Journal of Theoretical and Applied Information Technology
31st May 2014. Vol. 63 No.3

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

ROBUST BOUNDED CONTROL FOR UNCERTAIN NONLINEAR SYSTEMS: APPLICATION TO A NONLINEAR STRICT FEEDBACK WIND TURBINE MODEL WITH EXPLICIT WIND SPEED DYNAMICS

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ABSTRACT

In this paper, a robust bounded control law for a class of uncertain nonlinear systems is proposed. The proposed bounded controller guarantees asymptotic stability, asymptotic tracking and asymptotic disturbance rejection of systems in strict feedback form with the sum of unmatched uncertainties and the unbounded exogenous disturbance. A feedback law emerged from Artstein's Theorem and Sontag's universal formulas are known to be useful to limit the control signal. However, the formulas are not robust as in many cases, being applied to the systems without uncertainties and disturbances. The controller proposed in this paper takes advantages of a mixed backstepping and Lyapunov redesign, which employed to enrich the Sontag's universal formulas. Therefore, the appealing feature of the proposed controller is that it satisfies small control property in order to preserve performance robustness and stability robustness with less control effort. Another advantage of the proposed controller is the formulas become applicable to higher order systems (i.e. order > 0). This paper also discusses fuzzy logic tuning approach for the controller parameters such that the closed loop system matrix remain Hurtwitz. For practicality, the proposed technique is applied to a variable speed control of a new strict feedback wind turbine system with wind dynamics appeared explicitly in the system model. The proposed controller guarantees the asymptotic tracking of the turbine rotor speed; maintains the optimal tip speed ratio and produces maximum power coefficient. This yields maximum power output from the turbine.

Keywords: *Robust bounded control, wind turbine, asymptotic tracking, Backstepping, Lyapunov function*

1. INTRODUCTION

Stabilizing nonlinear systems with uncertainties and exogenous disturbances requires massive control energy. For linear systems, a traditional and classical approach to avoid excessive control effort is the anti-windup scheme. Anti-windup scheme has no standard design procedure. Principally, anti-windup compensator is augmented to the nominal controller to avoid integral controller from windup during control input saturation. This scheme is surveyed in [1-3]. Obtaining fast convergence of the systems' states to equilibrium points also require massive initial control inputs. As such, one may also consider bounded control problem as an optimal control problem in which, the control input has to be limited within admissible set of inputs. However, optimal control problem such as linear quadratic regulator and linear quadratic Gaussian are only useful to design linear controllers for linear systems [1, 4]. In linear systems, input/output frequency domain methods are known to be effective. However, nonlinear systems are unpredictable and solving them requires more advance mathematics. In nonlinear systems, poles and zeros, frequency domain, phase and gain margin are not defined. Linearization of nonlinear systems are normally obtainable by using the Jacobian at equilibrium points, afterward, simple linear controller can be applied to achieve stabilization. However, the controller will not be able to guarantee stabilization beyond wide range of nonlinear sector. For instance, nonlinear system $\dot{x} = y$, $\dot{y} = (1 - x^2)y + x$ can be linearized around its equilibrium point using Jacobian matrix. One

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

would obtain $\dot{x} = y$, $\dot{y} = y + x$ for simplicity. However, a control law designed using linearized model would not be robust within the wide range of operation.

For nonlinear systems, the Lyapunov function is a general tool for stability and robustness analysis. Nonlinear systems, contrasting linear systems, require more treatment from nonlinear controllers such as the one proposed in this paper - a backstepping and Lyapunov redesign technique. However, need to limit the control signal may offers some additional method to be pondered. In this paper, Sontag universal formulas [5-6] that mainly reported for systems without uncertainties are embedded with Backstepping and Lyapunov redesign, in order to obtain the asymptotic stability and the asymptotic disturbance rejection with less control effort. Theoretical background on backstepping technique can be reviewed in [7-9]. Theoretical background on mixed backstepping and Lyapunov redesign can be reviewed in [10-12].

In this paper, the robust bounded control law is designed to construct a variable speed control for a wind turbine system. Focuses of this paper are (Obj.1): to introduce a new wind turbine model so called a strict feedback wind turbine model. (Obj.2): to design robust controller in order to achieves asymptotic tracking of the rotor speed, to guarantees asymptotic disturbance rejection toward unmatched uncertainties cum unbounded exogenous disturbances and to obtain maximum generated output power, and (Obj.3): to introduce a bounded control law in order to reduce the energy consumed by the controller, to reduce high magnitude sparking in the control signal and to reduce the oscillation in the control signal. For typical wind turbine systems, the rotor speed is depending solely on the blade radius, the tip speed ratio and the wind speed. Hence, to fulfill objective (Obj.1), the rotor speed and its derivative are respectively transformed into a single variable (for instance, x_1 and x_2). This leads to the second order strict feedback wind turbine model with the sum of unmatched uncertainties and the unbounded exogenous disturbance. Based on this model, the stabilization of x_1 and x_2 in its equilibrium may results in the asymptotic tracking of the rotor speed and asymptotic disturbance rejection toward the sum of unmatched uncertainties and the unbounded exogenous disturbance. Upon achieving the asymptotic tracking of the rotor speed, the maximum power output from the wind turbine may be guaranteed as a result of the optimum tip speed ratio and the maximum power coefficient. Hence, this fulfills objective (Obj.2). The control algorithm in (Obj.2) is improved using mixed Sontag formulas, backstepping and Lyapunov redesign in order to limit the control magnitude, to reduce distortion and to reduce high frequency oscillation.

2. WIND TURBINE SYSTEM

This section discuses wind turbine system that consists of rotor model and aero-turbine model. Table 1 tabulates wind turbine parameters for the modeling phase in what follows.

Table 1: Nomenclature

Symbols	Definition
R	Rotor blade radius (m)
υ	Wind speed $(m.s^{-1})$
ρ	Air density $(Kg.m^{-3})$
$C_p(\lambda,\beta)$	Power coefficient
λ	Tip speed ratio
β	Pitch angle (deg)
ω_r	Rotor speed $(rad.s^{-1})$
ω_g	Generator speed $(rad.s^{-1})$
J_r	Rotor inertia $(Kg.m^2)$
J_g	Generator inertia $(Kg.m^2)$
K_g	Generator external damping $(N.m.rad^{-1}.s^{-1})$
K_r	Generator external damping $(N.m.rad^{-1}.s^{-1})$
B_r	Rotor stiffness $(N.m.rad^{-1})$
B_g	Generator stiffness $(N.m.rad^{-1})$
T_m	Aerodynamic torque $(N.m)$
T_g	Generator torque/Electromagnetic torque $(N.m)$
T_{hs}	High-speed shaft torque $(N.m)$
T_{ls}	Low-speed shaft torque $(N.m)$
θ_g	Generator-side angular deviation (rad)
θ_r	Rotor-side angular deviation (rad)

2.1 Rotor Model

Wind turbines work by converting the kinetic energy from the wind into rotational energy in the turbine. The rotational energy is then converted into electrical energy. The aerodynamic power produced by the turbine can be expressed as [13-19]:

$$P_m = P_{wind} C_p(\lambda,\beta) \quad (1)$$

where $P_{wind} = \frac{1}{2}\rho\pi R^2 \upsilon^3$ is the instantaneous power produced by the wind, and

$$\lambda = \frac{R\omega_r}{\upsilon} \quad (2)$$

is the tip speed ratio. Power coefficient C_p is a nonlinear function. It values can be obtained from look-up tables provided by turbine manufacturers. Other than look-up tables, the empirical expression for power coefficient can be found in [20-21].

Journal of Theoretical and Applied Information Technology
31st May 2014. Vol. 63 No.3

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

2.2 Aero-turbine Model

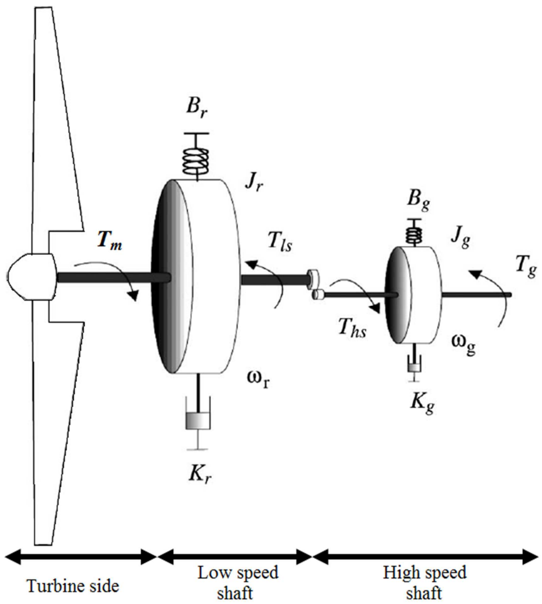

Figure 1: Two-mass wind turbine structure as appeared in [13, 17-18]

Let consider two-mass wind turbine system as shown in Figure 1. This model structure appears in many cases such as in [14, 16-17]. The model consists of a turbine side, a low-speed shaft and a high-speed shaft. The term two-mass model emerged from the turbine structure which impose a gear box that separates a low-speed mechanical dynamic and a high-speed mechanical dynamic. The torque produced by the turbine can be developed as:

$$T_m - T_{ls} = J_r\dot{\omega}_r + B_r\omega_r + K_r\theta_r \tag{3}$$

The transmission output torque:

$$T_{hs} - T_g = J_g\dot{\omega}_g + B_g\omega_g + K_g\theta_g \tag{4}$$

The gearing ratio is denoted as:

$$\gamma = \frac{\omega_g}{\omega_r} = \frac{T_{ls}}{T_{hs}} \tag{5}$$

From Eq. (5), the dynamic equations in Eq. (3) and Eq. (4) can be represented in a standard wind turbine model as follows:

$$J\dot{\omega}_r + B\omega_r + K\int_0^t \omega_r(\tau)d\tau = T_m - \gamma T_g \tag{6}$$

where the lumped system parameters are defines as:

$$J = J_r + \gamma^2 J_g \tag{7}$$
$$B = B_r + \gamma^2 B_g \tag{8}$$
$$K = K_r + \gamma^2 K_g \tag{9}$$

Universally accepted two-mass wind turbine model in Eq. (6) (also appeared in [13, 17-18]) does not consider wind dynamics explicitly in the system model. This is because of that wind dynamics are non-deterministic, having chaotic behavior and highly nonlinear in nature. As such, in this paper, wind dynamics are considered explicitly in the system model. This approach replenishes wind speed fluctuation in the wind turbine model which behaves as an exogenous disturbance to the system. As a modeling result, wind turbine model in this paper is represented in its new form so-called a strict feedback wind turbine model, that is required for practicality and actual application. Strict feedback form also smoothes the design progress of a backstepping and Lyapunov redesign concept that will be discussed thoroughly in what follows.

The aerodynamic torque applied to the hub of the wind turbine can be expressed as $T_m = \frac{P_m}{\omega_r}$. Using Eq. (1), the turbine dynamics in Eq. (6) can be further rewritten as:

$$J\dot{\omega}_r + B\omega_r + K\int_0^t \omega_r(\tau)d\tau = \frac{\rho\pi R^5 C_{p(max)}}{2\lambda_{opt}^3}\omega_r^2 - \gamma \tag{10}$$

Differentiating both sides of Eq. (10) yields:

$$\ddot{\omega}_r = -\frac{B}{J}\dot{\omega}_r - \frac{K}{J}\omega_r + \frac{\rho\pi R^5 C_{p(max)}}{J\lambda_{opt}^3}\omega_r\dot{\omega}_r - \frac{\gamma}{J}\dot{T}_g \tag{11}$$

Note that an optimum tip speed ratio λ_{opt} yields the maximum power coefficient $C_{p(max)}$. Thus, λ_{opt} and $C_{p(max)}$ induce the maximum output power P_m. Defining $\hat{T}_g \equiv -\frac{\gamma}{J}\dot{T}_g$, one may view the torque component $\hat{T}_g$ as the control input. Therefore, it can be established from Eq. (2) that the control objective is to stabilize the rotor speed at $\omega_r = \frac{\lambda_{opt}}{R}\upsilon$ such that the maximum power output is guaranteed. For the rotor speed maintains equilibrium at $\omega_r = \frac{\lambda_{opt}}{R}\upsilon$, the control must have a steady state component that satisfies:

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

$$\hat{T}_{g(ss)} = \frac{K}{J}\omega_r \tag{12}$$

To aid the control design, let choose the states variables:

$$x_1 = \omega_r - \frac{\lambda_{opt}}{R}v \tag{13}$$
$$x_2 = \dot{\omega}_r \tag{14}$$

and the control variable:

$$u = \hat{T}_g - \hat{T}_{g(ss)} \tag{15}$$

This implies that the 2nd-order strict feedback wind turbine model, becomes:

$$\dot{x}_1 = x_2 + \xi_1(v) \tag{16}$$
$$\dot{x}_2 = A_1x_2 + A_2x_1 + A_3x_1x_2 + \xi_2(x_2, v) + u \tag{17}$$

where the system parameters are defined as $A_1 = -\frac{B}{J}$, $A_2 = -\frac{K-KJ}{J^2}$, $A_3 = \frac{\rho\pi R^5 C_{p(max)}}{J\lambda_{opt}^3}$, $\xi_1(v) = -\frac{\lambda_{opt}}{R}\dot{v}$ and $\xi_2(x_2, v) = \frac{(A_2+A_3x_2)\lambda_{opt}v}{R}$. Smooth function $\xi_1(v)$ is an unbounded exogenous disturbance constituting wind speed fluctuation. While the smooth function $\xi_2(x_2, v)$ is the sum of unmatched uncertainties and the unbounded exogenous disturbance. A combination of Eq. (16) and Eq. (17) behaves as a transformed wind turbine model, which is useful for controller design. Figure 2 depicts the model configuration.

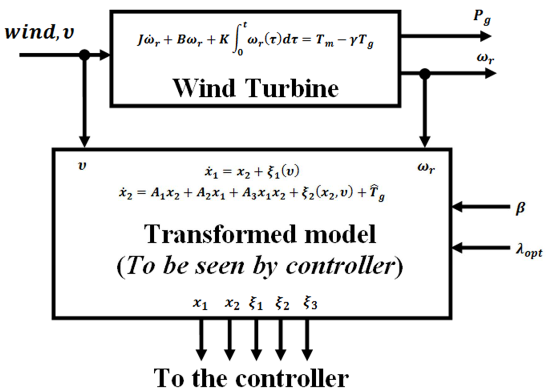

Figure 2: Model configuration - for controller design

3. CONTROLLER DESIGN

3.1 Power Coefficient

The power coefficient C_p is a unique nonlinear function that depends on turbine types [20]. As such, the value of C_p is provided via look-up-table by each turbine manufacturer. On the other hand, the power coefficient C_p can be expressed by a typical empirical formulas (for instance, see [20-21]). In [20], the power coefficient model is represented by:

$$C_p(\lambda, \beta) = 0.5\left(116\frac{1}{\phi} - 0.4\phi\beta - 5\right)e^{-21\frac{1}{\phi}} \tag{18}$$

where the function ϕ is given as:

$$\frac{1}{\phi} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3} \tag{19}$$

Figure 3 shows power coefficient characteristic for various β. For a regulated pitch angle at $\beta = 0^\circ$, one may obtain the expression for power coefficient as:

$$C_p = 0.5\left(\frac{116}{\lambda + 0.0001} - 9.06\right)e^{-\frac{21}{\lambda+0.0001}+0.735} \tag{20}$$

Then, the optimum tip speed ratio $\lambda_{opt} = 7.953925991$ yields the maximum power coefficient $C_{p(max)} = 0.4109631031$. Both $[\lambda_{opt} \;\; C_{p(max)}]$ are treated as a reference values and are embedded in the control algorithm.

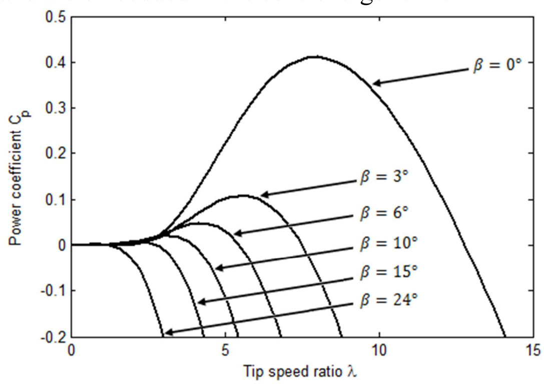

Figure 3: Power coefficient characteristic

3.2 Normal Variable Speed Control Design

Initially, by using normal backstepping and Lyapunov redesign technique, two-mass strict feedback wind turbine system in Eq. (16) and Eq. (17) are stabilized for stability robustness and performance robustness. In other words, the aim of normal robust control design is to regulate x_1 under the presence of $\xi_1(v)$ and $\xi_2(x_2, v)$. Recall the 1st-order wind turbine subsystem in Eq. (16), achieving asymptotic stability for x_1 implies the asymptotic tracking of the rotor speed ω_r. Prior to robust normal control design, a nominal unperturbed stabilizing function for 1st-order wind

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

turbine subsystem in Eq. (16) is obtained. One may observe that the unforced autonomous-like wind turbine subsystem in Eq. (16) can be stabilized by a simple continuously differentiable feedback control law:

$$x_{2_{nom}} = -C_1 x_1 \;\; ; \;\; \forall\, C_1 > 0 \tag{21}$$

Without loss of generality, one may also consider a continuous function $x_{2_{nom}}(0) = 0$ as a desired x_2 such that the closed-loop nominal subsystem $\dot{x}_1 = x_2$ is asymptotically stable. Therefore, there exist a smooth and proper positive definite Lyapunov function $V_1(x_1) = \frac{1}{2}x_1^2 \in \mathbb{R}^+$ such that its derivative along x_1 is $\dot{V}_1(x_1) = -C_1 x_1^2 \le 0$, i.e. negative definite. This imposes that the unwanted energy subjected by the inertia, stiffness and damping of the turbine must be always dissipative except at null condition. In the presence of $\xi_1(\upsilon)$, we introduce a saturated-like function $x_{2_{\xi_1}}$, that to be augmented into the nominal feedback control. Therefore, the feedback control law in Eq. (21) can be redesigned as:

$$x_2^* = x_{2_{nom}} + x_{2_{\xi_1}} \tag{22}$$

By substituting Eq. (22) into the 1st-order wind turbine subsystem in Eq. (16), one may obtain:

$$\dot{x}_1 = x_{2_{nom}} + x_{2_{\xi_1}} + \xi_1(\upsilon) \tag{23}$$

As such, the derivative of $V_1(x_1)$ along the system in Eq. (23) becomes:

$$\dot{V}_1(x_1) = -C_1 x_1^2 + x_1\left(x_{2_{\xi_1}} + \xi_1(\upsilon)\right) \tag{24}$$

The control problem now is to design $x_{2_{\xi_1}}$ such that the closed-loop dynamics for the 1st-order wind turbine subsystem in Eq. (16) is robust toward $\xi_1(\upsilon)$. This hence achieves the asymptotic disturbance rejection of the closed loop 1st-order wind turbine subsystem. One may also confirm the asymptotic stability by satisfying the inequality condition in:

$$x_1 x_{2_{\xi_1}} + x_1 \xi_1(\upsilon) \le 0 \tag{25}$$

Therefore, a robust stabilizing function for the 1st-order wind turbine subsystem in Eq. (16) is devised as:

$$x_2^*(x_1, t) = -C_1 x_1 + x_{2_{\xi_1}} \tag{26}$$

where

$$x_{2_{\xi_1}} = -\frac{x_1 \xi_1^2}{x_1 \xi_1 + \varepsilon_1 e^{-\alpha t}} \;\; ; \;\; \forall\, \varepsilon_1 > 0\,,\; \alpha > 0 \tag{27}$$

Proof of stability

With $x_{2_{\xi_1}}$ in Eq. (27), reconsider Lyapunov function $V_1(x_1)$. The derivative about x_1 yields the dissipation function for the 1st-order wind turbine subsystem in Eq. (16):

$$\begin{aligned}\dot{V}_1(x_1) &= -C_1 x_1^2 + x_1\left(-\frac{x_1 \xi_1^2}{x_1 \xi_1 + \varepsilon_1 e^{-\alpha t}} + \xi_1\right)\\ &= -C_1 x_1^2 - \frac{\|x_1 \xi_1\|^2}{\|x_1 \xi_1\| + \varepsilon_1 e^{-\alpha t}} + x_1 \xi_1\\ &\le -C_1 x_1^2 + \varepsilon_1 e^{-\alpha t}\end{aligned} \tag{28}$$

Eq. (28) preserves the negative definiteness of $\dot{V}_1(x_1)$. The exponential term $\varepsilon_1 e^{-\alpha t}$ may decay as soon as the control law achieve that asymptotic disturbance rejection. Hence, the control law satisfies the previous stability condition $\dot{V}_1(x_1) = -C_1 x_1^2 \le 0$ to confirm the asymptotic stability of the closed loop dynamics for the 1st-order wind turbine subsystem in Eq. (16). To design the overall stabilizing function, let define error dynamics between the desired state x_2^* and the actual state x_2 be:

$$z = x_2 - x_2^* \tag{29}$$

This renders a transformed system dynamics for the 2nd-order wind turbine subsystem in Eq. (17), as:

$$\begin{aligned}\dot{z} &= A_1 z + A_2 x_2^* + A_2 x_1 + A_3 x_1 z \ldots\\ &+ A_3 x_1 x_2^* + C_1 z + C_1 x_2^* + \frac{\partial x_{2_{\xi_1}}}{\partial x_1} x_2^* \ldots\\ &+ \frac{\partial x_{2_{\xi_1}}}{\partial x_1} z + \frac{\partial x_{2_{\xi_1}}}{\partial t} + u + \xi_3(x_2, \upsilon)\end{aligned} \tag{30}$$

where ξ_3 is the mapping of ξ_1 and ξ_2, which is defined as:

$$\xi_3(x_2, \upsilon) = \frac{\partial x_{2_{\xi_1}}}{\partial x_1} \xi_1(\upsilon) + C_1 \xi_1(\upsilon) + \xi_2(x_2, \upsilon) \tag{31}$$

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

Further, one would design a stabilizing function to diminish the error dynamics z such that the transformed wind turbine system in Eq. (30) is asymptotic stable. This concept gives some idea about backstepping since $x_2^*(x_1, t)$ is being stepped back by differentiation. Consider a smooth and proper positive definite Lyapunov function $V_2(x_1, z) = \frac{1}{2}x_1^2 + \frac{1}{2}z^2 \in \mathbb{R}^+$, a nominal stabilizing function for the unperturbed nominal system in Eq. (30) can be obtained as:

$$u_{nom} = -(C_1 + C_2)z - A_1(z + x_2^*) - (1 + A_2)x_1 \ldots$$
$$-C_1 x_2^* - A_3(x_1 z + x_1 x_2^*) \ldots$$
$$-\frac{\partial x_{2_{\xi_1}}}{\partial x_1}(z + x_2^*) - \frac{\partial x_{2_{\xi_1}}}{\partial t} \quad (32)$$

where $C_2 > 0$. In the presence of $\xi_3(x_2, v)$, the nominal stabilizing function in Eq. (32) is redesigned to reach final robust control law:

$$u = u_{nom} + u_{\xi_3} \quad (33)$$

where u_{nom} is defined in Eq. (32) and u_{ξ_3} is defined as:

$$u_{\xi_3} = -\frac{z\xi_3^2}{z\xi_3 + \varepsilon_2 e^{-\alpha t}} \quad ; \quad \forall\, \varepsilon_2 > 0, \alpha > 0 \quad (34)$$

Proof of stability

With the same stability proving concept in Eq. (28), the derivative of Lyapunov function $V_2(x_1, z)$ along $[x_1 \;\; z]^T$ renders a negative definite function:

$$\dot{V}_2(x_1, z) \le -C_1 x_1^2 - C_2 z^2 + \varepsilon_1 e^{-\alpha t} + \varepsilon_2 e^{-\alpha t} \quad (35)$$

This implies the asymptotic stability of the regulated state x_1, and also diminishes the error dynamics z. Hence, the rotor speed ω_r asymptotically tracks the demanded rotor speed ω_r^*, where

$$x_1 \equiv \omega_r - \omega_r^* \Longrightarrow \omega_r = \omega_r^*|_{x_1 = 0 \; as\, t\to\infty} \quad (36)$$

Recall the state variable in Eq. (13), the previous robust controller is designed under ideal assumption that $\omega_r^* = \frac{\lambda_{opt}}{R} v$. This implies the asymptotic tracking of ω_r:

$$\omega_r(t \to \infty) = \omega_r^*|_{\lambda = \lambda_{opt}, C_{p(max)}} \quad (37)$$

3.3 Bounded Variable speed Control Design

In this subsection, we improve the robust variable speed control law in Eq. (32), Eq. (33) and Eq. (34) such that the control signal is bounded and satisfies small control property. Yuandan and Sontag in [6] provide a universal formula for stabilization of bounded control for 1st-order nonlinear systems without uncertainties and disturbance. In this paper, we replenish the universal formula with backstepping and Lyapunov redesign in order to facilitate the higher order uncertain nonlinear systems (i.e. order > 1), and hence reduce the control magnitude. To illustrate bounded control design, let represent the 1st-order wind turbine subsystem in Eq. (16) in a form:

$$\dot{X} = f(x) + g(x)U + \xi_1(v) \quad (38)$$

Prior to design steps, we consider the nominal unperturbed system in Eq. (38). The control U can be designed such that U lies in open unit ball $B_m = \{U < |U_{max}|\}$. With Lyapunov theorem as before, there exists a positive definite, proper and smooth function $V_u(X)$. Hence, there also exists the operator $F = \left(\frac{\partial V_u}{\partial x}\right)^T \cdot f(X)$ and $G = \left(\frac{\partial V_u}{\partial x}\right)^T \cdot g(X)$ that contribute to the existence of a continuous and regular feedback law:

$$|U(F, G)| = -\frac{F + \sqrt{F^2 + G^4}}{G\left(1 + \sqrt{1 + G^2}\right)} \;, \quad G \ne 0 \quad (39)$$

If $U(F, G)$ continuous at origin, then $U(F, G)$ satisfies small control property with respect to the system in Eq. (38) as in *Definition 1*:

Definition 1(Small Control Property): For the system in Eq. (38) satisfies small control property, there is a known control Lyapunov function $V_u(X)$. For every $\epsilon > 0$, there exists a $\delta(\epsilon) > 0$ so that for all $X \ne 0$ and $\|X\| < \delta$, there is control $\|U(F, G)\| < \epsilon$ such that $\dot{X} = f(x) + g(x)U < 0$.

With *Definition 1*, we can use *Lemma 1* to reach the main results for bounded control.

Lemma 1: Assume that F, G and ϵ are real numbers such that $F < \epsilon|G|$, and $0 < \epsilon \le \varphi$ for $\varphi \in \mathbb{R}$, then there exists a stabilizing function $U(F, G)$ with property

Journal of Theoretical and Applied Information Technology
31st May 2014. Vol. 63 No.3

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

$$|U(F,G)| < min\{2\epsilon + |G|, \epsilon\} \tag{40}$$

Proof of Lemma 1:

Without loss of generality, we set $G > 0$, thus $F < \epsilon G$. If $F \leq 0$, then $F < \epsilon|G|$ is not valid. Therefore,

$$|U(F,G)| = -\frac{G}{1+\sqrt{1+G^2}} < min\left\{\frac{G}{2}, 1\right\} \tag{41}$$

When $F > 0$, we can see that $|U(F,G)|$ bounded by φ as $\epsilon \leq \varphi$, and also bounded by its numerator. This yield:

$$|U(F,G)| = \frac{\epsilon G + \sqrt{(\epsilon G)^2 + G^4}}{G\left(1+\sqrt{1+G^2}\right)}$$

$$= \frac{\epsilon + \sqrt{\epsilon^2 + G^2}}{1+\sqrt{1+G^2}}$$

$$< min\{2\epsilon + |G|, \varphi\} \tag{42}$$

Let consider the 1st-order wind turbine model in Eq. (16) be in the same form as the standard system in Eq. (38). By applying *Definition 1* and *Lemma 1*, one may obtain via backstepping and Lyapunov redesign, a bounded robust variable speed control for the overall strict feedback wind turbine model in Eq. (16) and Eq. (17), as follows:

$$u_{bound} = -\left(C_2 + \frac{C_1}{1+x_1^2+\sqrt{1+x_1^2}}\right)z \ldots$$

$$-A_1\left(z + x^*_{2bound}\right) - (1+A_2)x_1 \ldots$$

$$-A_3\left(x_1 z + x_1 x^*_{2bound}\right) \ldots$$

$$-\frac{C_1}{1+x_1^2+\sqrt{1+x_1^2}} x^*_{2bound} \ldots$$

$$-\frac{\partial x_{2_{\xi_1}}}{\partial x_1}\left(z + x^*_{2bound}\right) - \frac{\partial x_{2_{\xi_1}}}{\partial t}$$

$$-\frac{z\xi_3^2}{z\xi_3 + \varepsilon_2 e^{-\alpha t}} \tag{43}$$

where $C_1 > 0$, $C_2 > 0$, $\varepsilon_2 > 0$ and $\alpha > 0$. For $\varepsilon_1 > 0$, the bounded stabilizing function x^*_{2bound} is obtained as:

$$x^*_{2bound} = -\frac{C_1 x_1}{1+\sqrt{1+x_1^2}} - \frac{x_1 \xi_1^2}{x_1\xi_1 + \varepsilon_1 e^{-\alpha t}} \tag{44}$$

With the Lyapunov function $V_2(x_1, z) = \frac{1}{2}x_1^2 + \frac{1}{2}z^2 \in \mathbb{R}^+$, the bounded control law in Eq. (43) renders the derivative of $V_2(x_1, z)$ negative definite:

$$\dot{V}_2(x_1, z) \leq -\frac{C_1 x_1^2}{1+\sqrt{1+x_1^2}} - C_2 z^2 + \varepsilon_1 e^{-\alpha t} + \varepsilon_2 e^{-\alpha t} \tag{45}$$

Figure 4 shows the closed loop configuration of the variable speed wind turbine control system. The wind turbine is marked in box (a). The variable speed controller consists of a variable transformation (box (b)), uncertainties handling (box (c) and box (d)) and the main control algorithm in box (e). Box (b) transforms the wind speed and the rotor speed data from the wind turbine in box (a) into a variables that suitable to be processed by the algorithm (in this case, x_1 and x_2). Box (c) and box (d) handle the disturbance cum uncertainties that imposing by the wind fluctuation and system parameters.

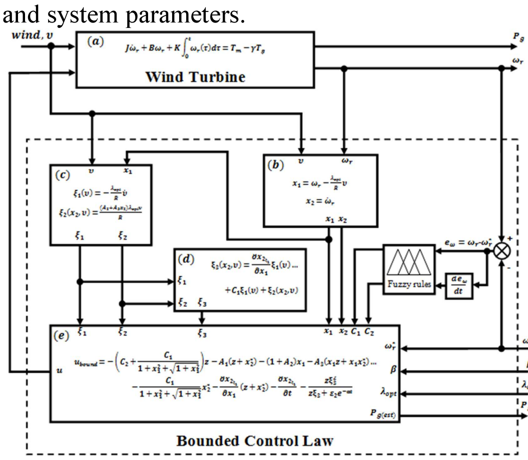

Figure 4: Variable speed control for strict feedback wind turbine model with robust bounded control law

The control parameters C_1 and C_2 are tuned by the fuzzy rules. In a testing condition, the demanded speed ω_r^* is inputted by the operator and being processed by the algorithm. Via the knowledge of x_1, optimum tip speed ratio λ_{opt}, regulated pitch angle $\beta = 0°$ and wind speed v, the aerodynamic power and the power output can be estimated as in Eq. (46), Eq. (47) and Eq. (48) respectively. One would estimate the power output by using Eq. (49). With that, the estimated generator speed in Eq. (50)

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can be obtained via the knowledge of $\gamma = \frac{\omega_g}{\omega_r}$ and $P_{m(est)}$. The appealing feature of this approach is that the power output can be estimated only using the transformed variable $X = [x_1 \quad x_2]^T$ and can be easily calculated by the controller processor.

$$P_{m(est)} = \frac{\rho\pi C_{p(max)} R^2 (\lambda_{opt} v + x_1 R)^3}{2\lambda_{opt}^3} \tag{46}$$

$$T_{m(est)} = \frac{\rho\pi C_{p(max)} R^3 (\lambda_{opt} v + x_1 R)^2}{2\lambda_{opt}^3} \tag{47}$$

$$T_{g(est)} = \frac{1}{\lambda}\left[T_{m(est)} - Jx_2 - B\left(x_1 + \frac{\lambda_{opt}}{R} v\right)\right] + \frac{1}{\lambda}\left[-K\int_0^t x_1(\tau) + \frac{\lambda_{opt}}{R} v \, d\tau\right] \tag{48}$$

$$P_{g(est)} = T_{g(est)}\omega_{g(est)} \tag{49}$$

where

$$\omega_{g(est)} = \left(\frac{2\lambda_{opt}^3 \gamma^3 P_{m(est)}}{\rho\pi C_{p(max)} R^5}\right)^{\frac{1}{3}} \tag{50}$$

4. RESULTS

4.1 Regulation and Parameter tuning

This subsection is devoted to the study of the regulation and tuning of the controller parameters. As a corollary of *Definition 1*, *Lemma 1* and a mixed backstepping and Lyapunov redesign technique, the robust control algorithm in Eq. (43) were successfully devised, where the asymptotic stability is confirmed via the Lyapunov stability criteria. In this subsection, we emphasize the significant of controller parameters C_1 and C_2 to achieve the asymptotic stability condition. We also reconfirm the stability by proving that, C_1 and C_2 determine the eigenvalues for the closed loop wind turbine system. When using the robust bounded variable speed control law in Eq. (43) for $\varepsilon_1 = \varepsilon_2 = \varepsilon$, the closed loop wind turbine system can be written as:

$$\begin{bmatrix}\dot{x}_1\\ \dot{z}\end{bmatrix} = \begin{bmatrix}-\frac{C_1}{1+\sqrt{1+x_1^2}} & 0\\ -1 & -C_2\end{bmatrix}\begin{bmatrix}x_1\\ z\end{bmatrix} \cdots + \begin{bmatrix}\xi_1\\ \xi_3\end{bmatrix}\varepsilon e^{-\alpha t} \tag{51}$$

It can be observed from Eq. (51) that the disturbance terms ξ_1 and ξ_3 will be diminished by the function $\varepsilon e^{-\alpha t}$ when $t > 0$, in order to guarantee the asymptotic disturbance rejection. Therefore, the parameters $\varepsilon > 0$ and $\alpha > 0$ impose no significant effect to the stability of the closed loop wind turbine system. This makes the tuning of both ε and α can be made easy. As such, the asymptotic stability of the closed loop wind turbine system is highly dependent on C_1 and C_2 because these parameters determine the *Hurwitzness* of the matrix in Eq. (52):

$$\bar{A} = \begin{bmatrix}-\frac{C_1}{1+\sqrt{1+x_1^2}} & 0\\ -1 & -C_2\end{bmatrix} \tag{52}$$

Assuming σ_1 and σ_2 be the eigenvalues of the closed loop wind turbine system, it can be seen that $C_1 > 0$ and $C_2 > 0$ locate the poles of the closed loop wind turbine system at the left hand side of the S-plane and hence, preserving the asymptotic stability of the closed loop wind turbine system. Let $|\sigma I \quad \bar{A}| = 0$, thus:

$$\left(\sigma_1 + \frac{C_1}{1+\sqrt{1+x_1^2}}\right)(\sigma_2 + C_2) = 0 \tag{53}$$

Hence, this initially gives the eigenvalues:

$$\begin{bmatrix}\sigma_1\\ \sigma_2\end{bmatrix} = \begin{bmatrix}-\frac{C_1}{1+\sqrt{1+x_1^2}}\\ -C_2\end{bmatrix} \tag{54}$$

In order to obtain the asymptotic tracking of the rotor speed ω_r, we aim to obtain good regulation. If good regulation takes place, x_1 becomes too small to be seen by σ_1 and finally decay to zero (i.e. $x_1^2 \ll 1$). This yields the eigenvalues:

$$\sigma_1 \approx -\frac{C_1}{2} \tag{55}$$

$$\sigma_2 = -C_2 \tag{56}$$

At this point, we can simply tune $C_1 > 0$ and $C_2 > 0$ by trial. Setting C_1 and C_2 based on trial-and-error is rather simple but incurring some drawback. Very large C_1 and C_2 give fast stabilization and reduces the tracking error but will increase the control energy. To overcome this shortcoming, let C_1 and C_2 are tuned by the Fuzzy Logic (FL) controller. In term of parameter upper bound and the lower bound, FL has some similarities with other intelligent computational techniques such as Particle Swarm Optimization

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(PSO), Genetic algorithm (GA) and Artificial Neural Network (ANN). The appealing feature is that, FL offers less computation time as compared to PSO, GA and ANN. PSO for instance requires objective function and iteration, incurring large computation time and inducing computational burden to the control system. Likewise, GA incurs high computational effort. ANN, on the other hand, has to learn the plant behavior before it can actually control the plant or tune the parameters. FL does not require iteration. Hence, FL search C_1 and C_2 on line when the system is running.

In this subsection, the objective is to minimize the tracking error ($e_\omega = \omega_r$-ω_r^*). The fuzzy rules vary the value of C_1 and C_2 according to the variation of tracking error e_ω and the rate of change of the tracking error $\frac{de_\omega}{dt}$. Therefore, the fuzzy system has 2 input linguistic variables and 2 output linguistic variables. The input linguistic variables are the tracking error e_ω and the rate of change of the error $\frac{de_\omega}{dt}$. The output linguistic variables are C_1 and C_2. The universe of discourse for the input and output is normalized and de-normalized respectively. For that reason, we introduce the antecedent linguistic terms:

$$\mathcal{A} = \{NB, NM, NS, ZE, PS, PM, PB\} \tag{57}$$

and the set of consequent linguistic terms:

$$\mathcal{B} = \{S, B\} \tag{58}$$

The antecedents NB for *Negative Big*, NM for *Negative Medium*, NS for *Negative Small*, ZE for *Zero*, PS for *Positive Small*, PM for *Positive Medium* and PB for *Positive Big*. The consequents S for *Small* and B for *Big*. Therefore, the conjunctive form of the antecedent (if-then rules) is given as:

$$\begin{aligned}\mathcal{R}_i : If\ e_\omega\ is\ \mathcal{A}_{i1}\ and\ \frac{de_\omega}{dt}\ is\ \mathcal{A}_{i2}\\ then\ C_1\ is\ \mathcal{B}_{i1} and\ C_2\ is\ \mathcal{B}_{i2}\end{aligned} \tag{59}$$

where $i = 1,2 \ldots \prod_i^P N_i$. P is the dimension of the input space (in our case $P = 2$), $\mathrm{N_i}$ is the number of linguistic terms of the $\mathrm{i^{th}}$ antecedent variable (in our case $\mathrm{N_i} = 7$). These *7* linguistic variables induce a maximum *72 = 49* if-then rules as tabulated in Table 2. The universes of discourse of the inputs are ranging from -1 to 1:

$$e_\omega \in [-1\ \ 1] \ \text{ and } \dot{e}_\omega \in [-1\ \ 1] \tag{60}$$

The de-normalized outputs of the tuning values for C_1 and C_2 are described as:

$$\left.\begin{aligned} C_1 \in \left[C_{1(lower)}\ C_{1(upper)}\right]\\ C_2 \in \left[C_{2(lower)}\ C_{2(upper)}\right]\end{aligned}\right\} \tag{61}$$

Figure 5(a) and Figure 5(b) show the membership functions for e_ω, $\frac{de_\omega}{dt}$ and C_1, C_2 respectively. Figure 5(c) and Figure 5(d) show the surface of the overall fuzzy system.

Table 2: Fuzzy rules for tuning C_1 and C_2

		$\dot{e}_\omega$						
		NB	NM	NS	ZE	PS	PM	PB
e_ω	NB	B	B	B	B	B	B	B
	NM	S	B	B	B	B	B	S
	NS	S	S	B	B	B	S	S
	ZE	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	B	B	B	B	B	S
	PB	B	B	B	B	B	B	B

Figure 6(a) and Figure 6(b) show the regulated x_1 and x_2 upon perturbation in initial states $X = [1 \quad 1]^T$, using both the normal control in Eq. (32) - Eq. (34) and the bounded control in Eq. (43) - Eq. (44). It can be observed that both controllers capable to stabilize the perturbed x_1 and x_2 with rather fast convergence rate (i.e. < 0.2 sec). Figure 6(c) shows the overall system trajectories. Figure 6(d) shows the comparison in control signal produced by both control laws. It can be observed from Figure 6(d) that the bounded control law reduces the initial control magnitude required to steer the perturbed $X = [1 \quad 1]^T$ toward equilibrium. Hence, the control law respects the system saturation as well as reducing control cost and energy. The history of fuzzy variation for controller parameters C_1 and C_2 are recorded in Figure 6(e) and Figure 6(f) respectively.

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ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

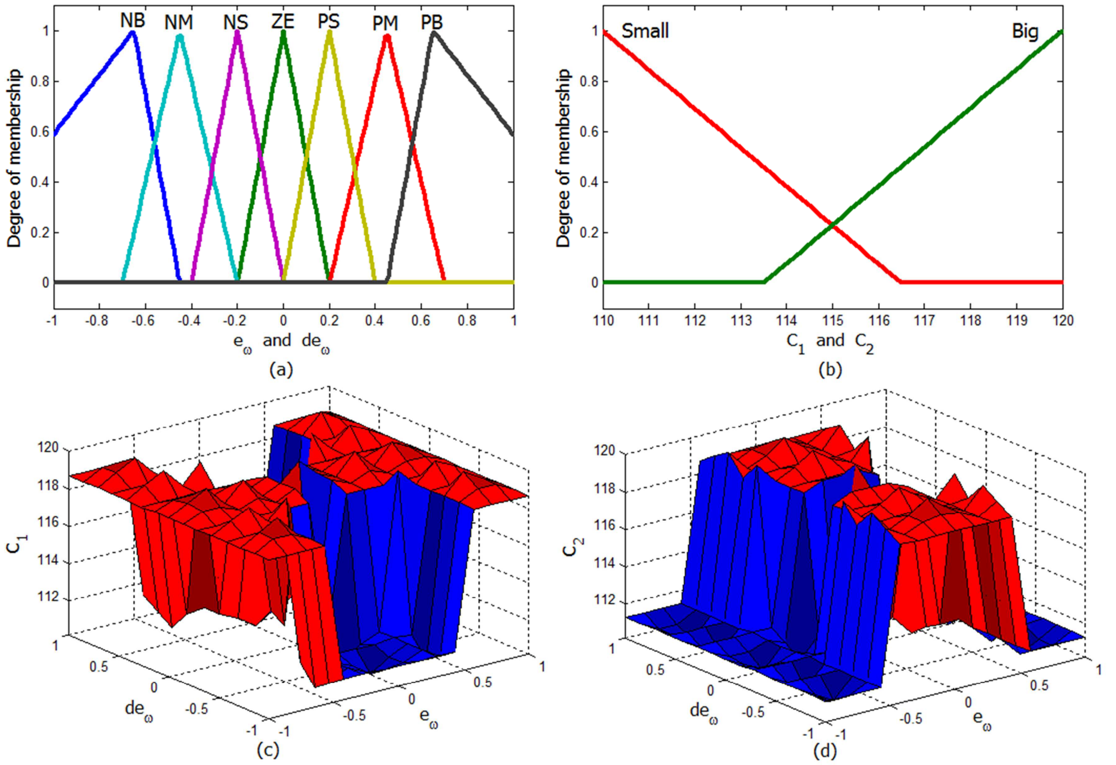
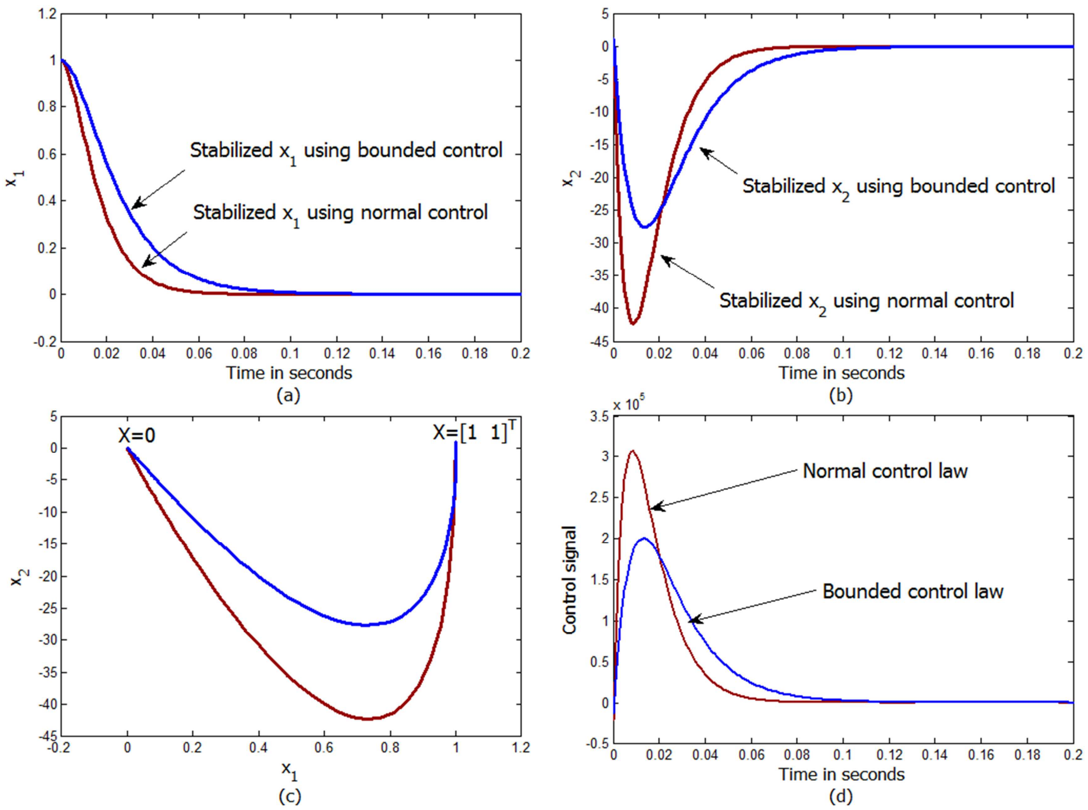


Figure 5: (a) - Membership functions for e_ω and de_ω/dt, (b) - Membership functions for C_1 and C_2 (c) - Surface of C_1, (d) - Surface of C_2



Journal of Theoretical and Applied Information Technology
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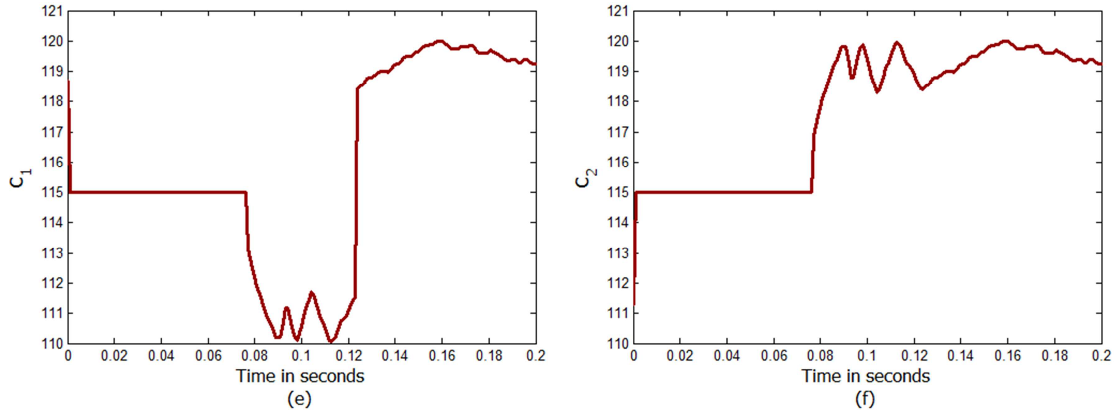

Figure 6: Response for regulation case. (a) - Regulation of x_1, (b) - Regulation of x_2, (c) - System trajectories, (d) - Control signals, (e) - History of C_1 within 0.2 seconds, (f) - History of C_2 within 0.2 seconds

4.2 Asymptotic Speed Tracking

4.2.1 Testing condition

To test the asymptotic tracking, the wind turbine variable speed control system is running under the tracking loop control, where the wind turbine is injected with a rotor speed command:

$$\omega_r^* = 15 + 10\, sin(0.2t)\; rad.s^{-1} \quad (62)$$

Figure 7(a) shows that the asymptotic tracking of the rotor speed ω_r with the speed error around $\pm 0.012\; rad.s^{-1}$ (see Figure 7(b)). Figure 8(a) and Figure 8(b) show the trajectories of the closed loop wind turbine system using the normal controller in Eq. (32) - Eq. (34) and the bounded controller in Eq. (43) - Eq. (44). When being controlled by the normal controller, it can be noticed from Figure 8(a) that the system states diverged away before return to the equilibrium. Whereas in Figure 8(b), when being controlled by the bounded controller, the system states oscillate near the equilibrium, regardless the variation in the demanded speed ω_r^*. During the system running, the tip speed ratio is maintained around its optimum value $\lambda_{opt} = 7.953925991$ as shown in Figure 9(a). This confirms the maximum power coefficient $C_{p(max)} = 0.4109631031$ in Figure 9(b).

Figure 10 shows the control signal produced by both normal control law and bounded control law for tracking the reference turbine rotor speed in Eq. (62). Normal control law produces large control magnitude (i.e. $4000 < u < -34{,}000\; N/Kg.m.s^2$). Whereas bounded control law shows it capability to limit the control signal, and produces the magnitude of around $1500 < u < -1500\; N/Kg.m.s^2$.

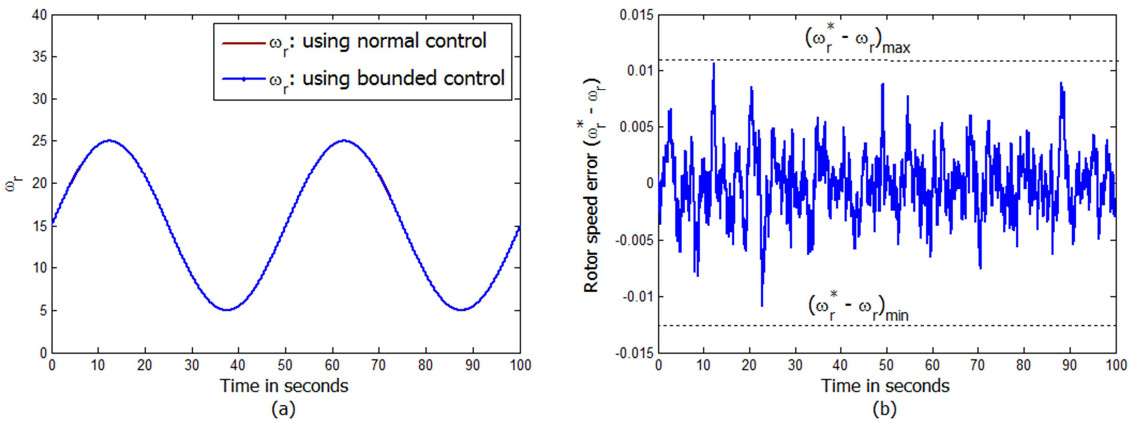

Figure 7: (a) - Controlled rotor speed ω_r, (b) - Speed tracking error

Journal of Theoretical and Applied Information Technology
31st May 2014. Vol. 63 No.3

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

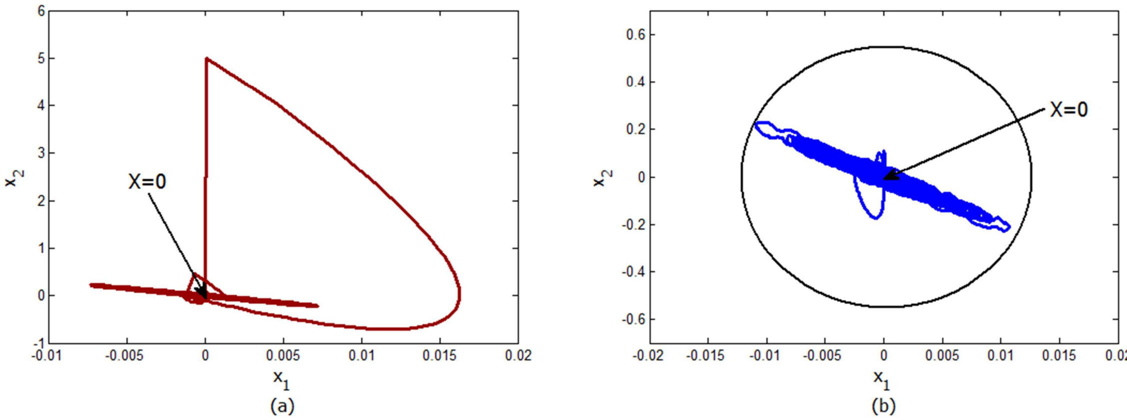

Figure 8: System trajectories, (a) - using normal controller, (b) - using bounded controller

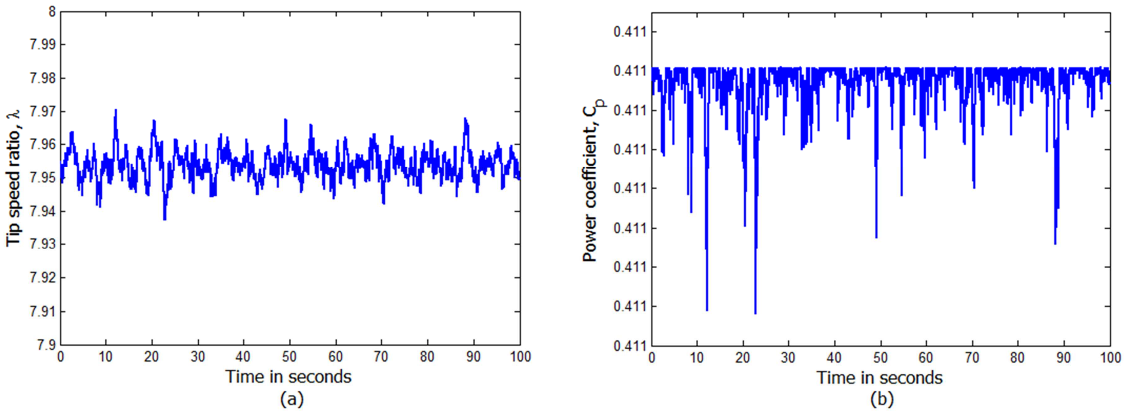

Figure 9: (a) - Tip speed ratio, (b) - Power coefficient

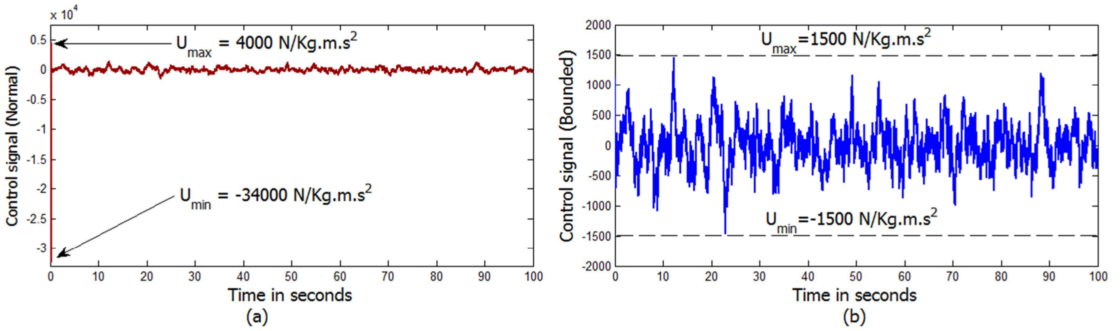

Figure 10: Control signal, (a) - Normal controller in Eq. (32) - (34), *(b) - Bounded controller in Eq.* (43) - (44)

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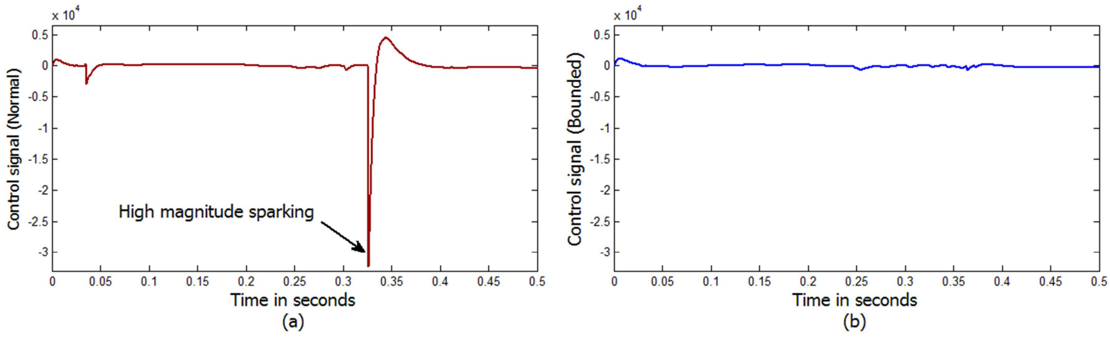

Figure 11: Initial control signal at $t = 0.5$ sec, (a) - Normal controller in Eq. (32) - (34), (b) - Bounded controller in Eq. (43) - (44)

At $t = 0.5$ seconds, the initial control signal for both normal control algorithm and bounded control algorithm is recorded in Figure 11. At $t = 0.325$ seconds, the normal control signal suffers from high magnitude distortion, which is then successfully eliminated by the bounded control algorithm (see Figure 11(b)). Therefore, an interesting ancillary result of using bounded control algorithm is the reduction in energy consumption and the elimination of high magnitude distortion in the control signal.

4.2.2 Normal condition

Under normal condition, the rotor speed must maintain equilibrium at $\omega_r^* = \frac{\lambda_{opt}}{R}\upsilon$ such that the maximum power is obtained. Under this condition, the power curve of the turbine is recorded in Figure 12(a). The turbine has rated power around *12.25 MW* with rated wind speed 18 ms^{-1}. This gives the rated rotor speed $\omega_{r_{rated}} = 6.1711\, rad.s^{-1}$. It can be observed that the turbine does not generate power output when the wind speed falls below 3 ms^{-1} (i.e. the cut-in wind speed). The asymptotic tracking expression $\omega_r = \omega_r^* \equiv \frac{\lambda_{opt}}{R}\upsilon$ indicates that the rotor speed ω_r is highly dependent on the wind speed distribution υ. With the fluctuation in υ, the most occurrence power output is recorded around *6 MW - 7 MW* (see the power distribution in Figure 12(b)). When the turbine is running at its rated rotor speed $\omega_{r_{rated}} = 6.1711\, rad.s^{-1}$, the most occurrence power output is recorded around *11 MW - 13 MW* as shown in Figure 13(a). These results show that the robust variable speed controller is capable to asymptotically tracks the turbine rotor speed in order to produce a maximum power output from the turbine. The history of the demanded rotor speed $\omega_r^* = 6.1711\, rad.s^{-1}$ and the history of the controlled rotor speed ω_r is recorded in Figure 13(b) and Figure 13(c) respectively. In Figure 13(c), despite small oscillation due to the wind speed fluctuation, the variable speed controller is capable to asymptotically tracks ω_r^* with small tracking error of around $\pm 0.02\, rad.s^{-1}$ (see Figure 13(d)). Hence, the turbine produces a maximum power output that to be fed to the power electronic conversion systems.

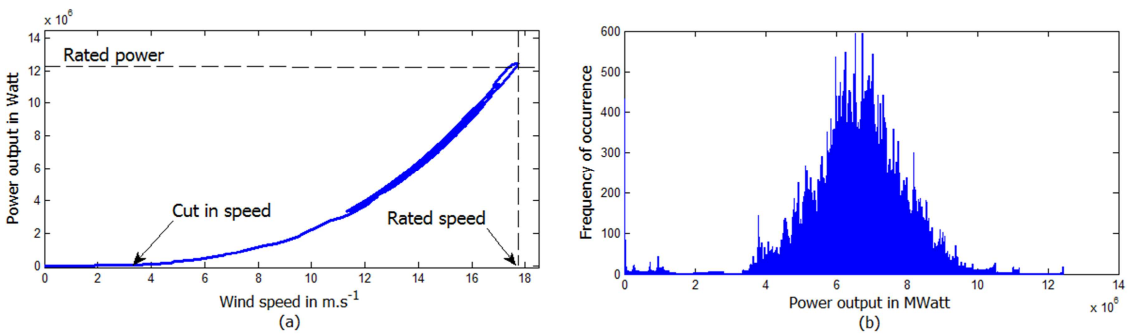

Figure 12: (a) - Power curve for demanded rotor speed $\omega_r^* = \frac{\lambda_{opt}}{R}\upsilon$, (b) - Power output distribution in response to a demanded rotor speed $\omega_r^* = \frac{\lambda_{opt}}{R}\upsilon$,

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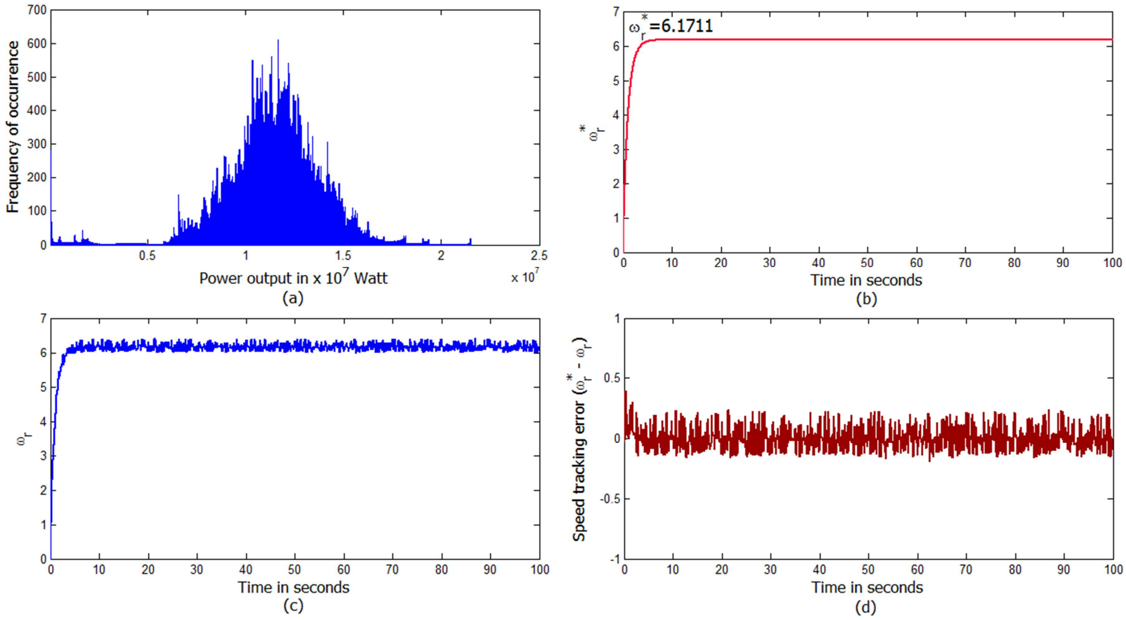

Figure 13: (a) - Power output distribution in response to a demanded rotor speed $\omega_r^* = 6.1711\ rad.s^{-1}$*, (b) - Demanded rotor speed* $\omega_r^* = 6.1711\ rad.s^{-1}$*, (c) - Controlled rotor speed, (d) - Rotor speed tracking error*

5. CONCLUSION

Stabilizing nonlinear unstable system requires massive control effort. In some cases, producing high magnitude distortion in the control signal and incurring oscillation in the control signal. Therefore, some challenge to be faced by engineers is the requirement to limit the control signal. In this paper, such tradeoffs are compensated by a robust bounded control law. The bounded control algorithm is then applied to a strict feedback nonlinear wind turbine model with unbounded exogenous disturbance and the sum of unbounded exogenous disturbance with uncertainties. With lesser energy consumption, robust variable speed control in this paper guarantees the asymptotic tracking of the turbine rotor speed, guarantees the asymptotic disturbance rejection due to wind fluctuations cum parameter uncertainties, and produces a maximum power output from the turbine. To highlight the effectiveness of the proposed control scheme, a didactic simulation studies are conducted, and the results are presented iteratively.

ACKNOWLEDGEMENT

We acknowledge the Ministry of Education Malaysia, Universiti Teknikal Malaysia Melaka (UTeM) and the Universiti Teknologi Malaysia (UTM) for research facilities and research collaboration.

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