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Output Feedback Adaptive Pitch Angle Control for Variable Speed Wind Turbine

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Abstract

This paper proposes a simple adaptive controller for pitch angle control of the variable speed wind turbine. The aim of the controller is to keep the speed of the generator at the rated value when the wind speed is above the nominal value. The controller contains two components: the output feedback component for stable purpose and the adaptive component to cancel the effect of nonlinearities, system uncertainties, and external disturbances. The controller does not need information of system parameters and wind speed then it is robust to the system uncertainties as well as wind speed varying. Moreover, this controller is quite simple, therefore it is easy for implementation. The stability of the closed loop and the convergence of the adaptive law is mathematically proven via the Lyapunov theory. The effectiveness of the given scheme is verified via simulation under two scenarios: step wind speed and random wind speed. Also, the comparisons are done between proposed adaptive controller, the corresponding nonadaptive controller, and the PID controller. The simulation results show that, for both cases, the given adaptive controller has the best responses with low steady state error of rotor speed, low overshoot, and smooth output power.

Keywords: Adaptive, output feedback, pitch angle control, wind turbine.

1. Introduction

Wind energy is one of the most popular renewable energy sources and has received the consideration from various researchers. The operation of wind turbines normally has two working regions: below rated wind speed and above rated wind speed. In the above rated wind speed area, the control problem is to keep output power or generator speed at the rated value by changing the pitch angle of the blades. However, pitch angle control is a difficult problem because wind turbine is a nonlinear system, the wind speed always changes during working time, the system model is uncertain, etc. Therefore, the design of control algorithms to limit the output power captured by wind turbine at high wind speed region is still a challenge for researchers.

One of the simplest methods in the pitch angle control problems is the PID controller [1-4]. The PID controller takes the rotor speed error or the output power error to generate the control signal for blade angles. However, wind turbine is a nonlinear system so using a linear controller cannot ensure the good responses. Therefore, many studies based on nonlinear control theory have been published to overcome this shortcoming. In [5, 6], the authors proposed a method using gain scheduling (GS) technique to design the controller for pitch angle of the variable speed wind turbine. In this method, parameters of the PI controller are adjusted to adapt with the change of wind speed. In [7], the PI controller combines with the back-propagation neural network (BPNN) to solve the problems of pitch angle control for variable speed wind turbine system. The parameters of PID controller are updated online. Also, the extended state observer is included to the scheme to estimate the states and disturbances of the system. This observer based BBNN PID controller gives a precise control for pitch blades.

Adaptive control algorithms are the good choice to deal with the disturbance and uncertain problems. In the field of pitch angle control of wind turbine system, the adaptive controller is also investigated by many researchers. In [8-10], the problems of pitch angle control are solved by using adaptive sliding mode control technique. In [8], the adaptive sliding mode observer is used in cooperating with fault-tolerant scheme to deal with the actuator fault. The given scheme shows good responses in recovering the system into normal mode and guarantees the stability of the wind turbine system under condition of low-pressure actuator fault. In [9], the electro-hydraulic servo pitch system is controlled by an adaptive robust integral sliding mode algorithm. The introduced controller helps the performance of the system to be improved regardless of various uncertainties and disturbances. Also, in [10], the adaptive sliding mode control is applied to a floating wind turbine system in high wind speed region. The pitch angle is controlled to remain the output power at the rated value with reducing knowledge of system model. In [11, 12], L1 adaptive control algorithms are introduced to regulate

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the collective pitch in the wind energy conversion system. The main advantages of these controllers are robustness to the uncertainties of the system model. However, these techniques require the measurement of wind speed [11] and inverse Laplace calculation [12] to complete the algorithm.

Linear Quadratic Regulator (LQR) is one of the techniques which is simple but has a good effect in many control applications [13]. One of the main drawbacks when applying LQR technique to the wind turbine system is that LQR is a linear controller while the wind turbine system is a complicated and nonlinear system. In [14], the linearized model of the system is presented then the LQR controller is introduced for pitch angle control system. This LQR controller gives better responses to the fault at the grid side than the PI controller does; however, the effect of the wind speed disturbance is not investigated. In [15], the LQR controller is combined with the state estimator and disturbance estimator to design the control system for pitch angle of the variable speed wind turbine. The scheme guarantees good responses under step wind speed and turbulent wind speed conditions. However, the structure of this algorithm is quite complicated and the stability of the closed loop is not given.

In this paper, a simple LQR based adaptive output feedback controller is proposed for the pitch angle control of the wind turbine system. The controller includes two components: the output feedback part to keep the system stable, the adaptive part which is added to cancel the effect of the external disturbances, system uncertainties as well as system nonlinearities. The proposed scheme does not require system parameters and the wind information in calculation, so the system is robust to the change of the working conditions. Also, the controller is output feedback then the number of sensors is reduced. Moreover, the algorithm is simple, therefore it is easy to understand as well as implementation. The stability of the system and the convergence of the adaptive law is mathematically proven through the Lyapunov theory. Finally, the simulation is executed to verify the effectiveness of the proposed controller based on the simple model of a 1.5 MW wind turbine. Also, the comparisons are done between proposed adaptive controller, the simple output feedback controller (which does not have adaptive component), and the PI controller. The simulation results show that the proposed controller, with simple structure, gives the best performance under both step wind speed and random wind speed conditions.

2. System Modelling and Controller Design

Considering to the simple two-mass model of wind turbine system as showing in the Fig. 1.

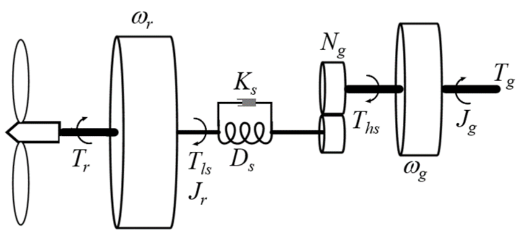


Fig. 1. Wind turbine model

The mechanical power obtained from the wind is as follows:

$$P_r = \frac{1}{2}\pi\rho R^2 V^3 C_p\left(\omega_r, \omega_g, V\right) \tag{1}$$

where R is the rotor radius, ρ is the air density, ω_r is rotor speed, ω_g is generator speed, V is the wind speed. Cp is the power conversion coefficient of wind turbine and is a nonlinear function of β and λ as follows [16]:

$$C_p = 0.22(116\lambda_t - 0.4\beta - 5)e^{-12.5\lambda_t} \tag{2}$$

in which

$$\lambda_t = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}; \quad \lambda = \frac{\omega_r R}{V} \tag{3}$$

β is the pitch angle.

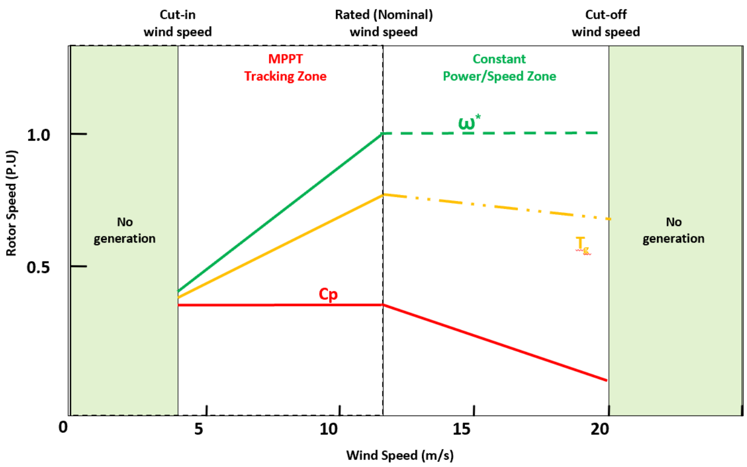


Fig. 2. Working regions of the wind turbine

As shown in Fig. 2, the working of the wind turbine is divided into three main regions: i) No generation region: as the wind speed is smaller than cut-in speed or bigger than cut-out speed, the wind turbine is set at no generation mode; ii) MPPT tracking region: in this region, the wind speed is smaller than the rated speed, the power coefficient is kept at maximum value, and the wind turbine is controlled to generate the maximum power; iii) Constant speed (power) region: when the wind speed is higher than the rated speed, the power coefficient is reduced by increasing the pitch angle then the output power and rotor speed remains at rated values.

The mathematical model of the system is illustrated as follows [17]:

$$\dot{\omega}_r = \frac{P_r(\omega_r,\beta,V)}{\omega_r J_r} - \frac{\omega_r D_s}{J_r} + \frac{\omega_g D_s}{N_g J_r} - \frac{\delta K_s}{J_r} \tag{4}$$

$$\dot{\omega}_g = \frac{\omega_r D_s}{N_g J_g} - \frac{\omega_g D_s}{N_g^2 J_g} + \frac{\delta K_s}{N_g J_g} - \frac{T_g}{J_g} \tag{5}$$

$$\dot{\delta} = \omega_r - \frac{\omega_g}{N_g} \tag{6}$$

$$\dot{\beta} = -\frac{1}{\tau_\beta}\beta + \frac{1}{\tau_\beta}\beta_u \tag{7}$$

where

T_g	generator torque
J_r, J_g	rotor and generator inertia
δ	twist angle
N_g	gear ratio
K_s	spring constant
D_s	drive-train damping
τ_β	time constants of pitch actuator
β_u	pitch angle control

The control objective of this work is to keep the rotor speed at the rated value by changing the pitch angle when the wind speed is higher than the rated speed.

Considering (4), it is rewritten as follows:

$$\begin{aligned}\dot{\omega}_r &= \frac{P_r(\omega_r,\beta,V)}{\omega_r J_r} - \frac{\omega_r D_s}{J_r} + \frac{\omega_g D_s}{N_g J_r} - \frac{\delta K_s}{J_r} \\ &= f(\omega_r,\omega_g,\delta,\beta,V)\end{aligned} \tag{8}$$

The time derivative of (8) is given as:

$$\ddot{\omega}_r = \frac{\partial f}{\partial \omega_r}\dot{\omega}_r + \frac{\partial f}{\partial \omega_g}\dot{\omega}_g + \frac{\partial f}{\partial \delta}\dot{\delta} + \frac{\partial f}{\partial \beta}\dot{\beta} + \frac{\partial f}{\partial V}\dot{V} \tag{9}$$

where

$$\frac{\partial f}{\partial \omega_r} = -\frac{1}{J_r\omega_r}\left(0.11\pi\rho R^3 V^2 \frac{178.5-1450\lambda_t+5\beta}{(\lambda+0.08\beta)^2}e^{-12.5\lambda_t} + \frac{P_r}{\omega_r}\right) - \frac{D_s}{J_r} \tag{10}$$

$$\frac{\partial f}{\partial \omega_g} = \frac{D_s}{N_g J_r} \tag{11}$$

$$\frac{\partial f}{\partial \delta} = -\frac{K_s}{J_r} \tag{12}$$

$$\frac{\partial f}{\partial \beta} = \frac{0.11\pi\rho R^2 V^3}{\omega_r J_r}\Big[(178.5-1450\lambda_t+5\beta)\times \left(\frac{-0.08}{(\lambda_t+0.08\beta)^2} + \frac{0.105\beta^2}{(\beta^3+1)^2}\right) - 0.4\Big]e^{-12.5\lambda_t} \tag{13}$$

$$\frac{\partial f}{\partial V} = \frac{0.11\pi\rho R^3 V}{J_r(\lambda+0.08\beta)^2}(178.5-1450\lambda_t+5\beta)e^{-12.5\lambda_t} \tag{14}$$

Replacing (4)-(7) and (10)-(14) into (9) and performing some manipulations, (9) can be shortened by the general equation as follows:

$$\ddot{\omega}_r = h\left(\omega_r,\omega_g,\delta,\beta,V,\dot{V}\right) + g\left(\omega_r,\omega_g,\delta,\beta,V,\dot{V}\right)\beta_u \tag{15}$$

where f (·), h (·), g (·) are continuous nonlinear functions. h (·) and g (·) contain unknown system parameters and external disturbances such as wind speed. Thus, in general, h (·) and g (·) can be consider as unknown nonlinear functions. For simplicity, they are shortened as $h(\omega_r,t)$ and $g(\omega_r,t)$.

Defining state variables $x_1 = \omega_r - \omega_{rd}$; $x_2 = \dot{x}_1$; $u = \beta_u$ where ω_{rd} is the desired rotor speed. The error dynamic model is obtained as:

$$\begin{cases}\dot{x}_1 = x_2 \\ \dot{x}_2 = h(x,t) + g(x,t)u \\ y = Cx\end{cases} \tag{16}$$

or

$$\begin{cases}\dot{x} = Ax + Bu + Dd(x,t) \\ y = Cx\end{cases} \tag{17}$$

where $x = \begin{bmatrix}x_1 & x_2\end{bmatrix}^T$

$$A = \begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix};\quad B = \begin{bmatrix}0\\1\end{bmatrix};\quad C = \begin{bmatrix}1 & 0\end{bmatrix};\quad D = \begin{bmatrix}0\\1\end{bmatrix};$$

$$d(x,t) = h(x,t) + g(x,t)u - u$$

$d(x, t)$ is considered as disturbance of the system.

Consider the system (17) without disturbance:

$$\dot{x} = Ax + Bu \tag{18}$$

The output feedback controller for (18) is determined as follows [18]:

$$u = -K_c y = -K_c Cx \tag{19}$$

where $K_c = R^{-1}B^T PC^T (CC^T)^{-1}$, P is the solution of the Riccati equation:

$$PA + A^T P - PBR^{-1}B^T P = -Q \tag{20}$$

where Q and R are positive symmetric matrices with the feasible size.

The purpose of this section is to build an adaptive controller which can deal with disturbances for the system (17). This controller is determined by the following theorem:

Theorem: If there exists a positive number η which satisfies $\eta > \|w^*\|$ and a controller (19) for linear system (18), then the following controller:

$$u = -K_c y - \mu CC^T \hat{\gamma} + \eta = -K_c Cx - \mu CC^T \hat{\gamma} + \eta \tag{21}$$

with the adaptive law

$$\dot{\hat{\gamma}} = \mu yBPC^T = \mu CxBPC^T \tag{22}$$

guarantees that the state of the uncertain system (17) and the approximation error converge to zero, where $w^* = \mu BCC^T \gamma^* - Dd(x,t)$ is minimum approximation error, γ^* is the ideal approximation parameter, μ is positive scalar.

Proof:

Substituting (21) and (22) into (17), the following result is obtained:

$$\dot{x} = (A - BK_c C)x - B\mu CC^T \hat{\gamma} + B\eta + Dd(x,t) \tag{23}$$

Adding and subtracting $\mu BCC^T \gamma^*$ in (23) yields:

$$\begin{aligned}\dot{x} &= (A - BK_c C)x + (Dd(x,t) - \mu BCC^T \gamma^*) \\ &\quad + (\mu BCC^T \gamma^* - \mu BCC^T \hat{\gamma}) + B\eta \\ &= (A - BK_c C)x - w^* + (\mu BCC^T \gamma^* - B\mu CC^T \hat{\gamma}) + B\eta\end{aligned} \tag{24}$$

Choose the Lyapunov function as:

$$V = x^T Px + (\hat{\gamma} - \gamma^*)^2 \tag{25}$$

The time derivative of (25) along with (24) is given by:

$$\begin{aligned}\dot{V} &= 2x^T P\dot{x} - 2\dot{\hat{\gamma}}(\gamma^* - \hat{\gamma}) \\ &= 2x^T P[(A - BK_c C)x - w^* + (\mu BCC^T \gamma^* \\ &\quad - \mu BCC^T \hat{\gamma}) + B\eta] - 2\mu CxBPC^T(\gamma^* - \hat{\gamma}) \\ &= 2x^T P(A - BK_c C)x + 2x^T PB\eta - 2x^T Pw^* \\ &\quad + 2\mu x^T PBCC^T(\gamma^* - \hat{\gamma}) - 2\mu CxBPC^T(\gamma^* - \hat{\gamma})\end{aligned} \tag{26}$$

According to (20), the following is obtained:

$$\begin{aligned}\dot{V} &< 2x^T PB\eta - 2x^T Pw^* + 2\mu x^T PBCC^T(\gamma^* - \hat{\gamma}) \\ &\quad - 2\mu CxBPC^T(\gamma^* - \hat{\gamma}) \\ &< \|2x^T P\|(\|B\eta\| - \|w^*\|) + 2\mu(\gamma^* - \hat{\gamma}) \times \\ &\quad \left(\|x^T\|\|P\|\|B\|\|C\|\|C^T\| - \|C\|\|x\|\|B\|\|P\|\|C^T\|\right) \\ &< \|2x^T P\|(\|B\eta\| - \|w^*\|)\end{aligned} \tag{27}$$

Due to $B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$ and $\eta > \|w^*\|$ then $\dot{V} < 0$. This implies that system (17) is asymptotically stable, or the state of uncertain system (17) converges to zero as $t \to \infty$.

3. Results and Discussions

The proposed algorithm is validated using Controls Advanced Research Turbine (CART) [20] with parameters as shown in Table 1.

Table 1. Two-mass model parameters of the 1.5 MW experimental wind turbine.

Wind turbine parameters	**Value**
Rotor radius (R_b)	35 m
Air destiny (ρ)	1.225 kg/m^3
Rotor inertia (J_r)	2.96 x 10^6 kg m^2
Generator inertia (J_g)	53.0 kg m^2
Drive – train spring factor (K_s)	5.6 x 10^9 N m/rad
Drive – train damping factor (D_s)	1.0 x 10^7 N m s/rad
Gearbox ratio (N_g)	87.965
Pitch actuator time constant (τ_β)	1 s
Nominal power output (P_e)	1.5 MW
Rated rotor speed ($\omega_{r,rated}$)	2.1428 rad/s
Rated generator torque ($T_{g,rated}$)	8376.6 N m
Pitch angle limit (β_{min} -β_{max})	-1^o to 90^o
Pitch rate limit ($\dot{\beta}_{lim}$)	± 10^o/s
Wind turbine efficiency (η)	0.95

By solving (20) with the following parameters:

$$Q = \begin{bmatrix} 800 & 0 \\ 0 & 800 \end{bmatrix}, \quad R = 0.008 \tag{28}$$

the solution K_c is obtained as follows:

$$K_c = 316.23 \tag{29}$$

Other parameters of the controller (21) are chosen as: $\eta = 10$, $\mu = 5$.

The effectiveness of the system including the wind turbine and the proposed controller is evaluated under both step wind speed and random wind speed. In each case, the performance of the proposed adaptive controller is compared with the responses of the nonadaptive controller which has the form as follows:

$$u_{non} = -Kx \quad (30)$$

where K has the same value at (29). Also, the PI controller is tested in this study for comparison. The gains for the PI controller are selected as K_I = 52, K_P = 140 [17].

3.1. Step Wind Speed

To verify the effectiveness of the proposed algorithm, the simulation is executed with the step change of wind speed in the range of 14 m/s to 24 m/s. The wave form of the wind speed is shown in Fig. 4.

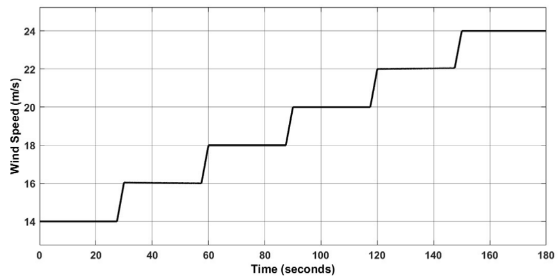


Fig. 4. The change of wind speed

The dynamic response of the wind turbine under the change of wind speed is tested with the proposed adaptive controller, the nonadaptive controller, and the PI controller. The simulation results are illustrated in Fig. 5 and the comparisons are depicted in Fig. 6.

In Fig. 5(a), the pitch angles corresponding with the adaptive controller and the PI controller are bigger than the nonadaptive controller at the same value of wind speed. This leads to the results that the wind turbine which is controlled by the nonadaptive controller captures more power from wind energy. In Fig. 5(b) and (c), the rotor speed and output power of the nonadaptive controller increase as the wind speed builds up. These increases in the high wind speed region may damage the system. With the PI and adaptive controllers, the rotor speed and output power are kept around the rated values even at the cut-out wind speed. However, the overshoot and oscillation of rotor speed and power in the transient time of the PI controller are higher than the adaptive controller (see Fig. 6). From these simulation results, it can be concluded that the proposed adaptive controller gives the best responses at both transient and steady state time. Meanwhile, the nonadaptive controller provides good transient responses (no overshoot, short settling time) but steady state error is too high. On the contrary, the PI controller has almost the same steady state error with adaptive controller but the overshoot and settling time are so high.

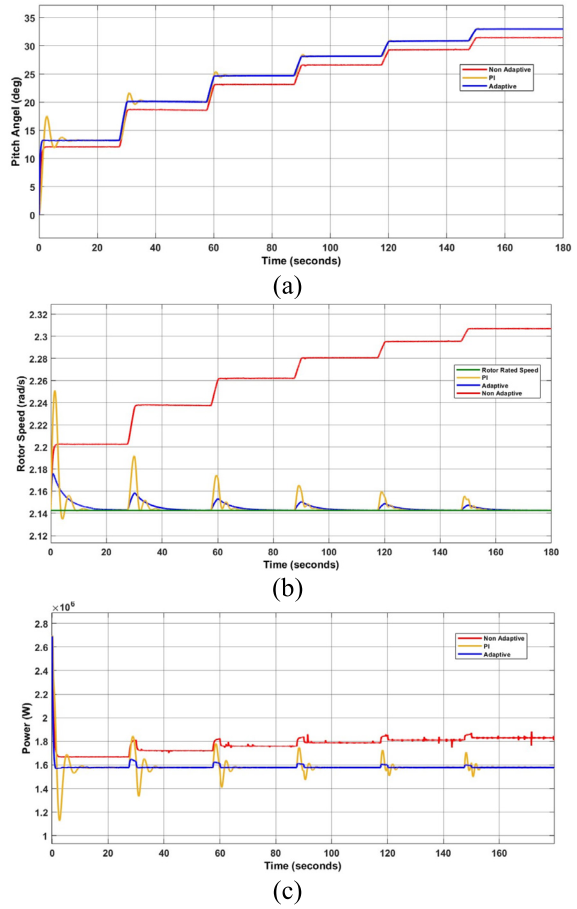


Fig. 5. Dynamic responses of the proposed adaptive controller, the nonadaptive controller, and the PI controller under step change of the wind speed

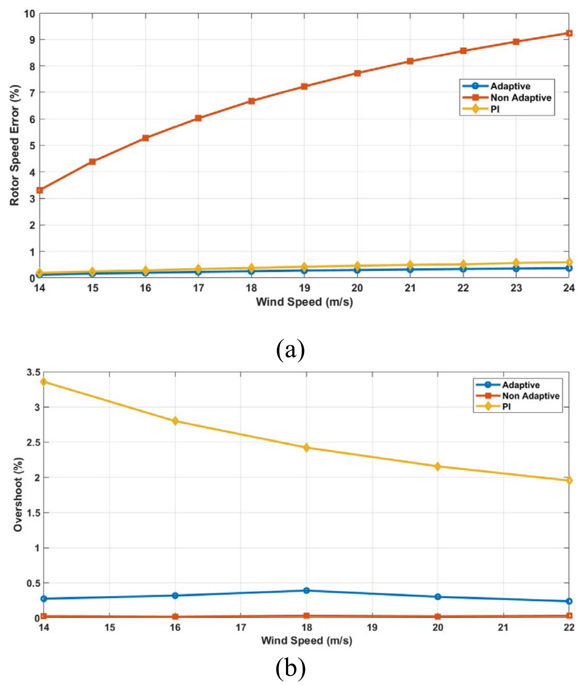


Fig. 6. Comparison summarizing of the proposed adaptive controller, the nonadaptive controller, and the PI controller

3.2. Random Wind Speed

In reality, wind speed always changes randomly, so the random wind speed test is required to check the ability to apply into the reality of the proposed controller. The waveform of wind speed in this test is provided in Fig. 7 with the value in the range of 12m/s to 18 m/s.

The time response and evaluated results of the proposed adaptive controller, the nonadaptive controller, and the PI controller under random wind speed are given in Fig. 8 and Fig. 9 respectively.

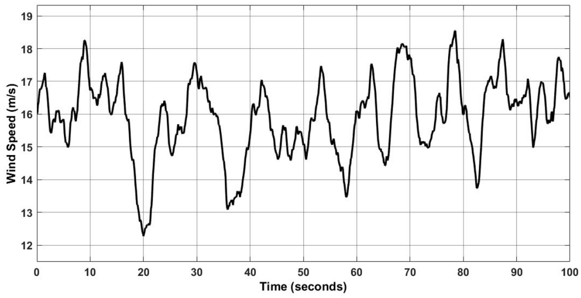
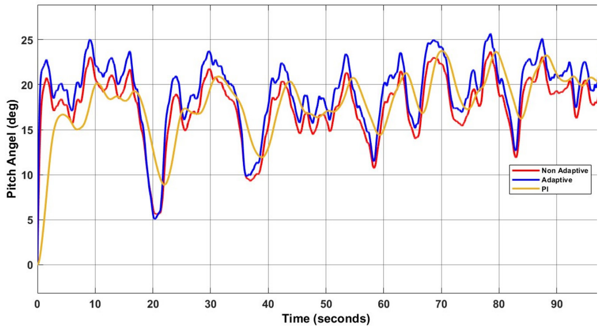
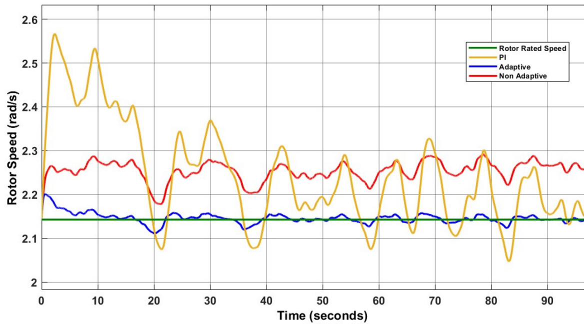


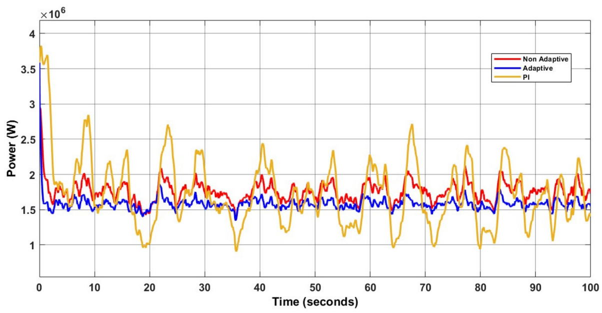
Fig. 7. Random wind speed



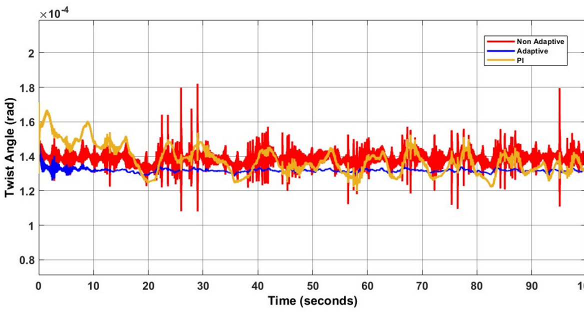
(a)



(b)



(c)



(d)

Fig. 8. Dynamic responses of the proposed adaptive controller, the nonadaptive controller, and the PI controller under random wind speed

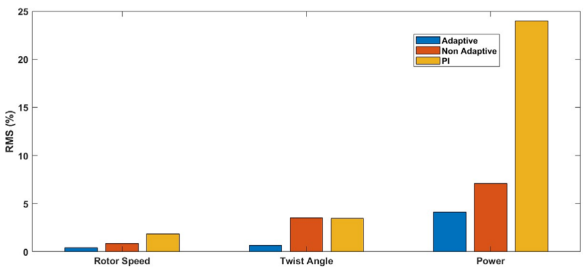


Fig. 9. Numerical evaluation responses of the proposed adaptive controller, the nonadaptive controller, and the PI controller under random wind speed

As shown in Fig. 8, in the random wind speed mode, the wind speed changes very fast but the dynamic of the PI controller is slow so it cannot adapt with the change of the wind speed. As the results, the pitch angle of the PI controller cannot reach the value which required to keep the rotor speed and output power at rated value. The dynamic of the nonadaptive controller is as fast as that of adaptive controller. However, the nonadaptive controller does not have the ability to cancel the effect of the nonlinearities and disturbances so the rotor speed is so high. Finally, the adaptive controller with the adaptive component, which can adapt to the system uncertainties and disturbances, has the rotor speed almost the same as the rated value. All these results are numerically concluded in Fig. 9. In Fig. 9, it is shown that the adaptive controller has the smallest oscillation in rotor speed, twist angle, and output power with the percentage of RMS being about 0.5%, 1%, and 8%

respectively. The swings for the nonadaptive and the PI controllers are much higher, i.e., 1%, 5%, 5% for the nonadaptive controller, and 5%, 7%, 24% for the PI controller.

From all above results, it can be seen that the proposed adaptive controller has the best performance in both step wind speed and random wind speed. The PI controller has small steady state error in step wind speed but it has the highest steady state error in the random wind speed. Similarly, the nonadaptive controller provides good transient responses in step wind speed but the steady state error is so high in both cases.

4. Conclusion

In this paper, a simple adaptive output feedback controller is proposed for pitch angle control of the wind turbine system to keep the rotor speed at rated value as the wind speed is over the rated speed. Firstly, the nonlinear and uncertain model of the wind turbine is introduced. Next, the adaptive controller is proposed to guarantee the stability of the system. The proposed controller does not require the system parameters as well as wind speed information, therefore it is robust to the system parameter uncertainties and external disturbances. The stability of the closed loop and the convergence of the adaptive law are mathematically proven via the Lyapunov theory. Finally, the comparison is done between the proposed adaptive controller, nonadaptive controller, and PI controller through simulation. The results show that the adaptive controller gives the best performance despite the change of the wind speed. Thoroughly, in the step wind speed case, the rotor speed error and overshoot are almost zero, the output power is constant in all range of the wind speed. For the random wind speed, the adaptive controller still gives the good results. Also, the fast response helps the adaptive controller to catch the fast change of wind speed. Meanwhile, the nonadaptive controller has a large rotor speed error and output power error in both cases, the PI controller works well under step wind speed, but the system responses are poor when the wind speed is random.

Acknowledgments

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