International Journal of Control
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713393989

Adaptive backstepping control of variable speed wind turbines

U. Ozbay [a]; E. Zergeroglu [a]; S. Sivrioglu [b]
[a] Gebze Inst. of Technology, Computer Engineering Department, Kocaeli, Turkey
[b] Gebze Inst. of Technology, Department of Energy Systems, Kocaeli, Turkey

First Published: June 2008

To cite this Article: Ozbay, U., Zergeroglu, E. and Sivrioglu, S. (2008) 'Adaptive backstepping control of variable speed wind turbines', International Journal of Control, 81:6, 910 — 919

To link to this article: DOI: 10.1080/00207170701519078
URL: http://dx.doi.org/10.1080/00207170701519078

International Journal of Control
Vol. 81, No. 6, June 2008, 910–919

Adaptive backstepping control of variable speed wind turbines

U. OZBAY†, E. ZERGEROGLU*† and S. SIVRIOGLU‡

†Gebze Inst. of Technology, Computer Engineering Department, P.K. 141, Gebze, 41400, Kocaeli, Turkey
‡Gebze Inst. of Technology, Department of Energy Systems, P.K. 141, Gebze, 41400, Kocaeli, Turkey

(*Received 27 November 2006; in final form 16 June 2007*)

Variable speed wind turbines maximize the energy capture by operating the turbine at the peak of the power coefficient, however parametric uncertainties in mechanical and electrical dynamics of the system may limit the efficiency of the turbine. In this study, we present an adaptive backstepping approach for the variable speed control of wind turbines. Specifically, to overcome the undesirable effects of parametric uncertainties, a desired compensation adaptation law (DCAL) based controller has been proposed. The proposed method achieves global asymptotic rotor speed tracking, despite the parametric uncertainty on both mechanical and electrical subsystems. Extensive simulation studies are presented to illustrate the feasibility and efficiency of the method proposed.

1. Introduction

Wind power generation is a growing sector in the electricity production industry owing to its renewable energy characteristics and reduced environmental problems. Most wind turbines used for power generation are operated at constant speed, however, there is considerable interest in variable speed wind turbines due to their increased energy capture and reduced drive train loads. In variable speed wind turbines, it is possible to control the rotor speed of turbine. This allows the wind turbine system to operate constantly near to its optimum tip-speed ratio. Mainly, it is aimed to follow wind-speed variations in low and moderate velocities to maximize aerodynamic efficiency. Therefore, variable speed wind turbines have potential to maximize energy generation.

The behaviour of the variable speed turbine is significantly affected by the control strategy employed in their operation (Muldaji *et al.* 1998). Effectiveness and reliability of the wind power generation is changing depending on the control techniques, that is to make wind power truly cost-effective and reliable for variable speed turbines, advanced control techniques are imperative. To increase the efficiency, model based control design approaches can be applied. One drawback, however, is that mechanical and electrical parameter values of wind turbines are not truly available. Especially in practical applications, uncertainties limit the efficient energy capture of a variable speed turbine. In literature different control strategies have been proposed for variable speed wind turbines (Muldaji *et al.* 1998, Song *et al.* 2000, Johnson *et al.* 2004, 2006, Boukhezzar *et al.* 2005). Muldaji *et al.* (1998) evaluated a variable-speed, stall-regulated strategy which eliminates the need for ancillary aerodynamic control systems. In Boukhezzar *et al.* (2005) a cascade structure non-linear controller has been proposed; however the proposed mechanism did not account for the parametric uncertainties of the system. Song *et al.* (2000) presented two non-linear controllers, one exact model knowledge and the other adaptive for the rotor velocity tracking. However, the proposed adaptive controller scheme could only compensate for the uncertainties in the mechanical subsystem and required the exact knowledge of electrical subsystem parameters. In this study, an adaptive backstepping control that can compensate for the uncertainties of both the mechanical and electrical subsystems is proposed. To achieve this result a DCAL based rule in conjunction with an integral term injected to the Lyapunov like function to ensures the stability of the system has been used. When compared to Song *et al.* (2000), owing to its contemporary design technique, the proposed adaptive controller compensates for the uncertainties throughout the

*Corresponding author. Email: ezerger@bilmuh.gyte.edu.tr

International Journal of Control
ISSN 0020–7179 print/ISSN 1366–5820 online © 2008 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/00207170701519078

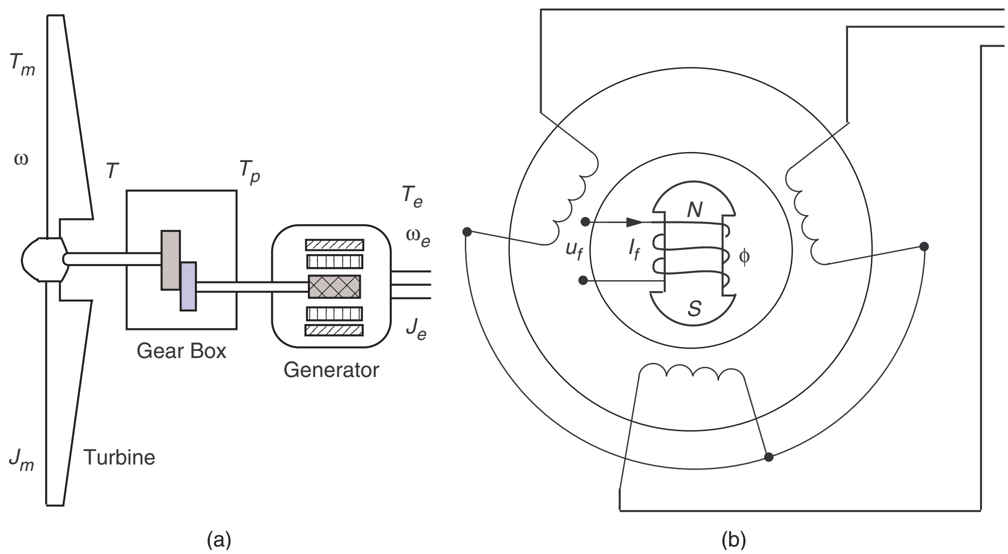

Figure 1. Illustration of wind turbine system: (a) The overall system: (b) The electrical subsystem.

entire system while the adaptive controller of (Song *et al.* 2000) requires the parameters of the electrical subsystem and since the proposed controller is based on a DCAL based design, it has the following implementation advantages: (i) the controller does not require the on-line computation of the non-linear regression vector, i.e., the desired version of the states are used for the feedforward term therefore most parts of the feedforward term can be calculated off-line before the implementation; (ii) contamination of the feedforward terms, due to state measurements (sensor noise), are also avoided. To our best knowledge, the controller proposed in this work, is the first in the literature that can compensate for the parametric uncertainties throughout the entire wind turbine system and still achieve global asymptotic stability for the variable speed turbines.

The remainder of the paper is organized as follows: in § 2 the model of the wind turbine used in this study and the problem statement is given; the error system development and the backstepping controller design scheme is presented in § 3; the stability and boundedness of the closed loop system are investigated in § 4; while the simulation studies and some concluding remarks are given in §§ 5 and 6 respectively.

2. System model and problem statement

The mathematical model governing the power extraction dynamics of a wind turbine, illustrated in figure 1(a), is assumed to be in the following form (Song *et al.* 2000):

$$J\dot{\omega} + B\omega + K\int_0^t \omega(\tau)\mathrm{d}\tau = T_m - \gamma T_e, \tag{1}$$

where ω, and $\dot{\omega}$ are the angular velocity of the shaft at turbine end and its time derivative respectively, ω_e is the angular velocity at the generator end, $J = J_m + \gamma^2 J_e$ is the total moment of inertia of the generator-turbine couple, with J_m, J_e being the inertia of the turbine, the inertia of the generator respectively and $\gamma \triangleq \omega_e/\omega$ represents the the gear ratio. Similarly $B = B_m + \gamma^2 B_e$ is the total friction related, $K = K_m + \gamma K_e$ is the torsion related constant parameters of the turbine and the generator couple, T_m is the turbine torque, and T_e is the generator torque. It is well known that (Bergen 1996), (Song *et al.* 2000) the turbine torque T_m, and the generator torque T_e, are related to the angular velocity term and the excitation current of the generator via the following relationships

$$\left.\begin{aligned} T_m &= k_w \cdot \omega^2, \\ T_e &= K_\phi \cdot c(I_f), \end{aligned}\right\} \tag{2}$$

where k_w is a wind speed to power transfer parameter depending on factors like air density, radius of the rotor, the wind speed and the pitch angle, K_ϕ is a machine-related constant, $c(I_f)$ is the flux in the generating system function, and I_f is the field current. Inserting for T_m, and T_e from equation (2) back into (1) we obtained generator end angular velocity free model of the system as

$$J\dot{\omega} + B\omega + K\int_0^t \omega(\tau)\mathrm{d}\tau = k_w\omega^2 - \gamma K_\phi c(I_f). \tag{3}$$

The exciter (electrical subsystem) dynamics of a wind turbine system is assumed to be governed by

$$L\dot{I}_f + R_f I_f = u_f, \tag{4}$$

where L is the constant inductance of the circuit, R_f is the resistance of the rotor field, I_f was defined in (2) and u_f is the field voltage. Our control objective is to design the field voltage which ensures that the angular velocity of the shaft at turbine end, ω, would follow a reference trajectory, $\omega_d \in C^2$, generated according to the operational modes of the turbine, despite the lack of exact knowledge of both the mechanical system parameters of (3) and electrical system parameters of (4). The controller design and the stability analysis also requires the desired reference trajectory to be first order integrable, that is

$$\int_0^T |\omega_d(\tau)| \mathrm{d}\tau < \infty \tag{5}$$

with T being finite (i.e., $\omega_d \in \mathcal{L}_1 \cap \mathcal{L}_\infty$ and $\dot{\omega}_d, \ddot{\omega}_d \in \mathcal{L}_\infty$).

3. Control design

To quantify the control objective, we defined the angular velocity tracking error signal $e(t)$ as follows:

$$e = \omega_d - \omega. \tag{6}$$

To this end we take the time derivative of (6), premultiply the resultant equation by the total moment of inertia of the generator-turbine couple to obtain

$$J\dot{e} = J\dot{\omega}_d + B\omega + K\int_0^t \omega(\tau)\mathrm{d}\tau - k_w\omega^2 + \gamma K_\phi c(I_f), \tag{7}$$

where (3) was utilized for the $J\dot{\omega}$ term. At this point of the analysis, we define an auxiliary term, which might be referred as "the desired version" of mechanical dynamics $f_d(\dot{\omega}_d, \omega_d)$ that will aid the analysis, as follows

$$f_d = J\dot{\omega}_d + B\omega_d - k_w\omega_d^2 + K\int_0^t \omega_d(\tau)\mathrm{d}\tau, \tag{8}$$

adding and subtracting $f_d(\dot{\omega}_d, \omega_d)$, the open loop mechanical dynamics of the wind turbine can be reformulated to have the following form:

$$J\dot{e} = \Omega + f_d - K\int_0^t e(\tau)\mathrm{d}\tau + \gamma K_\phi \cdot c(I_f), \tag{9}$$

where the $\Omega(.) \in \Re$ is explicitly defined as

$$\Omega \;= B(\omega - \omega_d) - k_\omega(\omega^2 - \omega_d^2). \tag{10}$$

Remark 1: Note that the auxiliary term defined in (8) can be written as a multiple of a known regression vector and unknown parameter vector in the following form:

$$f_d = W_d\theta, \tag{11}$$

where the regression vector $W_d \in \Re^{1\times 4}$, and the unknown but constant parameter vector $\theta \in \Re^{4\times 1}$ are defined as

$$\left.\begin{aligned} W_d &= \begin{bmatrix} \dot{\omega}_d & \omega_d & \int_0^t \omega_d(\tau)\mathrm{d}\tau - \omega_d^2 \end{bmatrix}, \\ \theta &= \begin{bmatrix} J & B & K & k_w \end{bmatrix}^T, \end{aligned}\right\} \tag{12}$$

Remark 2: Due to the structure of (10), the auxiliary function Ω can be upper bounded as follows:

$$\|\Omega\| \le \zeta_B|\omega_d - \omega| + \zeta_K|\omega_d - \omega||\omega_d + \omega|, \tag{13}$$

where ζ_B and ζ_K are positive bounding constants for the variables B and k_w respectively and $\|\cdot\|$ denotes the standard Euclidean norm. Using the definition of the tracking error term and applying some algebraic manipulations 13 can be further be bounded as

$$\|\Omega\| \le \rho(\|e\|)\|e\|, \tag{14}$$

with $\rho(\cdot)$ being a positive, non-degreasing bounding function of the form

$$\rho = \zeta_K\|e\| + (\zeta_B + 2\zeta_d\zeta_K), \tag{15}$$

where ζ_d is the upper bound of the desired reference trajectory signal ω_d. The bound given in 14 will be exploited to obtain the stability result delineated in the following sections.

Applying a backstepping (Kristic *et al*. 1995) argument on (7) we can rearrange (9) to have the following form:

$$J\dot{e} = \Omega + f_d - K\int_0^t e(\tau)\mathrm{d}\tau + z + \alpha, \tag{16}$$

where the $\alpha(t)$ is an auxiliary control design variable and $z(t)$ is backstepping variable explicitly defined as follows:

$$z \triangleq \gamma K_\phi \cdot c(I_f) - \alpha. \tag{17}$$

From the subsequent stability analysis the auxiliary control signal $\alpha(t)$ can be designed to have the following form:

$$\alpha = -k_o e - W_d\hat{\theta} - k_n\rho^2 e, \tag{18}$$

where the bounding function ρ was defined in (14), k_o and k_n are positive constant control gains, the regression vector for the mechanical terms, W_d, was defined in (12), and $\hat{\theta} \in \Re^{4\times 1}$ contains the dynamic parameters estimates that are explicitly defined by the following update rule

$$\dot{\hat{\theta}} = \Gamma_\theta W_d^T e, \tag{19}$$

with $\Gamma_\theta \in \Re^{4\times4}$ being a positive definite, diagonal adaptation gain matrix. After substituting (18) into (16), the closed-loop dynamics for $e(t)$ is obtained as

$$J\dot{e} = -k_o e - K\int_0^t e(\tau)\mathrm{d}\tau + W_d\tilde{\theta} + \Omega - k_n\rho^2 e + z, \quad (20)$$

where $\tilde{\theta} \triangleq \theta - \hat{\theta}$ is the parameter estimation error for the mechanical subsystem. The backstepping design procedure applied in (16) also requires the dynamics of the auxiliary term $z(t)$. To this end, we take the time derivative of (17) and multiply by the positive generator inductance term L to obtain

$$L\dot{z} = \gamma K_\phi \frac{\partial c(I_f)}{\partial I_f\%} L\dot{I}_f - L\dot{\alpha}. \quad (21)$$

Substituting for $L\dot{I}_f$ and the time derivative of α from (4) and (18) respectively, (21) can be reconstructed to have the following form:

$$L\dot{z} = \gamma K_\phi \frac{\partial c(I_f)}{\partial I_f}(u_f - R_f I_f) + L\Big(\big(k_o + k_n\rho^2\big)\dot{e} + \dot{W}_d\hat{\theta} + W_d \cdot \dot{\hat{\theta}}\Big), \quad (22)$$

inserting for the $\dot{e}$ term form (7) and rearranging the terms we have

$$L\dot{z} = \gamma K_\phi \frac{\partial c(I_f)}{\partial I_f} u_f + Y\phi, \quad (23)$$

where $Y(\dot{\omega}_d, \omega, I_f) \in \Re^{1\times6}$ is a regression vector that contains the known and measurable signals while $\phi \in \Re^{1\times6}$ is the unknown parameter vector containing the combination of both mechanical and electrical uncertain parameters. The explicit definitions of $Y(\dot{\omega}_d, \omega, I_f)$ and ϕ terms are given in Appendix A.

From the structure of (23), (20) and the subsequent stability analysis the field voltage u_f is designed in the following form:

$$u_f = \frac{1}{\gamma K_\phi (\partial c(I_f))/(\partial I_f)}\Big(-k_z z - e - Y\hat{\phi}\Big), \quad (24)$$

where k_z is a positive constant control gain, the regression vector, Y, was defined in (23), and $\hat{\phi} \in \Re^{6\times1}$, similar to the definition of $\hat{\theta}$ given in (18) contains the dynamic parameter estimates for the unknown parameter vector ϕ, that is explicitly defined as follows:

$$\dot{\hat{\phi}} = \Gamma_\phi Y^T z, \quad (25)$$

with $\Gamma_\phi \in \Re^{6\times6}$ being a positive definite and diagonal adaptation gain matrix.

Substituting (24) into (23), the closed-loop dynamics for the backstepping variable z is obtained to have the following form

$$L\dot{z} = -k_z z + Y\tilde{\phi} - e, \quad (26)$$

where $\tilde{\phi} = \phi - \hat{\phi}$ is the parameter estimation error for the combined (electrical and mechanical) subsystems.

4. Analysis

Forming the closed loop error dynamics for the signals $e(t)$ and $z(t)$, we are now ready to state the following Theorem

Theorem 1: *The adaptive controller give by* (24) *and the auxiliary control input* (18) *with the parameter update laws* (19) *and* (25) *guarantees global asymptotic angular velocity tracking for the variable speed wind turbine system having mechanical dynamics given* (3) *with exciter dynamics of* (4), *in the sense that*

$$\lim_{t\to\infty} e(t) = 0. \quad (27)$$

Proof: We start our proof by defining the following non-negative scalar function

$$V = \tfrac{1}{2}\Big(Je^2 + Lz^2 + K\xi^2 + \tilde{\theta}^T\Gamma_\theta^{-1}\tilde{\theta} + \tilde{\phi}^T\Gamma_\phi^{-1}\tilde{\phi}\Big), \quad (28)$$

where the term ξ is explicitly defined as follows:

$$\xi \triangleq \int_0^t e(\tau)\mathrm{d}\tau. \quad (29)$$

After taking time derivative of (28) along (20), (26) (19) and (25) and cancelling common terms, we obtain

$$\dot{V} = -k_o e^2 - k_z z^2 + \big[\Omega - k_n\rho^2 e\big]e, \quad (30)$$

adding and subtracting $\|e\|^2/4k_n$, and then completing the squares of the bracketed term of (30), we obtain the following upper bound for the time derivative of $V(t)$ as

$$\dot{V} \le -\left(k_o - \frac{1}{4k_n}\right)\|e\|^2 - k_z\|z\|^2 \le -\min\left\{\left(k_o - \frac{1}{4k_n}\right), k_z\right\}\|x\|^2, \quad (31)$$

where $x \in \Re^{2\times1}$ is defined as follows:

$$x = \begin{bmatrix} e^T & z^T \end{bmatrix}^T. \quad (32)$$

From the structure of (28) and (31), we can conclude that when the control gain k_n is selected sufficiently high, $V \in \mathcal{L}_\infty$; hence $e(t)$, $z(t)$, $\int_0^t e(\tau)\mathrm{d}\tau$, $\tilde{\theta}$ and $\tilde{\phi} \in \mathcal{L}_\infty$. Due to the boundedness of these signals we can follow the standard signal chasing arguments to show that all of the signals in the closed loop error system are bounded.

Due to boundedness of $\dot{e}(t)$ and $\dot{z}(t)$ we know that $e(t)$ and $z(t)$ are uniformly continuous. In addition from the structure of (31) and the boundedness of $V(t)$ we can show that $x(t)$ therefore $e(t) \in \mathcal{L}_2$. We can know apply Barbalat's Lemma (Kristic *et al.* 1995 to conclude that the argument given in (27) is valid.

5. Simulation results

To verify the performance of the proposed adaptive controller, two different sets of simulation studies were performed using same system parameters given in Song *et al.* (2000). On the first simulation the reference angular velocity signal $\omega_d(t)$ selected as

$$\omega_d(t) = 2 + \sin(t) \tag{33}$$

and on the second one a more realistic reference rotor velocity signal of the form

$$\omega_d(t) = \left\{ \begin{array}{ll} 0, & u(k) < u_c, \\ X_m\left(1 + \sin\left(\frac{\pi}{2}\frac{(u(k)-s_1)}{d_1}\right)\right), & u(k) < u_r, \\ X_m, & u(k) < u_f, \\ X_m\left(1 + \sin\left(\frac{\pi}{2}\frac{(u(k)-s_2)}{d_2}\right)\right), & u(k) < u_f, \\ 0, & u(k) > u_f \end{array} \right\} \tag{34}$$

have been applied where

$$\begin{array}{ll} s_1 = \dfrac{u_c + u_r}{2}, & d_1 = \dfrac{u_r - u_c}{2}, \\ s_2 = \dfrac{u_f + u_r}{2}, & d_2 = \dfrac{u_r - u_f}{2}, \\ u_s = 21.3\,\text{m/sec}, & X_m = 4.1\,\text{rad/sec}, \\ u_c = 4.3\,\text{m/sec}, & u_r = 7.7\,\text{m/sec} \quad u_f = 17.9\,\text{m/sec}. \end{array} \tag{35}$$

Note that the parameter X_m is specified according to the allowable rotor speed. The system parameters for both simulations are considered as

$$\begin{array}{l} R_f = 0.02\Omega, \quad L = 0.001H, \\ J = 24490, \quad B = 52, \quad K = 52, \quad k_w = 3 \quad K_\phi = 1.7 \\ c(I_f) = 1000 I_f. \end{array} \tag{36}$$

For both simulations the controller gains are selected as

$$k_o = 50, \quad k_z = 2.6, \quad k_n = 50, \quad \rho = 15, \tag{37}$$

and the adaptation gains are set to

$$\begin{array}{l} \Gamma_\theta = \text{diag}\{24400 \quad 52 \quad 3 \quad 10\} \\ \Gamma_\phi = \text{diag}\left\{ \begin{array}{ccc} 0.02 & 0.001 & 2.12 \times 10^{-6} \\ 1.22 \times 10^{-7} & 2.12 \times 10^{-6} & 4 \times 10^{-8} \end{array} \right\} \end{array} \tag{38}$$

Remark 3: As opposed to classical methods, like proportional (P), proportional–derivative (PD) or proportional–integral–derivative (PID) controllers, to our best knowledge, there is no standard procedure for gain tuning for non-linear controllers. However in simulation studies of non-linear adaptive controllers, the tedious trial and error based procedure can be shortened using the following procedure which was also applied in our simulation studies: set all the initial values of the parameter estimates to the actual values then set the adaptation gains to zero and tune the feedback gains similar to that of a classical PD type controller. When the best tracking error performance is achieved, back up the feedback gains by 10% and set the initial values of the parameter estimated to zero then continue with the tuning process by slowly increasing the adaptation gains until all parameter estimates converge and steady state performance of the tracking error is as good as the values with zero adaptation. Though this procedure is only valid for simulations, our experience with various systems have shown that the gains obtained using this procedure in simulation studies is a good starting point when the actual system gains have to be adjusted.

To ease the presentation, the mechanical system parameter estimates used for the calculation of the auxiliary control input α of (18) are referred to as the inner loop adaptations and the combined mechanical and electrical dynamics parameter estimates defined in (23) are referred to as the outer loop adaptations. The results of the first simulation (with sinusoidal reference trajectory) are shown in figures 2–6. Figure 2 illustrates the reference and actual rotor velocities during the simulation and figure 3 presents the angular velocity tracking error. The parameter estimates for the

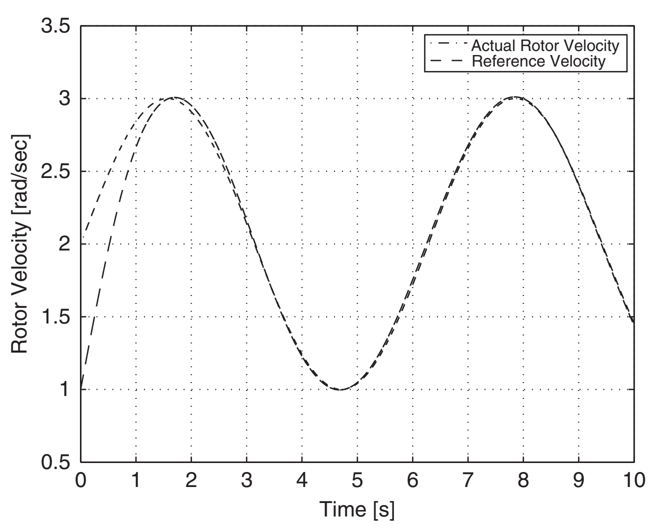

Figure 2. Reference and actual rotor velocities for simulation 1.

inner and outer loop adaptations are given in figures 4 and 5 respectively while the control effort (field voltage) is presented in figure 6. As can be seen from the figures, both the mechanical and outer loop parameter adaptations are all settled around 40 sec. Another issue to point out is the convergence of the parameters referred as the outer loop parameters (shown figure 5). The estimates of these parameters converge to very small values, we believe this is due to the comparably large value of the total inertia of the system that appears in the denominator of the outer loop adaptation parameters. As can be seen from the tracking error figure, the adaptive controller achieves good performance. Figures 7–11 are presented to illustrate the performance of the second simulation. Similar to Simulation #1, the reference and actual rotor velocities are presented in figure 7 while the velocity tracking error graphed in figures 8–10 presents the parameter estimates and figure 11 gives the applied control input to the system. From the results of the second simulation which represents a more realistic case both the adaptations and the controller achieves nearly perfect performance in considerably small amount of time.

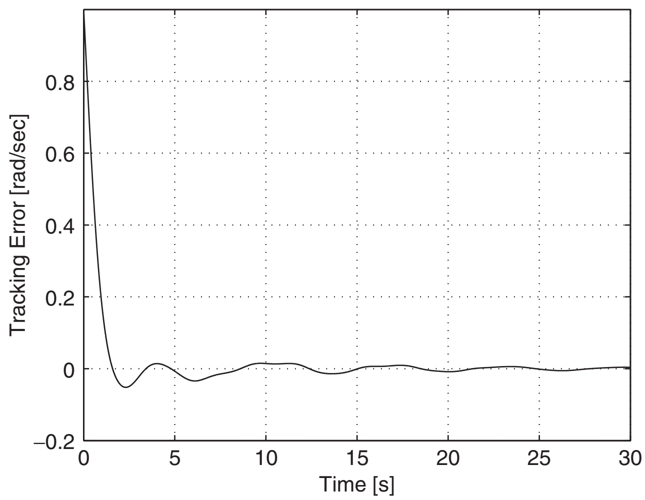

Figure 3. Angular tracking error of simulation 1.

To compare the results of the proposed controller with the non-linear controllers of Song *et al*. (2000), we have simulated the algorithms given in Song *et al*. (2000) using the controller and adaptation gains given in the paper. Similar results were obtained for the non-linear controller of Song *et al*. (2000), however we were unable to regenerate the results given in the paper for the adaptive type controller. Therefore only a comparative analysis between the exact model knowledge non-linear

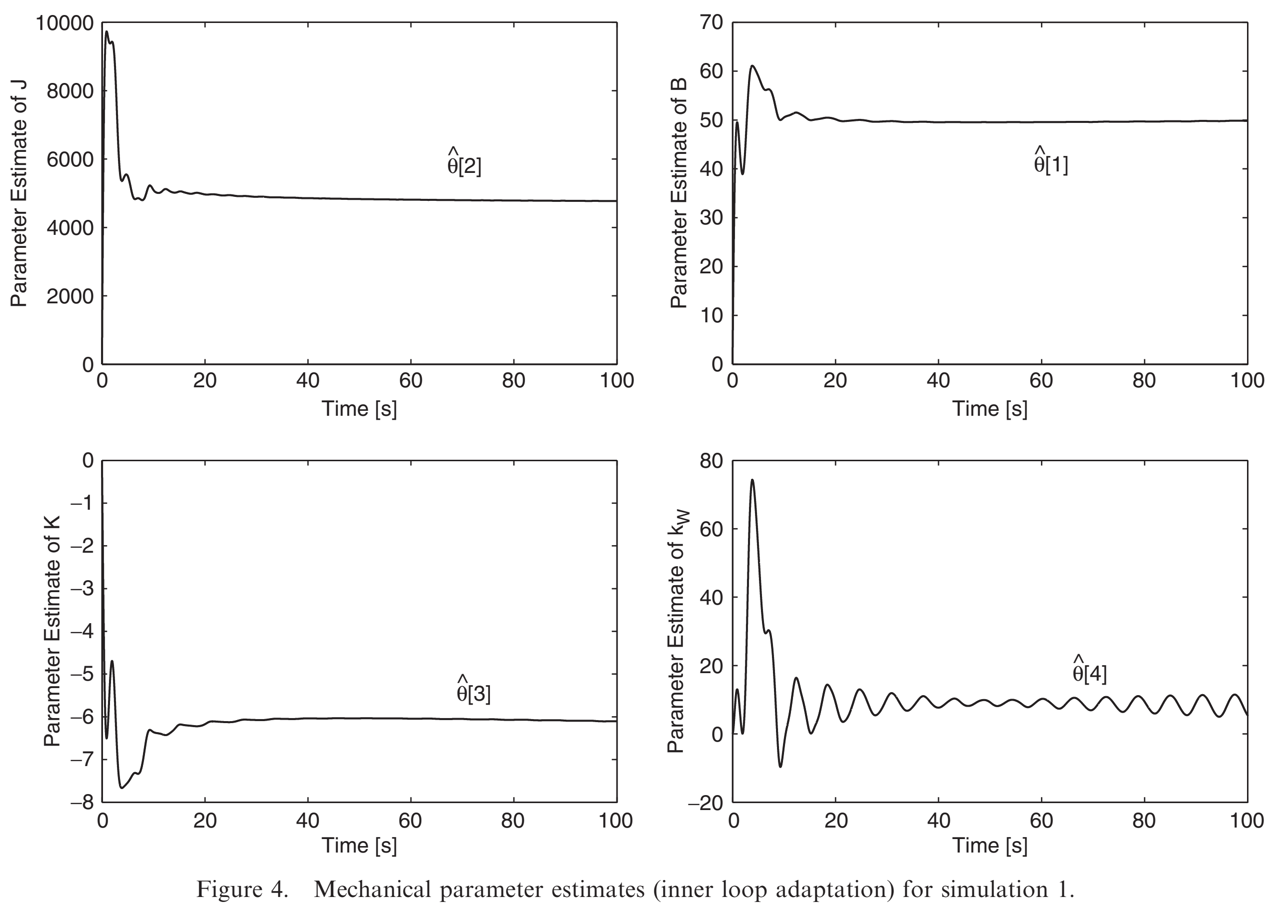

Figure 4. Mechanical parameter estimates (inner loop adaptation) for simulation 1.

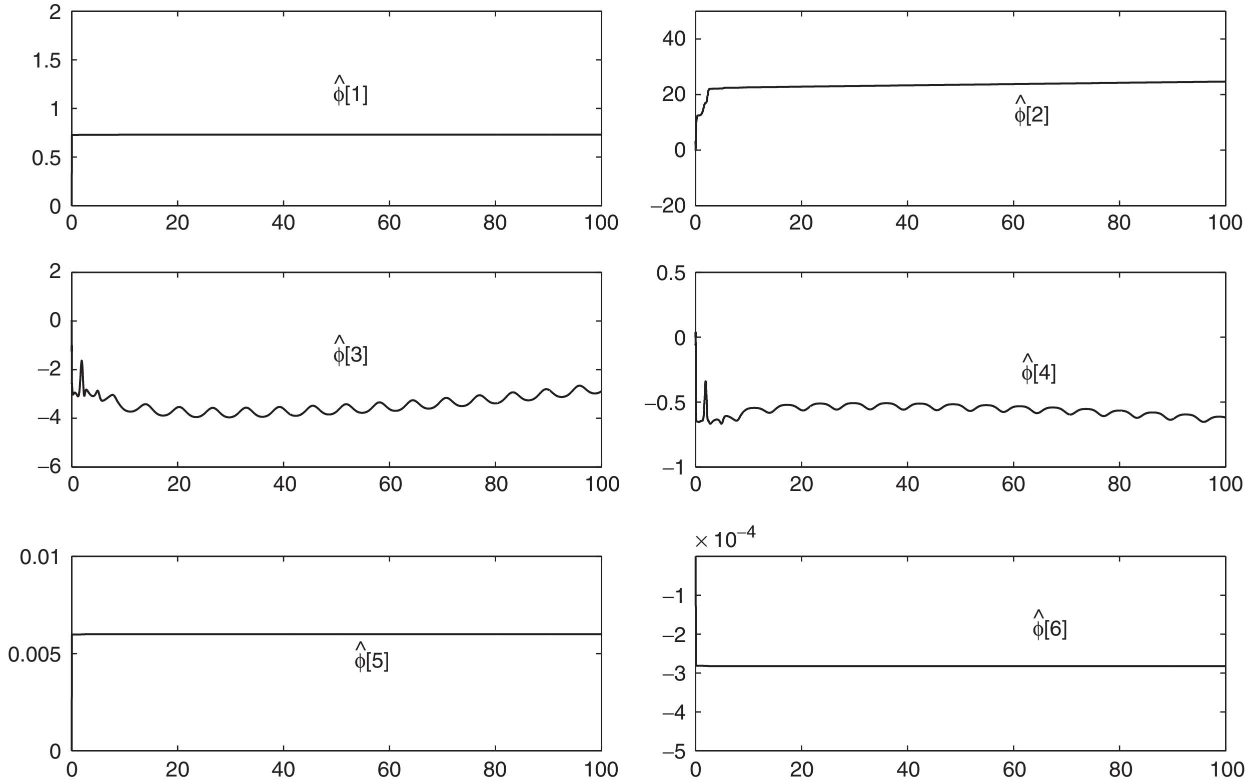

Figure 5. Outer loop parameter estimates for simulation 1.

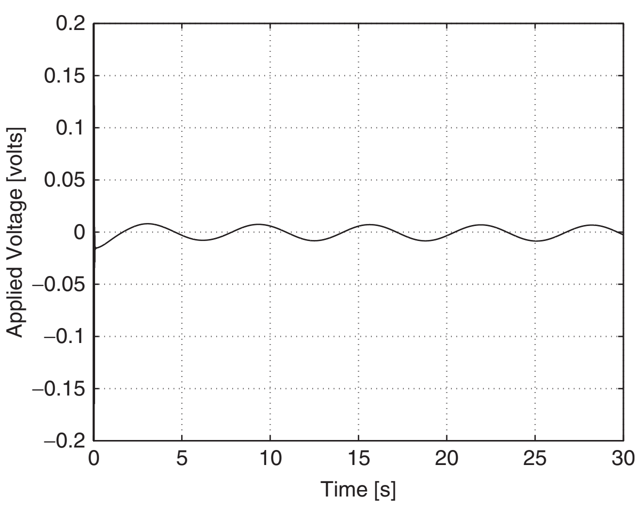

Figure 6. Control effort (field voltage) for simulation 1.

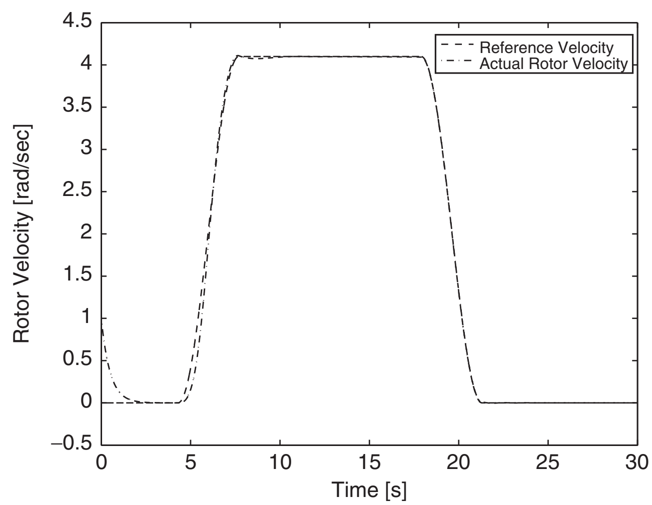

Figure 7. Reference and actual rotor velocities for simulation 2.

controller of Song *et al.* (2000) and the proposed adaptive controller is available. The $\mathcal{L}_2$ norms (i.e., $(\int_0^T |f(\cdot)|^2 \mathrm{d}t)^{1/2}$) of the applied control effort, $u_f(t)$, from 1–100 sec., the overall error performance, $e(t)\rfloor_{t=0}^{t=100}$, and steady state error performance, $e(t)\rfloor_{t=50}^{t=100}$, for both controllers with the desired velocity profiles of (33) and (34) are given in table 1. The notation EMK is used for the non-linear controller of Song *et al.* (2000) and ADP is used for the proposed adaptive controller.

As can be viewed from table 1, for the sinusoidal reference trajectory of (33), both controllers guarantee the convergence of the error term very quickly, and as expected, the EMK controller requires less control effort as all, normally uncertain, system parameters are

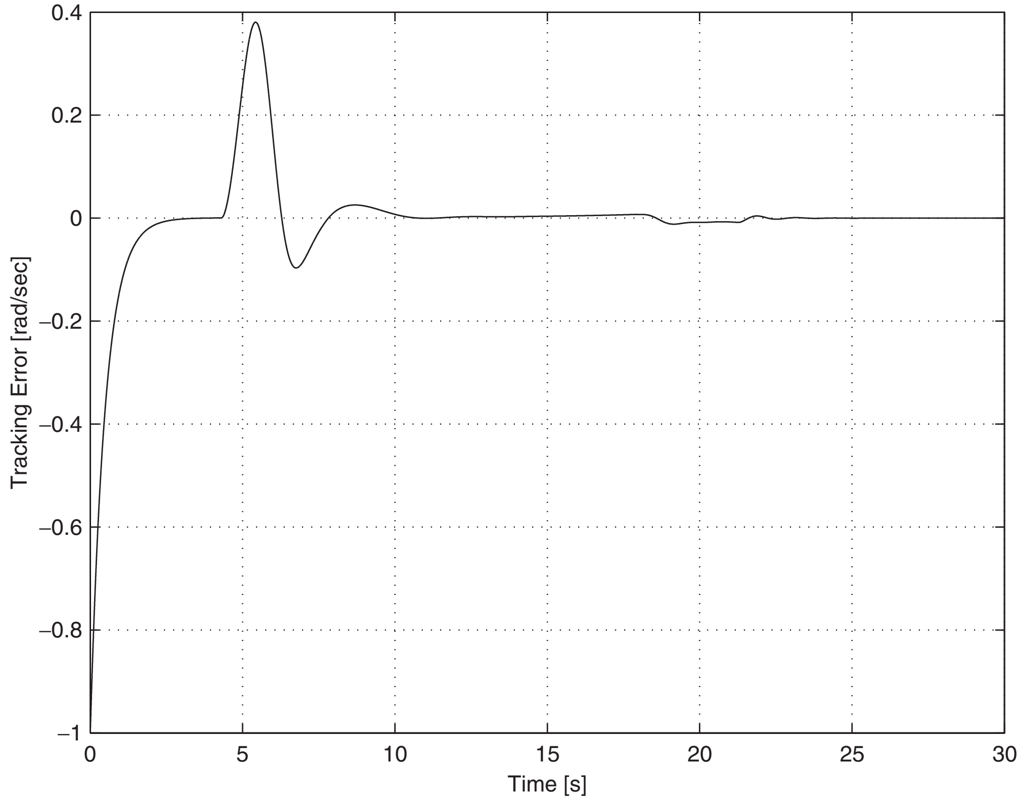

Figure 8. Angular tracking error term of simulation 2.

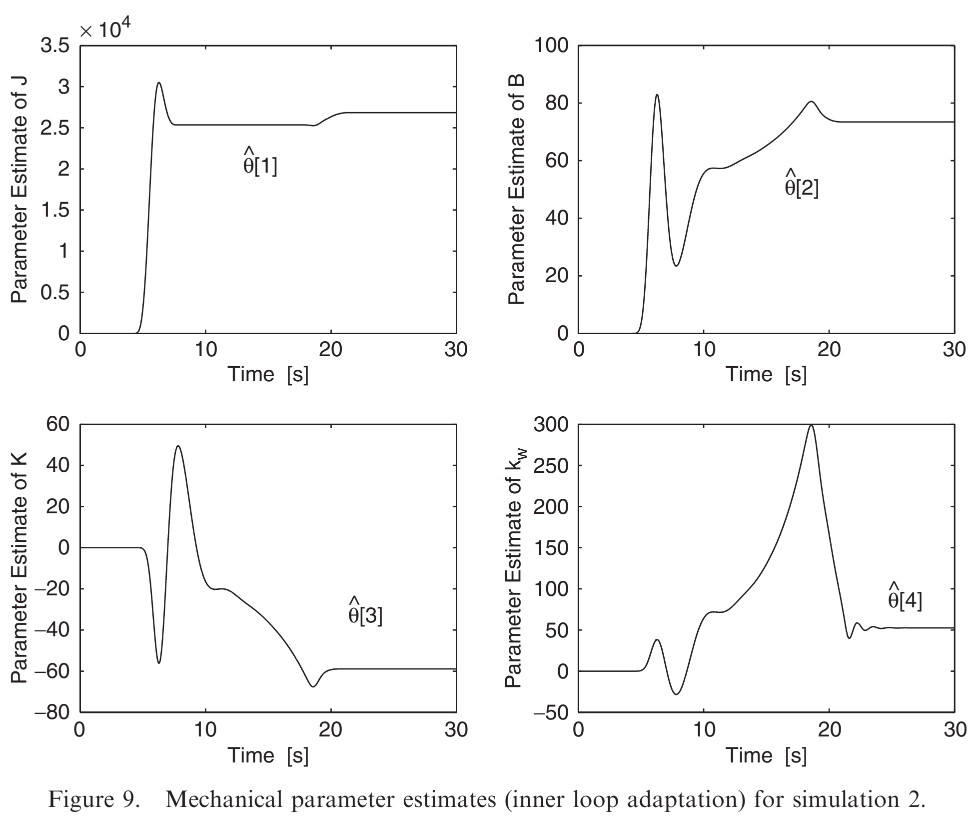

Figure 9. Mechanical parameter estimates (inner loop adaptation) for simulation 2.

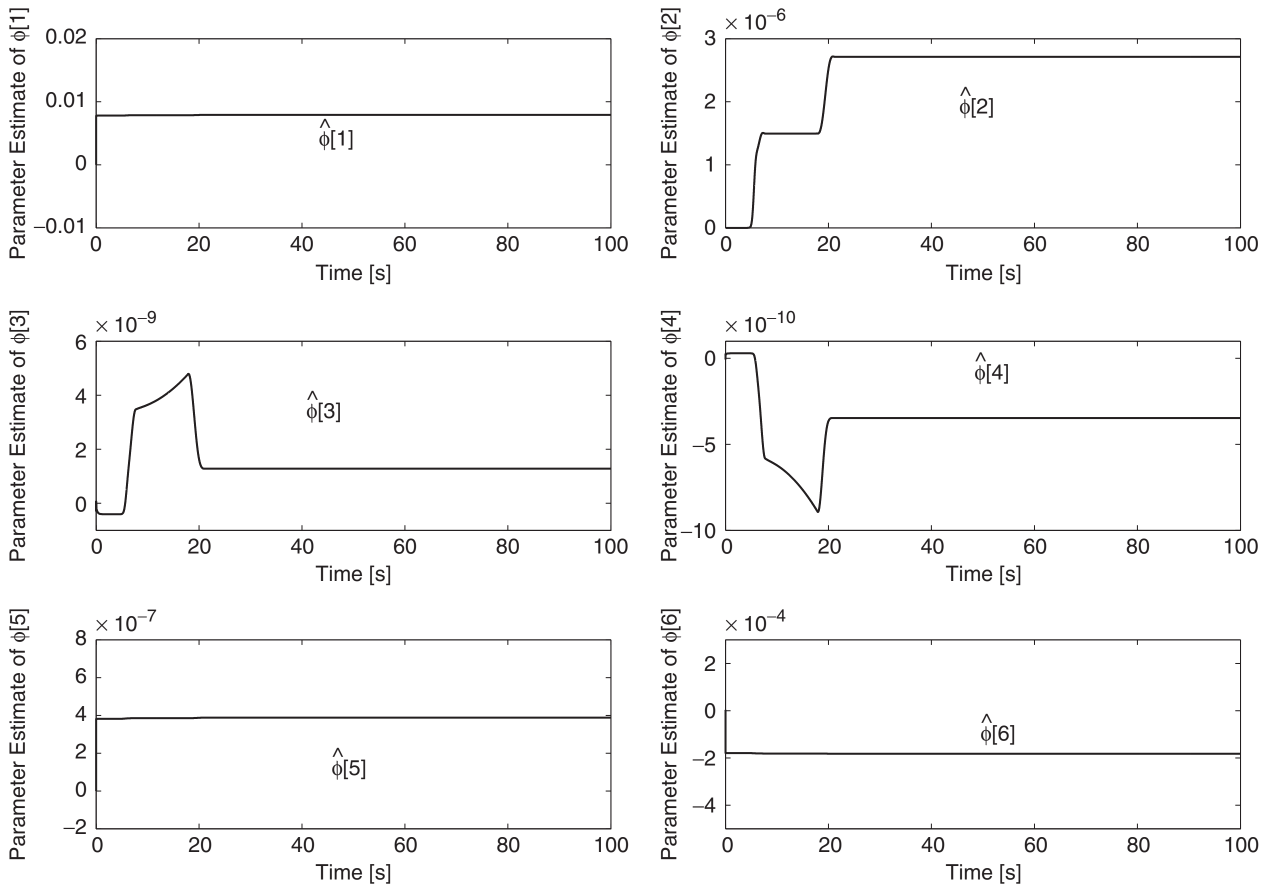

Figure 10. Outer loop parameter estimates for simulation 2.

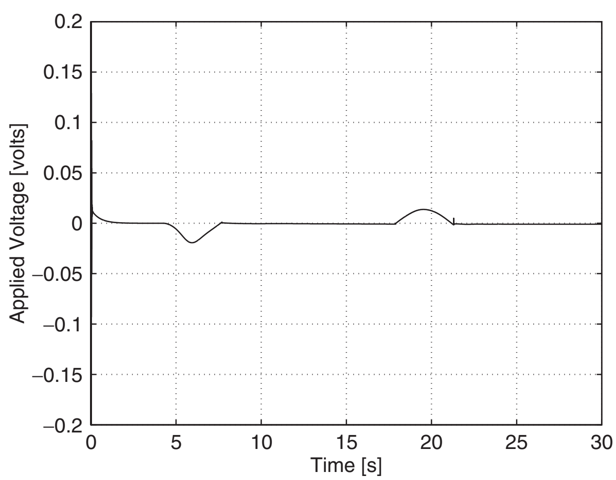

Figure 11. Control effort (field voltage) for simulation 2.

assumed to be available. The steady state error performances of both controllers are very close to each other with EMK performing a little better. For the second simulation, which we believe is a more realistic case, the desired reference trajectory is given on the form (34), though the controller effort of EMK controller is better (as expected); the steady state error performance of the ADP controller is slightly better. This is mainly due to the gradient base adaptation terms in the proposed controller. It is well-known that the adaptations injects integral-feedback like effects to the controller and improves the steady state performance of the adaptive controllers.

Table 1. Performances of the proposed controller (ADP) and the controller of Song *et al.* (2000) (EMK).

	Simulation #1			Simulation #2		
	$u_f(t)$	$e(t)\rfloor_{t=0}^{t=100}$	$e(t)\rfloor_{t=50}^{t=100}$	$u_f(t)$	$e(t)\rfloor_{t=0}^{t=100}$	$e(t)\rfloor_{t=50}^{t=100}$
EMK	2.037	0.526	0.0051	0.7818	0.5301	0.0092
ADP	4.956	0.8719	0.0088	1.653	0.8675	0.0023

6. Conclusion

In this paper, we have presented an adaptive backstepping non-linear controller scheme for the variable velocity control of wind turbines. The proposed method achieves globally asymptotic velocity tracking despite the parametric uncertainty on both mechanical and electrical subsystems. One drawback, however, is that the proposed controller requires the integral of the reference trajectory to be bounded which indicates that the stability of the proposed controller is valid only at some particular operation regions. Still, to our best knowledge the proposed method is the first in the literature that can compensate the uncertainties of both mechanical and exciter dynamics at the same time. Extensive simulation studies with comparison to prior work have been presented to illustrate the performance and feasibility of the proposed method.

Appendix A

The regression vector $Y(\dot{\omega}_d, \omega, I_f) \in \Re^{1\times 6}$ and the unknown parameter vector $\phi \in \Re^{6\times 1}$ of (23) are explicitly defined as follows:

$$Y = \begin{bmatrix} -\gamma K_\phi \dfrac{\partial c(I_f)}{\partial I_f} I_f & \chi\dot{\omega}_d + \dot{W}_d\hat{\theta} + W_d\dot{\hat{\theta}} & \chi\gamma K_\phi c(I_f) & \chi\omega \\ \chi\int_0^t \omega(\tau)\mathrm{d}\tau & & -\chi\omega^2 & \end{bmatrix} \tag{39}$$

$$\phi = \begin{bmatrix} R_f & L & \dfrac{L}{J} & \dfrac{LB}{J} & \dfrac{LK}{J} & \dfrac{Lk_w}{J} \end{bmatrix}^T, \tag{40}$$

where the auxiliary term χ of (39) is

$$\chi \triangleq k_o + k_n\rho^2. \tag{41}$$

References

E. Muldaji, K. Pierce and P. Migliore, "Control strategy for variable-speed, stall-regulated wind turbines, stall-regulated wind turbines", *Proceedings of the American Control Conference*, 3, pp. 1710–1714, 1998.

K.E. Johnson, Y.P. Lucy, M.J. Balas and L.J. Fingersh, "Control of variable speed wind turbines", *IEEE Control System Magazine*, 26, pp. 70–81, 2006.

K.E. Johnson, Y.P. Lucy, M.J. Balas, V. Kulkarni and L.J. Fingersh, "Stability analysis of an adaptive torque controller for variable speed wind turbines", *Proc. of the 43rd IEEE Conference on Decision and Control,* Atlantis, Paradise Island, Bahamas, pp. 4087–4094, 2004.

B Boukhezzar and H Siguerdidjane, "Nonlinear control of wind turbines for power regulation", *Proc. of the IEEE Conference on Control Applications*, Toronto, Canada, pp. 114–119, 2005.

Y.D. Song, B. Dhinarakaran and X.Y. Bao, "Variable speed control of wind turbines using nonlinear and adaptive algorithms", *Journal of Wind Engineering and Industrial Aerodynamics*, 85, pp. 293–308, 2000.

A.R. Bergen, *Power System Analysis*, Englewood Cliffs, NJ: Prentice-Hall, 1996.

M. Krstic, I. Kanellakopoulos and P. Kokotovic, *Nonlinear and Adaptive Control Design*, New York: John Wiley and Sons, Inc., 1995.