problems can benefit from adaptive control techniques [3]-[4], which are well suited to nonlinear applications that have unknown modeling parameters and poorly known operating conditions. The main nonlinearities in a wind turbine model come from the nonlinear aerodynamic loads on the turbine. Creating an accurate model of all the dynamic characteristics of a wind turbine is expensive and extremely difficult, if not impossible. Additionally, wind turbines operate in highly turbulent and unpredictable conditions. These complex aspects of wind turbines make them attractive candidates for the application of adaptive control methods. Adaptive control has been applied to wind turbine control problems in the past [5]-[7].

In this paper, we focus on the direct adaptive control (DAC) approach developed in [8]-[9]. This approach has been extended to handle adaptive rejection of persistent disturbances [10]-[11]. A new method to reduce the destabilizing effects of flexible modes on the adaptive controller will be developed and demonstrated in this paper. We extend our adaptive control theory to accommodate modal subsystems of a plant that might inhibit the adaptive controller or cause the controlled system to become unstable. Large wind turbines are an ideal application for this new theory, in part, because they often have lightly damped, low frequency modal subsystems that can become excited during operation, especially in turbulent conditions.

This paper will first develop new adaptive control theory and then apply this theory to design a region 3 adaptive collective pitch controller for a high-fidelity simulation of a utility-scale wind turbine.

II. DIRECT ADAPTIVE CONTROL WITH REJECTION OF PERSISTENT DISTURBANCES

We give important details of a direct adaptive control approach with adaptive rejection of persistent disturbances previously developed in [10]-[11]. It is assumed that the plant is well modeled by the linear time invariant (LTI) system:

$$\begin{cases} \dot{x}_p = A_p x_p + B_p u_p + \Gamma_p u_D \\ y_p = C_p x_p; x_p(0) = x_0 \end{cases} \quad (1)$$

where the plant state x_p is an N_p -dimensional vector, the control input vector u_p is M -dimensional, and the sensor output vector y_p is P -dimensional. The disturbance input vector u_D is M_D -dimensional and will be thought to come from the Disturbance Generator:

$$\begin{cases} u_D = \Theta z_D \\ \dot{z}_D = F z_D; z_D(0) = z_0 \end{cases} \quad (2)$$

where the disturbance state z_D is N_D -dimensional. All matrices in (1)-(2) have the appropriate compatible dimensions. Such descriptions of persistent disturbances were first used in [12] to describe signals of known form but unknown amplitude. Sometimes, it is easier to rewrite (2) in a form that is not a dynamical system:

$$\begin{cases} u_D = \Theta z_D \\ z_D = L \phi_D \end{cases} \quad (3)$$

where ϕ_D is a vector composed of known basis functions for the solution of $u_D = \Theta z_D$, i.e., ϕ_D has the basis functions which make up the known form of the disturbance, and L is a matrix of dimension N_D by $\dim(\phi_D)$. For the theory developed in this paper, only the form of the disturbance needs to be known; the amplitude of the disturbance does *not* need to be known, i.e. (L, Θ) can be unknown. Some examples of common basis functions are step functions, sine functions, and ramp functions. We can represent a step function of unknown amplitude in the form of (3) as $\phi_D \equiv 1$, with (L, Θ) unknown.

In [10], as with much of the control literature, it is assumed that the plant and disturbance generator parameter matrices $(A, B, C, \Gamma, \Theta, F)$ are known. With this knowledge, the Separation Principle of Linear Control Theory can be invoked to arrive at a State-Estimator based, linear controller that can suppress the persistent disturbances via feedback. In this paper, we will *not* assume that the plant and disturbance generator parameter matrices $(A, B, C, \Gamma, \Theta)$ are known. Instead, we will assume that we know the disturbance generator parameter F from (2), i.e., the form of the disturbance functions is known. In many cases, knowledge of F is not a severe restriction, since the disturbance function is often of known form but unknown amplitude. For example, disturbances caused by wind gusts encountering a turbine can be modeled by step functions and disturbances caused by motors running at constant speeds on flexible structures can be represented by sine functions.

Our control objective will be to cause the output of the plant, y_p , to asymptotically track zero while accommodating disturbances of the form given by the disturbance generator. In [11], our adaptive theory was developed to track a reference model while rejecting disturbances. Here we are concerned with an application that only requires regulation, so we eliminate the reference model to simplify the theory presented. We define the output error vector as:

$$e_y \equiv y_p - 0 \quad (4)$$

To achieve the desired control objective, we want

$$e_y \xrightarrow{t \rightarrow \infty} 0. \quad (5)$$

Consider the plant given by (1) with the disturbance generator given by (3). The control objective for this system is accomplished by an adaptive control law of the form:

$$u_p = G_e e_y + G_D \phi_D \quad (6)$$

where G_e and G_D are matrices of the appropriate compatible dimensions defined by the adaptive gain laws:

$$\begin{cases} \dot{G}_e = -e_y e_y^T h_e \\ \dot{G}_D = -e_y \phi_D^T h_D \end{cases} \quad (7)$$

and h_e and h_D are arbitrary, positive definite matrices. In [11], we showed that for a controllable, observable LTI plant that is almost strict positive real (ASPR), the adaptive controller specified by (6)-(7) produces asymptotic tracking, i.e., $e_y \xrightarrow{t \rightarrow \infty} 0$, and the adaptive gains G_e and G_D remain bounded. In [13] it was shown that a system (A, B, C) is ASPR when CB is positive definite and the open-loop system $P(s) = C(sI - A)^{-1}B$ is minimum phase.

In some cases the plant in (1) does not satisfy the controller's requirement of ASPR. Instead, there maybe be a modal subsystem that inhibits this property. In the next section, we develop new results extending our adaptive control theory to

restore the ASPR condition for certain plants.

III. RESIDUAL MODE FILTER AUGMENTATION OF ADAPTIVE CONTROLLER

We will modify the adaptive controller with a Residual Mode Filter (RMF) to compensate for non-minimum phase modal subsystems, or Q-modes, as was done in [14] for fixed gain non-adaptive controllers. The non-minimum phase modes are those modes that cause the open-loop plant transfer function to be non-minimum phase, i.e., the transfer function has one or more zeros in the right half plane. Here we present the theory for adaptive controllers augmented with Residual Mode Filters.

Let us assume that (1) can be partitioned into the following form:

$$\begin{cases} \begin{bmatrix} \dot{x} \\ \dot{x}_Q \end{bmatrix} = \begin{bmatrix} A & 0 \\ 0 & A_Q \end{bmatrix} \begin{bmatrix} x \\ x_Q \end{bmatrix} + \begin{bmatrix} B \\ B_Q \end{bmatrix} u_p + \begin{bmatrix} \Gamma \\ \varepsilon \Gamma_Q \end{bmatrix} u_D \\ y_p = \begin{bmatrix} C & C_Q \end{bmatrix} \begin{bmatrix} x \\ x_Q \end{bmatrix}; \varepsilon \geq 0 \end{cases} \quad (8)$$

where ε represents the amount of leakage of the disturbance into the Q-modal system. To simplify notation, define

$$x_p \equiv \begin{bmatrix} x \\ x_Q \end{bmatrix}, \quad A_p = \begin{bmatrix} A & 0 \\ 0 & A_Q \end{bmatrix}, \quad B_p = \begin{bmatrix} B \\ B_Q \end{bmatrix}, \quad C_p = \begin{bmatrix} C & C_Q \end{bmatrix}, \quad \Gamma_p = \begin{bmatrix} \Gamma \\ \varepsilon \Gamma_Q \end{bmatrix}$$

and use the disturbance generator as given before by (2) or (3). The Output Tracking Error and control objective remain as in (4)-(5), i.e. $e_y \equiv y_p \xrightarrow{t \rightarrow \infty} 0$.

However, now we will only assume that the subsystem (A, B, C) is ASPR rather than the full un-partitioned plant (A_p, B_p, C_p) , and that the modal subsystem (A_Q, B_Q, C_Q) will be *known and open-loop stable*, i.e. A_Q is stable. The disturbance input directly affects the modal subsystem by an amount determined by the parameter ε . So, in summary, the actual plant has an ASPR subsystem and a known modal subsystem that is stable but inhibits the property of ASPR for the full plant. Hence, this modal subsystem must be compensated or filtered away.

We define the *Residual Mode Filter* (RMF):

$$\begin{cases} \dot{\hat{x}}_Q = A_Q \hat{x}_Q + B_Q u_p \\ \hat{y}_Q = C_Q \hat{x}_Q \end{cases} \quad (9)$$

And the *compensated tracking error*:

$$\tilde{e}_y \equiv y_p - \hat{y}_Q \quad (10)$$

Now we let $e_Q \equiv \hat{x}_Q - x_Q$ and obtain:

$$\dot{e}_Q = A_Q e_Q - \varepsilon \Gamma_Q u_D \quad (11)$$

Consequently,

$$\begin{aligned} \tilde{e}_y \equiv y_p - \hat{y}_Q &= Cx + C_Q x_Q - [C_Q x_Q + C_Q e_Q] \\ &= Cx - C_Q e_Q \end{aligned} \quad (12)$$

As in [7]-[8], we define the *Ideal Trajectories*, but only for the ASPR subsystem:

$$\begin{cases} \dot{x}_* = Ax_* + Bu_* + \Gamma u_D \\ y_* = Cx_* = 0 \end{cases} \quad (13)$$

with $\begin{cases} x_* = S_1^* z_D \\ u_* = S_2^* z_D \end{cases}$. This is equivalent to the Matching Conditions:

$$\begin{cases} S_1^* F = AS_1^* + BS_2^* + \Gamma \theta \\ CS_1^* = 0 \end{cases} \quad (14)$$

which are *known to be uniquely solvable when CB is nonsingular* [15]. Since we are assuming CB is nonsingular, there exists a solution to the matching conditions, but we do *not* need to know the actual solutions, since they do not appear in the final formulation of the adaptive control law.

Let $\begin{cases} \Delta x \equiv x - x_* \\ \Delta u \equiv u_p - u_* \\ \Delta \tilde{y} \equiv \tilde{e}_y = Cx - C_Q e_Q \end{cases}$. Then we have:

$$\begin{cases} \Delta \dot{x} = A\Delta x + B\Delta u \\ \Delta \tilde{y} = Cx - y_* - C_Q e_Q = C\Delta x - C_Q e_Q \end{cases} \quad (15)$$

because, from (13), $y_* = \mathbf{0}$. This system can be rewritten:

$$\begin{cases} \begin{bmatrix} \Delta \dot{x} \\ \dot{e}_Q \end{bmatrix} = \begin{bmatrix} A & 0 \\ 0 & A_Q \end{bmatrix} \begin{bmatrix} \Delta x \\ e_Q \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} \Delta u + \varepsilon \begin{bmatrix} 0 \\ -\Gamma_Q \end{bmatrix} u_D = \bar{A} \begin{bmatrix} \Delta x \\ e_Q \end{bmatrix} + \bar{B} \Delta u + \varepsilon \bar{\Gamma}_Q u_D \\ \Delta \tilde{y} = \begin{bmatrix} C & -C_Q \end{bmatrix} \begin{bmatrix} \Delta x \\ e_Q \end{bmatrix} = \bar{C} \begin{bmatrix} \Delta x \\ e_Q \end{bmatrix} \end{cases} \quad (16)$$

Now we have the following:

Lemma: $\left(\bar{A} = \begin{bmatrix} A & 0 \\ 0 & A_Q \end{bmatrix}, \bar{B} = \begin{bmatrix} B \\ 0 \end{bmatrix}, \bar{C} = \begin{bmatrix} C & -C_Q \end{bmatrix} \right)$ is ASPR if and only if (A, B, C) ASPR.

Proof: Assume (A, B, C) ASPR. Then $\bar{C}\bar{B} = \begin{bmatrix} C & -C_Q \end{bmatrix} \begin{bmatrix} B \\ 0 \end{bmatrix} = CB$ with $CB > 0$ given and

$$\bar{P}(s) \equiv \bar{C}(sI - \bar{A})^{-1} \bar{B} = \begin{bmatrix} C & -C_Q \end{bmatrix} \begin{bmatrix} (sI - A)^{-1} & 0 \\ 0 & (sI - A_Q)^{-1} \end{bmatrix} \begin{bmatrix} B \\ 0 \end{bmatrix} = C(sI - A)^{-1} B = P(s) \text{ with } P(s) \text{ minimum phase}$$

given. The reverse is also true. This proves the lemma. #

So by this lemma and the definition of ASPR, there exists G_e^* such that $(\bar{A}_C \equiv \bar{A} + \bar{B}G_e^* \bar{C}, \bar{B}, \bar{C})$ is Strictly Positive Real (SPR) when (A, B, C) is ASPR. Consequently, as is well known from the Kalman-Yacubovic Theorem, there exists $\bar{P}, \bar{Q} > 0$ such that

$$\begin{cases} \bar{A}_C^T \bar{P} + \bar{P} \bar{A}_C = -\bar{Q} \\ \bar{P} \bar{B} = \bar{C}^T \end{cases} \quad (17)$$

We now *augment the adaptive control law with an RMF*:

$$\begin{cases} u_p \equiv G_e \tilde{e}_y + G_D \phi_D \\ \tilde{e}_y \equiv y_p - \hat{y}_Q \\ \dot{\hat{x}}_Q = A_Q \hat{x}_Q + B_Q u_p \\ \hat{y}_Q = C_Q \hat{x}_Q \end{cases} \quad (18)$$

with modified adaptive gains:

$$\begin{cases} \dot{G}_e = -\tilde{e}_y \tilde{e}_y^T h_e; h_e > 0 \\ \dot{G}_D = -\tilde{e}_y \phi_D^T h_D; h_D > 0 \end{cases} \quad (19)$$

Finally, we have the following stability result:

Theorem: In (8), let (A, B, C) ASPR, A_Q stable, ϕ_D bounded. Then the Augmented Adaptive Controller with RMF in

(18)-(19) produces $e_y = y_p$ and e_Q ultimately bounded into a ball of radius $R_* \equiv \varepsilon \frac{(1 + \sqrt{p_{\max}})}{a\sqrt{p_{\min}}} M_v$ with exponential rate

and bounded adaptive gains (G_e, G_D) .

Proof: From (18), we have $u_p \equiv G_e \tilde{e}_y + G_D \phi_D$ so we can write

$$\Delta u \equiv u_p - u_*$$

$$= [G_e \tilde{e}_y + G_D \phi_D] - [S_2^* L] \phi_D$$

$$= G_e^* \tilde{e}_y + \Delta G \eta$$

$$\text{where } \begin{cases} \Delta G_e \equiv G_e - G_e^* \\ \Delta G_D \equiv G_D - (S_2^* L) \\ \Delta G \equiv G - G_* = [\Delta G_e \quad \Delta G_D] \end{cases}. \text{ Then } \eta \equiv \begin{bmatrix} \tilde{e}_y \\ \phi_D \end{bmatrix}$$

$$\begin{cases} \dot{\zeta} = \bar{A} \zeta + \bar{B} \Delta u = \bar{A}_c \zeta + \bar{B} w + \varepsilon \bar{\Gamma}_Q u_D \\ \tilde{e}_y = \bar{C} \zeta \end{cases} \quad (20)$$

$$\text{with } \zeta \equiv \begin{bmatrix} \Delta x \\ e_Q \end{bmatrix}, w \equiv \Delta G \eta, \bar{A}_c \equiv \bar{A} + \bar{B} G_e^* \bar{C}$$

From (19), we can see that

$$\dot{G} = \Delta \dot{G} = -\tilde{e}_y \eta^T h; h \equiv \begin{bmatrix} h_e & 0 \\ 0 & h_D \end{bmatrix} > 0 \quad (21)$$

Since (A, B, C) is ASPR, and by the lemma, so is $(\bar{A}, \bar{B}, \bar{C})$, we can use the following result from [16] where $v \equiv \bar{\Gamma}_Q u_D$ is bounded because the disturbance $u_D = L \phi_D$ is bounded.

Result: Consider the nonlinear, coupled system of differential equations,

$$\begin{cases} \dot{\zeta} = \bar{A}_c \zeta + \bar{B} (G(t) - G^*) \eta + \varepsilon v \\ \tilde{e}_y = \bar{C} \zeta \\ \dot{G}(t) = -\tilde{e}_y \eta^T h - a G(t) \end{cases} \quad (22)$$

where G^* is any constant matrix and h is any positive definite constant matrix, each of appropriate dimension. Assume the following:

i) the triple $(\bar{A}, \bar{B}, \bar{C})$ is SPR,

ii) there exists $M_K > 0$ such that $\left\| (G^*)^T G^* \right\| \leq M_K$, using the trace norm,

iii) there exists $M_v > 0$ such that $\sup_{t \geq 0} \|v(t)\| \leq M_v$,

iv) there exists $a > 0$ such that $a \leq \frac{q_{\min}}{2p_{\max}}$, and

v) h satisfies $\|h^{-1}\|_2 \leq \left(\frac{\varepsilon M_v}{a M_K} \right)^2$, where p_{\min}, p_{\max} are the minimum and maximum eigenvalues of \bar{P} and q_{\min} is the minimum

eigenvalue of \bar{Q} in the system $\begin{cases} \bar{A}_c^T \bar{P} + \bar{P} \bar{A}_c = -\bar{Q} \\ \bar{P} \bar{B} = \bar{C}^T \end{cases}$

Then the matrix $G(t)$ is bounded and the state $\zeta(t)$ exponentially approaches the ball of radius $R_* \equiv \varepsilon \frac{(1 + \sqrt{p_{\max}})}{a \sqrt{p_{\min}}} M_v$ with

$\varepsilon > 0$.

From this result, we have ζ is ultimately bounded into the ball of radius R_* , which leads to $e_y \equiv y_p = y_p - y_* = C \Delta$ and e_Q is ultimately bounded as well. Therefore $G = G_* + \Delta G$ is bounded, as desired. This proves the theorem. #

Observe that the radius of the error ball R_* is determined by both the size of ε , which is related to the amount of

disturbance leakage into the Q-modes, and the desired rate of convergence, a . It can be seen that, when there is no leakage of the disturbance into the Q-modes, i.e., $\varepsilon=0$, the convergence is asymptotic to zero. Also, when $\Gamma = B$ and $\Gamma_Q = B_Q$, it is possible to choose $S_1^* = 0$ and $S_2^* = -\theta$ in (14). Then, even if $\varepsilon = 1$, the tracking error will asymptotically go to zero.

This concludes the theory section where we have developed new theory for direct adaptive control with adaptive rejection of persistent disturbances of known waveform, but unknown amplitude using residual mode filters to restore the ASPR property of the plant. Next we apply this theory to design an adaptive collective pitch controller for a high-fidelity utility-scale wind turbine simulation.

IV. DESIGN AND SIMULATION OF ADAPTIVE COLLECTIVE PITCH CONTROLLER USING RMF

A. Wind Turbine Simulation

In this section, we use the theory developed above to design an adaptive collective pitch controller to regulate generator speed in region 3 while accommodating changes in wind speed. The controller is developed for a simulation of the 2-bladed Controls Advanced Research Turbine (CART2), an upwind, active-yaw, variable-speed horizontal axis wind turbine (HAWT) located at the National Renewable Energy Laboratory's (NREL) National Wind Technology Center (NWTC) in Golden, Colorado [17]-[18]. The CART2 is used as a test bed to study control algorithms for medium-scale turbines. The pitch system on the CART2 uses electromechanical servos that can pitch the blades up to ± 18 deg/s. In region 3, the CART2 uses a conventional variable-speed approach to maintain rated electrical power, which is 600 kW at a low-speed shaft [LSS] speed of 41.7 RPM and a high-speed shaft [HSS] speed of 1800 RPM. Power electronics are used to command constant torque from the generator and full-span blade pitch controls the turbine rotational speed. The maximum rotor-speed for the CART2 for region 3 is 43 rpm (on the low-speed side) or 1856.1 rpm on the generator side. Whenever the rotor-speed reaches this value the turbine shuts down due to an over-speed condition.

The CART2 has been modeled using the Fatigue, Aerodynamics, Structures, and Turbulence Codes (FAST), a well-accepted simulation environment for HAWTs [19]. The FAST code is a comprehensive aeroelastic simulator capable of predicting both the extreme loads and the fatigue loads of two- and three-bladed horizontal axis wind turbines [20]. Wind turbines can be modeled with FAST as a combination of rigid and flexible bodies connected by several degrees of freedom (DOFs) that can be individually enabled or disabled for analysis purposes. Kane's method is used by FAST to set up equations of motion that are solved by numerical integration. FAST computes the nonlinear aerodynamic forces and moments along the turbine blade using the AeroDyn subroutine package [21]. The FAST code with AeroDyn incorporated in the simulator was evaluated in 2005 by Germanischer LloydWindEnergie and found suitable for 'the calculation of onshore wind turbine loads for design and certification' [22].

B. Region 3 Collective Pitch Controllers

Two region 3 controllers for the FAST simulation of the CART2 will be compared. The parametric information for the FAST simulator as we configured it is available from [19]. The control objective is to regulate generator speed at 1800 rpm and to reject wind disturbances using collective blade pitch. The inputs to the FAST plant are generator torque, blade pitch angle, and nacelle yaw. The FAST simulator can be configured to output many different states or measurements of the plant, such as generator speed and low speed shaft velocity. In this study, the yaw is assumed fixed, so that the wind inflow is normal to the rotor. In addition, the generator torque is assumed constant in region 3. Thus collective blade pitch is the only controller output. Turbine rotational speed, measured on the low-speed shaft side of the gearbox, is the only plant output used by the region 3 controllers. A classical PI collective pitch controller (the baseline PI pitch controller) has been implemented and tested in the FAST simulator and a similar controller was field tested on the CART2 [2], [23] for validation of the codes. We use the baseline PI pitch controller as a basis for comparison with the adaptive pitch controller.

The adaptive collective pitch controller designed for this paper replaces the baseline PI pitch controller in the FAST simulator. The adaptive pitch controller is designed with the direct adaptive control approach described in section II to regulate generator speed. The uniform wind disturbance, without shear, across the rotor disk of a turbine can be modeled as a step disturbance [24]. Hence, to improve controller performance and reduce loads due to changes in wind speed, we design the adaptive collective pitch controller to reject step disturbances of unknown amplitude. The control objectives are accomplished by collective blade pitch.

A control law of the form given in (6) with gains specified by (7) is used to design the adaptive collective pitch controller. A step function is used as the disturbance generator function, i.e., $\phi_D = 1$ from (3). Recall that the amplitude of the disturbance function does *not* need to be known. This adaptive controller is implemented in Simulink™ for the FAST simulation of the CART2. The adaptive controller gains h_e and h_D were tuned to minimize the generator speed error, while keeping the blade pitch rate in a range similar to that of the baseline PI controller. The gains used in the adaptive controller are: $h_e = 6.5$ and $h_D = 0.3$.

The adaptive controller was tested in simulation and compared with the baseline PI collective pitch controller. The FAST simulations were run from time 0 seconds to 100 seconds with an integration step size of 0.006 seconds. The simulation used

step wind inflow resulting in region 3 turbine operation, see fig. 1(a). The generator and drive-train rotational-flexibility DOFs were enabled and the other DOF switches were turned off. Aerodynamic forces were calculated and applied to the turbine during the runs. Figure 1(b) shows the generator speed for both controllers with step wind inflow after the transients due to startup have decayed. Testing continued with additional DOFs being added to the turbine model.

C. Design of Adaptive Controller using RMF

When the blade first flap-wise bending DOF was enabled along with the drive-train mode, the adaptively controlled turbine saturated the blade pitch actuators after 60 seconds of steady uniform wind inflow at 18 mps, causing the turbine to enter over-speed condition. The baseline PI controller remained within acceptable operating limits, but the generator speed tracking was unacceptable at wind speeds above 17 mps, see fig. 2. Frequency analysis of several signals from the simulation, including the LSS velocity, the generator speed, the drive train torque, and the blade flap displacement, showed a large frequency content centered at 3 Hz for both the PI and the adaptive controller. The adaptively controlled system had a wider band of frequencies with larger magnitudes than the PI controlled system. Both systems included frequencies at the drive-train rotational flexibility mode that is estimated at 3.5 Hz. A low-pass filter was designed to filter this frequency content from the measured turbine rotational speed before it is input to the controller. The filter transfer function is given by $T(s) = 10/(s+10)$. The results of incorporating the low-pass filter with the baseline PI controller are shown in fig. 2(c), demonstrating improved generator speed tracking. The low-pass filter improved the adaptive controller results, but the blade pitch rate activity was unacceptably high.

A stability condition of the adaptive controller is an ASPR plant, i.e. CB positive definite and the open-loop transfer function of the plant has no non-minimum phase zeros. The turbine simulation is trimmed at a wind speed of 18 mps with the generator and drive-train DOFs enabled to obtain a linear model of the plant. The open-loop transfer function of the linearized plant model has two non-minimum phase zeros at $0.0111 \pm 5.499i$. Hence the plant does not satisfy the ASPR condition for the adaptive controller. We use the theory from section III above to design a Residual Mode Filter to remove the non-minimum phase modes from the plant to restore the ASPR property of the plant.

A Residual Mode Filter is designed from the linear model by first converting the linear system to a modal system. We partition the modal system into two subsystems, one minimum phase subsystem and a second stable subsystem with two non-minimum phase zeros. The second subsystem contains the Q-modes, so it is used as the Residual Mode Filter given in (9) to augment the adaptive controller to remove the plant's non-minimum phase modes. The transfer function for the RMF is

$$T(s) = \frac{790.52s - 38.32}{s^2 + 0.02s + 430.30}. \quad (22)$$

The RMF is placed in a loop around the controller in the Simulink™ model of the turbine. The controller output is fed to both the plant and the RMF. The RMF output is subtracted from the plant output before it is passed to the controller. The RMF removes the modes from the plant output that inhibit the ASPR property. Previous results from [14] showed that fixed gain controllers could be augmented with RMFs, so the same RMF is added to the original baseline PI pitch controller (without the low-pass filter). An advantage of RMF augmentation is that it requires no modification to the control laws or control gains. The RMF is designed to remove only the Q-modes, whereas a low-pass filter attenuates or removes frequencies above a certain value. Next we present simulation results using these controllers.

D. Simulation Results using RMF

The two controllers augmented with the RMF given by (22) were compared in simulation. For the initial analysis, the generator, drive-train rotational-flexibility, and blade first flap-wise DOFs were enabled with the step wind inflow shown in fig. 1(a). Both controllers using RMF demonstrated improved generator speed regulation with acceptable blade pitch activity, see fig. 3. We then tested the baseline PI with low-pass filter, the baseline PI using RMF, and the adaptive using RMF controllers with additional DOF's enabled, including the tower fore-aft and tower side-side modes. Steady uniform 18 mps wind was used to compare the steady state tracking and blade pitch activity of each controller, see fig. 4. The adaptive controller achieves better regulation either of the PI controllers under these conditions. Also, the baseline PI controller using RMF outperforms the PI controller with the low-pass filter.

Simulations with both controllers using the RMF with were run with more realistic turbulent wind inflow to excite the nonlinear turbine model. The turbulent wind primarily results in region 3 operation, see fig. 5. The generator, drive-train, blade first flap-wise, blade first edge-wise, tower fore-aft and tower side-side modes were enabled for the simulation. The generator speed and the commanded blade pitch of the two controlled systems are shown in fig. 6(a) and fig. 6(b), respectively. The PI controller exceeds the generator speed limit at 30 seconds. The root-mean squared error (RMSE) for the controllers with turbulent wind were: 14.38 rpm for the adaptive RMF controller and 29.56 rpm for the baseline PI RMF controller. Frequency analysis of the closed-loop systems using RMF showed a marked reduction in the frequency content near 3 Hz when compared with the closed-loop systems without RMF.

V. CONCLUSIONS

We proposed new theory for adaptive control with disturbance accommodation using residual mode filters. Often plants with flexible structure dynamics, including large wind turbines, have non-minimum phase modes that interfere with the almost strict positive real requirement for adaptive control. We used theory developed in this paper to design an adaptive controller using an RMF to accommodate a plant with non-minimum phase zeros. A goal of this study was to design a collective pitch controller for region 3 operation of a wind turbine operating in the presence of turbine structural modes, including the blade flap-wise bending mode. The RMF successfully removed the non-minimum phase modes from the plant, thereby restoring the ASPR property to the plant. The adaptive controller using RMF showed improved overall generator speed regulation when compared with the baseline PI controller using RMF. Adaptive control augmented with RMF could benefit many more general flexible structure control problems, where non-minimum phase modes in the plant inhibit the ASPR property.

The adaptive control approach presented here could have many positive consequences for wind turbine operation, including improved power generation and reduced loads due to better tracking and disturbance rejection. Design of adaptive controllers is much quicker and simpler than design of gain-scheduled PI controllers. Adaptive controllers generally outperform gain-scheduled PI controllers in applications with widely fluctuating operating conditions, such as large changes in wind speed, or when there are slowly changing plant characteristics. The certification process for adaptive controllers can be more complex than for fixed gain controllers, since phase and gain margins cannot be determined for nonlinear controllers. However one adaptive controller can sometimes be used for multiple platforms, whereas a fixed gain control approach might require multiple controllers. Adaptive control methods have been certified and successfully deployed in many real world applications with good results.

The performance of adaptive controller using RMF designed with new theory presented here was demonstrated through simulation of the NREL 2-bladed Controls Advanced Research Turbine located at the National Wind Technology Center. These simulations used both artificial stepwise changes in wind-speed as well as more realistic turbulent wind cases to excite the turbine model and to test the performance of these controllers. The adaptive controller presented here demonstrate improved performance compared to the standard classical controllers typically used on commercial turbines, especially for cases in which the plant characteristics change slowly over time. The next step in proving the performance of these adaptive controllers will involve actual field tests on such a machine.

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