2011 American Control Conference
on O'Farrell Street, San Francisco, CA, USA
June 29 - July 01, 2011

Region II Wind Power Capture Maximization Using Robust Control and Estimation with Alternating Gradient Search

Tony Hawkins, Warren N. White, Guoqiang Hu, Faryad Darabi Sahneh

***Abstract*—A two-fold control method is proposed consisting of a nonlinear robust controller working in conjunction with an extremum seeking gradient search controller. The robust controller provides stable control of the rotor angular velocity while also producing an estimation of the hard to measure and nonlinear aerodynamic torque provided by the wind. The gradient search method uses the estimate to update the tip-speed ratio and blade pitch which will drive the system in the direction of increasing turbine power capture. The efficacy of the control method is demonstrated through simulation in the presence of a realistic wind signal and measurement noise in the wind velocity feedback.**

I. Introduction

WIND turbines provide a means of generating clean electric power by utilizing an almost limitless natural resource. The lack of fuel combustion and associated greenhouse gas emissions is a very attractive feature of wind turbine power generation. Downsides of wind turbines include mechanical reliability, unpredictability of wind, remote location of facilities, blade aerodynamic disturbances from air turbulence created by upwind turbines, and variable power capture efficiencies that depend on rotor speed and blade pitch. This paper addresses the last point, controlling the blade pitch and rotor speed in order to capture the greatest amount of power possible for a given turbine.

The power available in a wind stream of speed v is

$$P_{avail} = \frac{1}{2}\rho A v^3 \tag{1}$$

where ρ is the air mass density, A is the rotor swept area, and P_{avail} is the available power (watts, BTU/hr, etc.) in the wind. The power captured by the turbine is

$$P_{aero} = C_p(\lambda, \beta) \cdot P_{avail} \tag{2}$$

where $C_p(\lambda,\beta)$, the coefficient of performance, is the ratio of the captured power to the available power, β is the blade pitch, and λ is the tip speed ratio given by

$$\lambda = \frac{\omega R}{v}. \tag{3}$$

Manuscript received September 27, 2101. The work was supported in part by the Kansas State University Electric Power Affiliates Program. The authors gratefully acknowledge the support.

T. Hawkins is a Controls Engineer with Kasa Industrial Controls, Salina, KS 67401, USA (e-mail: thawkins84@gmail.com).

W. N. White is with the Mechanical and Nuclear Engineering Dept. at Kansas State University, Manhattan, KS 66506 USA (phone: 785-532-2615, fax: 785-532-7057,e-mail: wnw@ksu.edu).

G. Hu is with the Mechanical and Nuclear Engineering Department. at Kansas State University, Manhattan, KS 66506 (e-mail: gqhu@ksu.edu).

F.D. Sahneh is with the Electrical and Computer Engineering Department at Kansas State University, Manhattan, KS 66506(e-mail: faryad@ksu.edu).

The quantity $C_p(\lambda,\beta)$ is a nonlinear function that is difficult to measure, is difficult to predict analytically, and can differ between like model turbines. Figure 1 illustrates a $C_p(\lambda,\beta)$ curve that is found in [1].

Wind turbine operation is divided into three regions. In the first region, the wind speed is too low for turbine operation and no power is generated. In region 2, both the blade pitch and rotor speed can be varied. In region 3, the turbine has reached its rated speed and the speed is controlled by either the use of brakes or by changing the blade pitch. A common operation scenario is to vary the tip speed ratio by changing the generator loading for speed control in region 2 and by varying the blade pitch, if so equipped, in region 3. Note that both variables do play a role in changing the C_p value.

A good description of the fundamentals behind wind power is contained in [2].

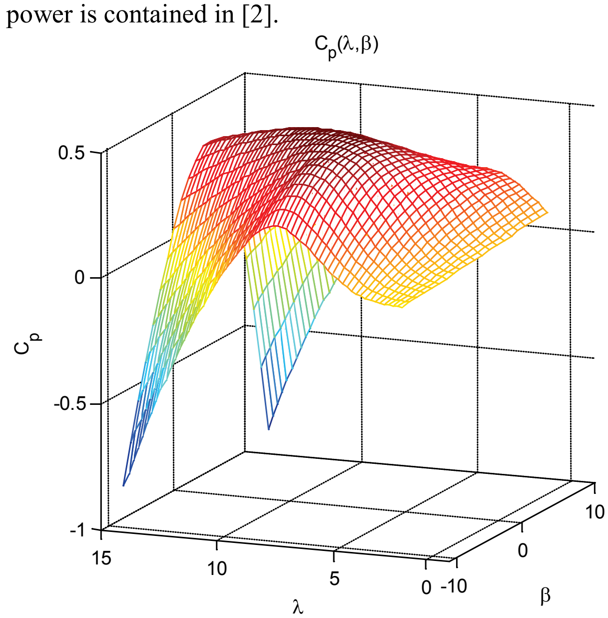

Fig. 1: Coefficient of performance curve as a function of blade pitch and tip-speed ratio. Peak value of $C_p^* = 0.4735$ at $\lambda^* = 7.8$ and $\beta^* = -1°$. Entire C_p data table contains information for $0 \leq \lambda \leq 20$ and $-90° \leq \beta \leq 90°$.

The difficulty in changing the tip speed ratio and blade pitch in order to increase the size of C_p is that the value of C_p is not a directly measureable quantity. The wind turbine power capture control system has the duties of regulating rotor speed as well as to choose better values of λ and/or β. To this end, many types of control schemes have been tried. Linear control methods have been used to regulate wind turbines [3]. Such approaches use PID or similar controllers. Gains are then tuned to each wind turbine system. These control methods assume prior knowledge of the optimal

978-1-4577-0079-8/11/$26.00 ©2011 AACC

operating point, as well as manual re-tuning in the event of any parameter variation.

Sliding mode control has also been used as a nonlinear control approach. In [4] and [5], sliding mode controllers were proposed for a system in order to provide trajectory tracking of blade pitch and tip speed ratio set points. The sliding mode results provided good tracking control; however, the approach still needed a reference track to be provided from a known C_p curve.

Adaptive control has been used for rotor speed control and C_p identification. Johnson et al. proposed a nonlinear controller, [2] and [6], where an adaptive gain is tuned based on an estimation of the power captured over a period of time to provide torque control. Although the adaptation period was lengthy, this control scheme was applied to a real turbine and was able to achieve convergence to the region of maximum power capture.

Other estimation approaches have also been studied such as Ma's wind turbine controller given in [7]. The Kalman filter is used to estimate the unknown nonlinearities while a proportional-integral controller regulates the turbine to a desired set point. In [7], it is assumed that the optimal point is known. Ma's paper also excludes blade pitch control.

Creaby *et al.* [8] made use of extremum seeking algorithms studied in [9] to maximize the captured power. These extremum seeking control (ESC) methods rely on 1) a dither perturbation signal, usually a sinusoidal type, added to the peak seeking variable and then demodulated in the feedback loop, and 2) measurements of the cost function. The ESC-based power maximization method introduced in [8] does not require wind velocity measurement. The simulation results show a very promising improvement in power capture, even under turbulent wind conditions. Chen *et al.* [10] used a similar ESC method to maximize the captured electric power. They, at least, improved the previous results in two ways. First, the maximized power was the electric power, which is of more interest than maximization of the rotor power. Second, the performance of the ESC algorithm was improved by considering the variations in the power map and studying the robustness stability condition of the method.

Requirements of any non-dither based control scheme for wind turbine power capture are the rotor speed regulation, estimation of C_p, and the choosing of a new set point at which the C_p value would be higher. Recently, a new robust control strategy, termed as Robust Integral of the Sign of the Error (RISE) [11], was developed in [12, 13] that can accommodate for sufficiently smooth bounded disturbances. A significant advantage of this new control method is that it enables asymptotic stability in the presence of uncertain disturbances, which has been demonstrated in [14-17], just to name a few. In [14], the authors leveraged this strategy to develop a tracking controller for nonlinear systems in the presence of additive disturbances and parametric uncertainties. In [15], the authors utilized this strategy to propose a new output feedback discontinuous tracking controller for a general class of second-order nonlinear systems. In [16], the authors combined the high gain feedback structure with a high gain observer at the sacrifice of yielding a semi-global, uniformly ultimately bounded result. In [17], the authors leveraged this strategy to develop a tracking controller for a general Euler–Lagrange system that contains a new continuously differentiable friction model with uncertain nonlinear parameterizable terms. Iysare et al. [18,19] used this method for estimating the rotor torque. A similar idea was employed by Hawkins *et al.* [20].

The significant contribution of this paper is that it does not rely on introducing a sinusoidal perturbation or dither signal to the generator torque command together with the necessity to perform a demodulation for feedback purposes in order to drive the estimation process. The perturbation introduced by changing the rotor angular velocity set point is sufficient to drive the robust estimation. The generator power output is not required to estimate the captured power. A measured wind turbine data set is used in modeling and simulating the turbine. The control algorithm does not make any use of this information. So that new set points in rotor speed and blade pitch can be determined that increase the power capture, the extremum seeking controller makes use of the gradient of C_p with respect to λ and β. As C_p nears the peak, the gradient becomes small and is susceptible to noise. Two procedures are presented that reduce the numerical difficulties that sometimes occur when trying to estimate a small gradient component.

Assumptions made in this analysis are:

1. The rotor pitch change time constant is small compared to the time necessary to respond to a rotor angular velocity set point change and to estimate C_p.
2. The time necessary to change the generator torque loading is small.
3. Both rotor angular velocity and wind speed feedback is available.
4. The yaw angle is steady.

II. WIND TURBINE ENERGY CAPTURE MODEL

The wind turbine model considered in this paper consists of a known lumped inertia, J, a torque provided by the wind acting on the rotor, τ_{aero}, a known lumped damping coefficient, C_D, and a control torque, τ_c, which will be provided by the loading of the electric power generator. The wind turbine system dynamic model is described by the first order differential equation

$$\dot{\omega} = \frac{1}{J}(\tau_{aero} - C_D\omega - \tau_c) \quad (4)$$

where ω is the shaft angular velocity and is one state variable of the inner loop control system. The remaining state variables are the tip speed ratio, λ, the blade pitch, β, and the filtered tracking error introduced in the next section. Another way to express the captured power is

$$P_{aero} = \tau_{aero}\omega. \quad (5)$$

The function $C_p(\lambda,\beta)$ is an unknown nonlinear relationship described by a three dimensional surface. In general, the C_p function shape is convex and has a single maximum denoted as $C_p(\lambda^*,\beta^*) > 0$ for some λ^* and β^*. $C_p(\lambda,\beta)$ is maximized as $\lambda \to \lambda^*$ and $\beta \to \beta^*$. The function in Figure 1 is convex and shows a single extremum.

In Eqs. (1) and (3), the air density ρ and the wind speed v are presumed measurable with some measurement error w.

It is also assumed that the shaft angular velocity is a measurable quantity. The angular shaft acceleration, $\dot{\omega}$, however, is not available from measurements. Combining (1), (2), and (5) shows that the aerodynamic torque is

$$\tau_{aero} = \frac{1}{2}\rho AR\frac{C_p(\lambda,\beta)}{\lambda}v^2 . \tag{6}$$

A Lyapunov-based approach is proposed for developing the wind turbine control law. The constraints to be satisfied by the controller include robust estimation of the turbine aerodynamic properties, stabilization of the tip speed ratio about a set point, and optimization of the power capture coefficient, C_p. The controller design will be divided into two steps. The first is the control of the inner loop which is accomplished by the use of a robust identifier-based controller. This controller is responsible for the regulation of the angular shaft velocity, ω, to the desired shaft velocity, ω_d. This controller also provides an estimate of the unknown aerodynamic torque, denoted as $\hat{f}$. The second step is the development of the Lyapunov-based controller which uses $\hat{f}$ for generating the desired state trajectories for the robust controller to regulate. This is known as the outer loop controller. A Lyapunov candidate function will be used to ensure that the values of the outer loop states, λ and β, converge towards the optimal values of λ^* and β^* which maximize C_p, thus C_p converges to C_p^*.

III. TWO-FOLD CONTROL METHOD DEVELOPMENT

A. Robust Control Development

A nonlinear robust controller is developed to regulate the angular velocity of the system to a desired set-point. As a result, an estimation of the unknown parameter, τ_{aero}, is also obtained. A loading torque from the generator, denoted as τ_c, is used to control the shaft speed of the system. As stated previously, the open-loop dynamics are stated in (4).

The objective of this identifier-based control design is twofold:

(1) Achieve asymptotic tracking in the sense of $\omega \rightarrow \omega_d$ where ω_d represents a desired angular velocity.

(2) Estimate the unknown value of the nonlinear function τ_{aero}.

An angular velocity tracking error is defined as

$$e = \omega - \omega_d \tag{7}$$

To facilitate the subsequent control design and analysis, a filtered tracking error, denoted as $r(t)$ is defined as

$$r = \dot{e} + \alpha e \tag{8}$$

where α denotes a positive constant. The filtered tracking error $r(t)$ is not measurable because it depends on $\dot{\omega}(t)$ which is also not measurable. The quantity $r(t)$ is the last state variable.

Multiplying (4) by J gives

$$Jr = -J\dot{\omega}_d + J\alpha e - C_D\omega + \tau_{aero} - \tau_c \tag{9}$$

where (7) and (8) were utilized. Based on the expression in (9) the control torque is designed as

$$\tau_c = -J\dot{\omega}_d + J\alpha e - C_D\omega + \hat{f}(t) \tag{10}$$

where $\hat{f}(t)$ denotes a subsequently designed control term. By substituting (10) into (9), the result is

$$Jr = \tau_{aero} - \hat{f}(t) \tag{11}$$

From (11) it is evident that as $r(t)\rightarrow 0$, $\hat{f}(t)$ will identify the unknown input torque τ_{aero}. Therefore, it is desirable to design a controller such that $r(t)\rightarrow 0$. To facilitate the design of $\hat{f}(t)$, (11) is differentiated to get

$$J\dot{r} = \dot{\tau}_{aero} - \frac{d\hat{f}(t)}{dt} . \tag{12}$$

Based on (12) and the subsequent analysis, the control law for $\hat{f}(t)$ is designed as [13, 17]

$$\hat{f}(t) = (k_s+1)e(t) - (k_s+1)e(0) + \int_0^t [(k_s+1)\alpha e(\tau) + \beta_c \operatorname{sgn}(e(\tau))]d\tau \tag{13}$$

where k_s, α, and β_c are positive control gains and sgn(denotes the standard signum function. Note that α was previously defined in (8). The time derivative of (13) is given by

$$\frac{d\hat{f}(t)}{dt} = (k_s+1)r + \beta_c \operatorname{sgn}(e) . \tag{14}$$

After substituting (14) into (12), the closed-loop error dynamics are obtained as

$$J\dot{r} = -(k_s+1)r - e - \beta_c \operatorname{sgn}(e) + N \tag{15}$$

where the auxiliary function N denotes the unmeasurable auxiliary term of

$$N(\omega,\dot{\omega},t) = \dot{\tau}_{aero} + e . \tag{16}$$

Before analyzing the stability of the error dynamics, we introduce a new, unmeasurable auxiliary parameter N_d that is defined as

$$N_d(t) = \dot{\tau}_{aero} . \tag{17}$$

The reason to introduce N and N_d is to facilitate the stabilizing analysis. These quantities are used in the proof of the theorem that is about to be presented.

Theorem 1: The controller given in (10) and (13) achieves semi-global asymptotic position tracking in the sense that

$$e(t)\rightarrow 0 \quad \text{as} \quad t\rightarrow\infty$$

provided that β_c is selected according to the sufficient condition

$$\beta_c > \dot{\tau}_{aero} + \frac{\ddot{\tau}_{aero}}{\alpha} .$$

In addition, all system signals are bounded, and τ_{aero} can be identified in the sense that.

$$\left(\hat{f}(t) - \tau_{aero}\right) \rightarrow 0 \ as \ t \rightarrow \infty .$$

Proof: The proof is similar to that shown in [13].

B. Estimating the Coefficient of Performance

As a result, the quantity $\hat{f}(t)$ will be used to estimate the quantity τ_{aero}, which, in turn, will be used in the estimate of C_p. Under the stability analysis of the identifier-based controller, $\hat{f}(t) \rightarrow \tau_{aero}$ as t becomes large. Let ε be a specified angular velocity stabilization error tolerance. For a given set point when $\omega = \omega_d \pm \varepsilon$, then $\tau_{aero} = \hat{f}(t) + \zeta$ where ζ represents the resulting estimation error in $\hat{f}(t)$. At this point, $\hat{f}(t)$ very closely approximates τ_{aero}. Now define a bounded estimation of $\hat{P}_{aero}$ as

$$\hat{P}_{aero} = \hat{f}\omega . \tag{18}$$

By substituting (18) into (2), we now have an estimation of the unknown function of energy capture coefficient

$$\hat{C}_p = \frac{\hat{P}_{aero}}{P_{avail}} \tag{19}$$

or rewritten by using (18) and (1), the estimate becomes

$$\hat{C}_p = \frac{\hat{f}\omega}{\frac{1}{2}\rho A v^3} . \tag{20}$$

The closed loop control in (10) and (13) have driven the angular velocity to ω_d and, in the process, has provided an estimate for $C_p(\lambda,\beta)$. This is the inner loop of the turbine control.

C. Lyapunov Extremum Seeking Controller

Now that the state, ω, is regulated, a control law is needed to generate new angular velocity set points, ω_d. The sequence of set points constitutes a trajectory for ω_d. It is desired that the trajectory converges to the optimal point by means of choosing new values of blade pitch and tip-speed ratio. We begin with the development of the Lyapunov controller. The Lyapunov candidate function is

$$V = \frac{1}{2}\tilde{C}_p^2 \tag{21}$$

where

$$\tilde{C}_p = C_p^* - C_p . \tag{22}$$

Taking the time derivative of V provides

$$\dot{V} = -\tilde{C}_p \dot{C}_p . \tag{23}$$

We assume that the optimal operating point, C_p^*, is either constant or slowly time varying. The time derivative of C_p^* is then small and can be neglected. Replacing $\dot{C}_p$ with

$$\dot{C}_p = \frac{\partial C_p}{\partial \lambda}\dot{\lambda} + \frac{\partial C_p}{\partial \beta}\dot{\beta} , \tag{24}$$

the Lyapunov time derivative becomes

$$\dot{V} = -\dot{C}_p\left(\frac{\partial C_p}{\partial \lambda}\dot{\lambda} + \frac{\partial C_p}{\partial \beta}\dot{\beta}\right). \tag{25}$$

To ensure that $\dot{V}$ always remains negative semi-definite, $\dot{\lambda}$ and $\dot{\beta}$ are selected to parallel their respective gradients of C_p, namely, $\frac{\partial C_p}{\partial \lambda}$ and $\frac{\partial C_p}{\partial \beta}$. The term $\tilde{C}_p$ is guaranteed to be always greater than zero because of its definition in (22).

The outer loop Lyapunov controller developed in this section works in conjunction with the identifier-based controller. The Lyapunov controller will choose a new set-point once the shaft angular velocity has been stabilized within a given tolerance by the inner loop robust controller. Because of the different rates at which the inner and outer loops execute which can be appreciated by the necessary time for the regulation of $\omega \rightarrow \omega_d$, the outer loop becomes discrete. Using numerical differentiation, $\frac{\partial C_p}{\partial \lambda}$ and $\frac{\partial C_p}{\partial \beta}$ are determined approximately as

$$\frac{\partial C_p}{\partial \lambda} \approx \frac{\partial \hat{C}_p}{\partial \lambda} \approx \frac{(\hat{C}_{p_k} - \hat{C}_{p_{k-1}})}{\lambda_k - \lambda_{k-1}} \tag{26}$$

and

$$\frac{\partial C_p}{\partial \beta} \approx \frac{\partial \hat{C}_p}{\partial \beta} \approx \frac{(\hat{C}_{p_k} - \hat{C}_{p_{k-1}})}{\beta_k - \beta_{k-1}} \tag{27}$$

where $\hat{C}_p$ is the estimate of C_p. The time derivatives of the state variables, λ and β, are chosen so that the Lyapunov time derivative $\dot{V}$ remains negative semi-definite. For the tip speed ratio, we choose

$$\dot{\lambda} = \gamma_\lambda \frac{\partial C_p}{\partial \lambda} \tag{28}$$

where γ_λ is a positive constant. For the blade pitch, we choose

$$\dot{\beta} = \gamma_\beta \frac{\partial C_p}{\partial \beta} \tag{29}$$

and γ_β is also a positive constant.

The time derivatives $\dot{\lambda}$ and $\dot{\beta}$ provide a way of updating both set points so that $C_p \rightarrow C_p^*$. Because the gradients of $\frac{\partial C_p}{\partial \lambda}$ and $\frac{\partial C_p}{\partial \beta}$ must be estimated, as shown in (26) and (27), a discrete update law is written to represent (28) and (29). Let the subscript k denote the current time step and let k+1 denote the next, future time step. For the tip speed ratio, the discretized update law is given by

$$\lambda_{d_{k+1}} = \lambda_{d_k} + \gamma_\lambda \operatorname{sgn}\left(\frac{\partial \hat{C}_p}{\partial \lambda}\right) \tag{30}$$

where λ_{d_k} is the current value of the desired tip-speed ratio set point and $\lambda_{d_{k+1}}$ is the new value of the set point. A similar expression for the discretized blade pitch update is found to be

$$\beta_{k+1} = \beta_k + \gamma_\beta \operatorname{sgn}\left(\frac{\partial \hat{C}_p}{\partial \beta}\right) . \tag{31}$$

The signum function is used to extract the sign information from the estimated gradient partial derivatives. The dynamics of actuating β have been neglected under the assumption that they are small compared to the stabilization of $\omega \rightarrow \omega_d$. The set point ω_d is determined by rewriting (3) in terms of $\lambda_{d_{k+1}}$ as

$$\omega_d = \frac{\lambda_{d_{k+1}} v}{R}. \tag{32}$$

D. Implementation of Alternating Gradient Search

The implementation of the update laws require them to be executed in an alternating fashion. Because C_p is a scalar quantity, only one gradient component can be extracted at a time. The gradient information is necessary for the extremum seeking control to properly compute the update laws. To extract the gradient information, a two-loop alternating method is used. In the first loop, the tip-speed ratio is updated while the blade pitch is held constant. When the loop executes a second time, λ is held constant and β is updated. In this manner, the estimated changes in C_p are known to be only as a consequence of the parameter which was varied in the previous step.

E. Techniques for Reduction of Error Effects

Two sources of uncertainty are present in the wind turbine system with this control method. One is inherent in the wind velocity measurement. The other is the uncertainty in the estimation of the aerodynamic torque computed by the robust controller. To reduce the influence of these sources of uncertainty, two compensation techniques are developed. The first technique is a continuous gain weighting function which is applied to the update law gains of γ_λ and γ_β. The second is an averaging method which uses previous data points to assist in computing the computation of the gradients of C_p with respect to λ and β. Gradient estimate through finite difference can be influenced by noise and uncertain values. The purpose of the gain weighting function is to reduce the influence of gradient value uncertainty on choosing new set points of λ and β. As the peak of C_p is approached, uncertainty can contribute larger influences on the result because the gradient magnitude becomes small. Using a function of the form

$$\gamma = 0.75\left(1 - \tanh(12 * \hat{C}_p - 4.5)\right), \qquad (36)$$

gains γ_λ and γ_β are weighted as a function of C_p.

The second compensation technique is an averaging filter applied to the values of the set points and estimates of C_p. The moving average retains the previous n values of C_p, λ, and β. Figure 2 shows the manner in which these arrays are constructed through time. By averaging the data points before the partial derivatives of (26) and (27) are computed, both the effects of measurement noise and estimation error are reduced.

Beta Array		Lambda Array	
$\hat{C}_{p_k}$	β_k	$\hat{C}_{p_{k-1}}$	λ_{k-1}
$\hat{C}_{p_{k-2}}$	β_{k-2}	$\hat{C}_{p_{k-3}}$	λ_{k-3}
$\hat{C}_{p_{k-4}}$	β_{k-4}	$\hat{C}_{p_{k-5}}$	λ_{k-5}
⋮	⋮	⋮	⋮
$\hat{C}_{p_{k-(2n-1)}}$	$\beta_{k-(2n-1)}$	$\hat{C}_{p_{k-2n}}$	λ_{k-2n}

Fig. 2: The left array is built for the averaging of blade pitch. The right arry is for the averaging of tip-speed ratio.

IV. Simulation

The proposed control method is modeled and simulated using MATLAB/Simulink. The parameters used in Table 2 have been chosen to emulate a commercial scale wind turbine. The C_p plot, shown in Figure 1, is a graph of the coefficient of performance data used in this simulation [1]. The peak of value of C_p is 0.4735 at $\lambda^* = 7.8$ and $\beta^* = -1^\circ$. The initial conditions of the simulation are the turbine starting from rest (which implies that $\lambda = 0$) and the blade pitch at 3º. The wind generator is initialized at 10 m/s. These conditions have intentionally been selected to be distant from the optimal values of λ^* and β^* to demonstrate the extremum seeking behavior of the control method.

A Kaimal wind model generator is used from the Simulink Wind Blockset, [1], to create a realistic wind condition with a mean value of 10 m/s and a turbulence of 12%. The time history of the wind is shown in Fig. 3. A zero mean, white noise is also generated and added to the wind velocity signal. The parameters used to generate this wind signal can be seen in Table 2.

Fig. 4 shows the evolution of C_p as it approaches the optimal value. Fig. 5 shows τ_{aero} as a function of time. Fig. 6 shows a comparison of the power captured to the maximum possible power capture.

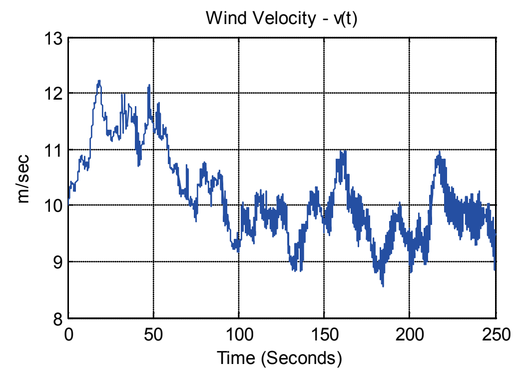

Fig.3: Graph of the wind velocity produced by the Kaimal wind velocity generator.

As shown in the simulation figures, the coefficient of performance is maximized and thus the power captured is maximized. Not only has the control method achieved stable control of the angular velocity, it has also been able to find the peak of the C_p curve with respect to tip-speed ratio and blade pitch. The controller has also maintained operation of the turbine at the peak value of C_p.

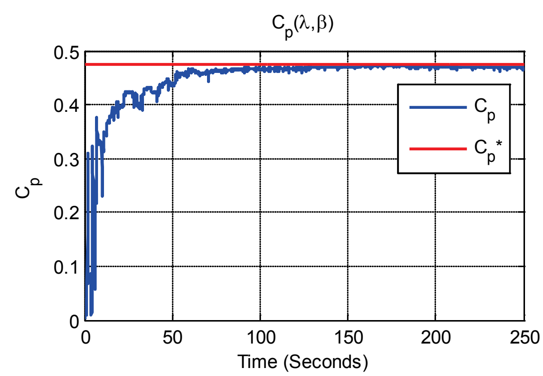

Fig.4: Graph of the coefficient of performance shown in blue plotted in comparison with the optimal value shown in red.

V. Conclusion and Future Work

A controller for achieving wind turbine peak power capture has been presented. An advantage of the extremum seeking control is that it does not require the introduction of a dither signal for providing plant perturbations. The simulation made use of available wind turbine aerodynamic data. Two means of inhibiting numerical problems in the

TABLE 2
WIND TURBINE SIMULATION PARAMETERS

Symbol	Quantity	Value
J	Rotational Inertia	100,000 kg m^2
C_D	Damping Coefficient	1 kg m^2/s
R	Swept Radius	40 m
$v(t)$	Wind Velocity	10 m/s (avg)
$w(t)$	Feedback Noise	N(0, 0.05) m/s
λ_0	Initial Tip-Speed Ratio	0.001 dimensionless
β_0	Initial Blade Pitch	3 degrees

Wind turbine model parameters and initial conditions used in the simulation.

gradient calculation of C_p were presented. These techniques consisted of a weighting method where diminishing weights were applied as the gradient magnitude decreased and an averaging technique where previous values of tip speed ratio, blade pitch, and C_p were utilized to eliminate spikes and unpredictable behavior in the new set points for λ and β. The controller showed robust behavior in the presence of turbulent wind and wind speed sensor noise. The proposed controller is attractive alternative to other ESC.

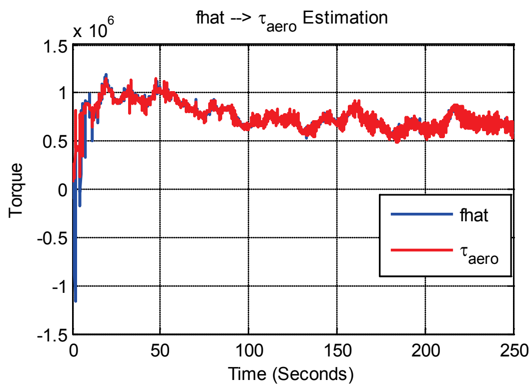

Fig. 5: Graph of the performance of the robust controller estimation of the unknown nonlinear aerodynamic torque

The wind turbine block set of [1] was used in the simulation and testing of the controller presented in this work. The immediate next step of this investigation is to incorporate the turbine model of FAST in the analysis. The challenge of doing this is that the dynamic model of FAST will change the assumed turbine dynamics and these dynamics must be incorporated into the control laws of the inner loop. The turbine dynamics assumed so far in this development have allowed the non-dither controller concepts to be proved and demonstrated.

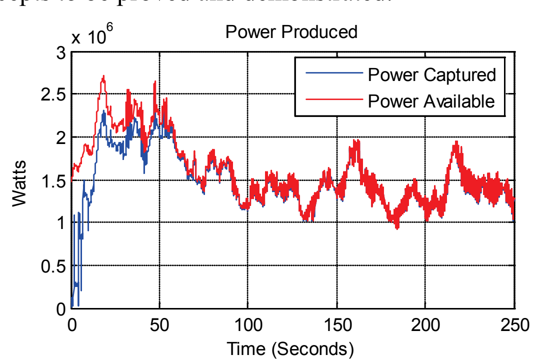

Fig 6. Graph of the power captured by the wind turbine, shown in blue, compared to the maximum possible power capture.

REFERENCES

[1] F. Iov, A.D. Hansen, P. Sorensen, F. Blaabjerg, "Wind Turbine Blockset in Matlab/Simulink," tech. rep. Aalborg University, Denmark, 2004.

[2] Kathryn E. Johnson, Lucy Y. Pao, Mark J Balas, Lee J. Fingersh, "Control of Variable-Speed Wind Turbines," *IEEE Control Systems Magazine*, June 2006.

[3] B. Malinga, J. Sneckenberger, J, Feliachi, "Modeling and Control of a Wind Turbine as a Distributed Resource," *Proc. 35th Southeastern Symp. Syst. Theory*, Morgantown WV, 2003, pp. 108-112.

[4] Brice Beltran, Tarek Ahmed-Ali, Mohamed El Hachemi Benbouzid, "Sliding Mode Power Control of Variable-Speed Wind Energy Conversion Systems," *IEEE Transactions on Energy Conversion Vol. 23, No. 2*, June 2008.

[5] Boubekeur Boukezzar, Mohamed M'Saad, "Robust Sliding Mode Control of a DFIG Variable Speed Wind Turbine for Power Production Optimization," *16th Mediterranean Conference on Control and Automation*, June 2008.

[6] Kathryn E. Johnson, Lee J. Fingersh, Mark J. Balas, Lucy Y. Pao, "Methods for Increasing Region 2 Power Capture on a Variable-Speed Wind Turbine," *Transactions of the ASME Vol. 126*, November 2004.

[7] Xin Ma, "Adaptive Extremum Control and Wind Turbine Control," *Ph. D. Thesis Denmark Technical University*, May 1997.

[8] Justin Creaby, Yaoyu Li, John E. Seem, "Maximizing Wind Turbine Energy Capture using Multivariable Extremum Seeking Control," *Wind Engineering Vol. 33, No. 4, pp 361-388*, 2009.

[9] Kartik B. Ariyur, Miroslav Kristic, "*Real-Time Optimization by Extremum-Seeking Control,*" John Wiley and Sons Inc, 2003

[10] Q. Chen, Y. Li, Z. Yang, J. E. Seem, J. Creaby, "Self-optimizing Robust Control of Wind Power Generation with Doulby-Fed Induction Generator," *ASME Dynamic Systems and Control Conference*, USA, Sep. 2010.

[11] P. M. Patre, W. MacKunis, C. Makkar, and W. E. Dixon, "Asymptotic tracking for systems with structured and unstructured uncertainties," *IEEE Trans. Contr. Syst.Technol.*, vol. 16, no. 2, pp. 373–379, 2008.

[12] Z. Qu and J. Xu, "Model-based learning controls and their comparisons using Lyapunov direct method," *Asian Journal of Control*, vol. 4, no. 1, pp. 99–110, Mar. 2002.

[13] B. Xian, D. M. Dawson, M. S. de Queiroz, and J. Chen, "A continuous asymptotic tracking control strategy for uncertain nonlinear systems," *IEEE Trans. Automat. Contr.*, vol. 49, no. 7, pp. 1206–1211, Jul. 2004.

[14] Z. Cai, M. S. de Queiroz, and D. M. Dawson, "Robust adaptive asymptotic tracking of nonlinear systems with additive disturbance," *IEEE Trans. Automat. Contr.*, vol. 51, pp. 524–529, 2006.

[15] B. Xian, M. S. de Queiroz, D. M. Dawson, and M. McIntyre, "A discontinuous output feedback controller and velocity observer for nonlinear mechanical systems," *Automatica*, vol. 40, pp. 695–700, 2004.

[16] X. Zhang, A. Behal, D. M. Dawson, and B. Xian, "Output feedback control for a class of uncertain MIMO nonlinear systems with non-symmetric input gain matrix," in *Proc. IEEE Conf. on Decision and Control, and the European Control Conf.* , pp. 7762–7767, Spain, 2005.

[17] C. Makkar, G. Hu, W. G. Sawyer, and W. E. Dixon, "Lyapunov-based tracking control in the presence of uncertain nonlinear parameterizable friction," *IEEE Trans. Automat. Contr.*, vol. 52, no. 10, pp. 1988–1994, 2007.

[18] E. Iyasere, M. Salah, D. Dawson, J. Wagner, "Nonlinear Robust Control to Maximize Energy Capture in a Variable Speed Wind Turbine," *American Control Conference*, June 2008.

[19] E. Iyasere, M. Salah, D. Dawson, J. Wagner, "Nonlinear Robust Control to Maximize Energy Capture in a Variable Speed Wind Turbine Using a Separately Excited DC Generator," *College of Engineering and Science Control and Robotics Technical Report*, June 2008.

[20] T. G. Hawkins, W. N. White, G. Hu, F. D. Sahneh, "Wind Turbine Power Capture Control with Robust Estimation," *ASME Dynamic Systems and Control Conference*, USA, Sep. 2010.