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Research Article

Feedforward Feedback Pitch Control for Wind Turbine Based on Feedback Linearization with Sliding Mode and Fuzzy PID Algorithm

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After exceeding rated power, variable speed variable pitch wind turbines need to keep output powers at rated value by adopting pitch angles. With the typical nonlinear characteristics of the wind turbines, it is difficult to control accurately by conventional linear controller. Though feedback control can realize the stability of the system, it is effective only when deviations are produced. As such, feedforward control can be applied to compensate the time-delay produced by feedback control. Accordingly, we propose a compound control strategy that combines feedback controller with feedforward controller in this paper. In feedback loop, we adopt fuzzy algorithm to adjust the parameters of PID controller. Furthermore, to overcome large variation of input wind speed, variable universe theory is proposed to optimize fuzzy algorithm. In feedforward loop, we propose feedback linearization to address nonlinear problem. Furthermore, sliding mode algorithm is supplied to improve the robustness of feedback linearization. Therefore, feedforward loop can efficiently compensate time-delay deficiency of wind turbine systems. Simulation results show that the proposed controller can enhance the control accuracy and robustness of the system.

1. Introduction

Wind energy is an important renewable energy so that wind turbines are rapidly developing in the world for decades [1–4]. In the beginning, small wind turbine is the mainstream as its construction is simple and control algorithms are rarely used and therefore its power control greatly depends on aerodynamics itself. With the development of modern control theories and power electronic technologies, variable speed variable pitch technology is widely used to adjust the output powers of wind turbines [5–9]. Thus, large wind turbine is rapidly developed and occupies the main commercial market.

Usually, the working scope of wind turbine can be divided into three regions in Figure 1 [10, 11]. Region I is from cut in wind speed to rated speed of electric motor. In this stage, the optimal output power is extracted from wind by controlling electromagnetic torque. The process of working is shown in region II when wind speed is over the rated value. With the increasing of wind speed, output power is increasing. Output power reaches its nominal value when wind speed approaches the rated value. If wind speed continues to increase, the output power would be kept at the rated value for the requests of mechanism and security operation, which is called region III. In this region, it is an effective method that adjusts pitch angle to keep output power at constant.

Various control algorithms have been greatly studied these years. Classic PID controller is widely employed in control system because its structure is simple and can be easily realized. However, wind turbine is a strongly nonlinear system so that linear PID controller cannot meet the requests of the system. Usually, PID algorithm is combined with intelligent algorithm to build a new controller whose control performance can be greatly improved. In [11], a nonlinear PI controller is proposed for realizing the optimum performance of wind turbine system. The introduced nonlinear controller consists of an extended-order state and perturbation observer (ESPO) with a classic PI controller. The ESPO can tackle nonlinear and disturbance problems. However, the presented algorithm needs the same accuracy system model as the feedback linearization method. In [12], an adaptive

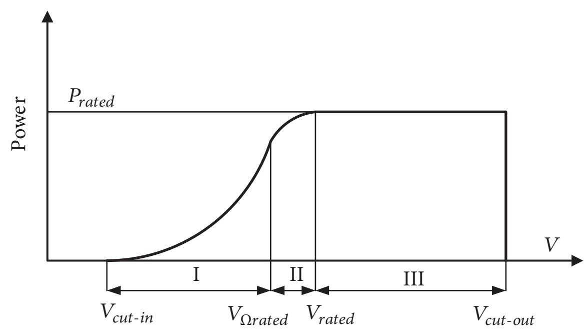


Figure 1: The operation regions of wind turbine.

pitch controller is adopted to solve system uncertainty by updating parameters online. The controller includes two parts: reference model and adaptive algorithm. Adopting this method, the generator speed can be kept at constant, while load is reduced. In [13], a two-degree-of-freedom (2-DOF) controller is designed to adjust output power. The control structure comprises a feedforward controller and a feedback controller. In feedforward loop, a feedback linearization algorithm is proposed that can compensate the nonlinear feature. On the other hand, a PID controller is adopted as feedback loop, which can tackle unknown disturbance and parameter variation. In [14], a new intelligent genetic algorithm is used to optimize proportional-integral-derivative parameters, in which two operations are suggested in order to search the local minimum or the maximum value, including increasing mutation rate and crossover point. In [15], artificial neural networks are adopted to solve system nonlinearization and difficultly inverse function. In [16], a controller for adjusting both blade pitch and generator torque is suggested. In this control method, measurement values of wind speeds will not be needed by means of designing a sliding surface to guarantee the estimated aerodynamic power that is equal to the actual one. Therefore, the structure of the system is simplified. In [17], a control strategy mixing H_2/H_∞ algorithm based on global exact linearization is suggested, which can implement better performance in large range near operation points and alleviate loads of wind turbine. In [18], in order to improve pitch system performance of wind turbine, optimization, estimation, and compensation are synthetically proposed. Firstly, an optimal PI controller is developed by utilizing direct search optimization, which has better control performance in delay-free pitch system. Moreover, a delay estimator is used to estimate the interference in order to address time-delay problem. As delay-perturbation affects output value, a signal compensation method is further utilized to offset the error. In [19], an adaptive sliding mode controller and a back-stepping controller based on pump displacement and stroke piston of pitch system for wind turbine are proposed, which can accurately track the desired values of pitch angle. In [20], a fuzzy sliding mode controller is used to adjust pitch angle without accurate mathematical models. In pitching, fuzzy controller is adopted to approximate the main controller input while fuzzy sliding mode controller is used to compensate the difference between the former two controllers. In [21], H. Camblong et al. firstly linearized wind turbine system at the operating point. Subsequently, linear quadratic Gaussian (LQG) controllers are designed to reduce fatigue load and the suggested method is verified by test experiments. As wind speed is constantly changing, in order to improve control performance, LPV gain scheduling is often adopted [22–26]. However, design of classic LPV algorithm requires much time and cannot guarantee global stability. Therefore, LPV usually combines variable gain scheduling with robust control. The above all studied control algorithms for adjusting output power of wind turbine have already obtained excellent control performance in different situations. However, some control strategies can be further improved.

As time-delay of pitch system, the output power of wind turbine shows overshoot phenomenon. Although feedback control can fulfill tracking control, it cannot overcome power overshoot problem. However, overshoot could be decreased by feedforward control in presetting control variables. Accordingly, we adopt the same control structure as in [13], which consists of feedback control combining with feedforward control. In [13], a feedback control strategy combining with feedforward control was proposed. However, in feedback loop, only a conventional PID controller was applied as feedback controller, which cannot meet the control requirements of the nonlinear system. To improve the performance of the feedback controller, we adopt a variable universe fuzzy algorithm to optimize the parameters of the PID controller. In [13], feedback linearization theory was proposed to overcome the nonlinear feature of wind turbines in feedforward loop. However, the robustness of the feedback linearization controller should be improved as it needs precise objective model. Nevertheless, sliding mode variable structure algorithm can overcome model uncertainty problem for its adaptive capability. Accordingly, in feedforward loop, we adopt sliding mode algorithm to optimize feedback linearization controller so that robustness can be enhanced.

2. Model of Wind Turbine Generator System

Wind rotates turbine. Then, wind energy can be converted into electrical energy through electric generator motivated by drive train that is connected to the turbine rotor. Energy conversion system is depicted in Figure 2. Shaft power extracted by wind turbine can be given from [11, 12, 27].

$$P = T_r \omega_r = \frac{1}{2}\rho \pi R^2 v^3 C_p(\lambda, \beta) \quad (1)$$

$$J_r \dot{\omega}_r = T_r - T_l \quad (2)$$

$$C_p(\lambda, \beta) = (0.44 - 0.0167\beta)\sin\left(\frac{\pi(\lambda - 3)}{15 - 0.3\beta}\right) - 0.00184(\lambda - 3)\beta \quad (3)$$

$$\lambda = \frac{\omega_r R}{v} \quad (4)$$

where P is the shaft power of wind turbine, T_r is the aerodynamic torque of turbine rotor, ω_r is the rotor speed

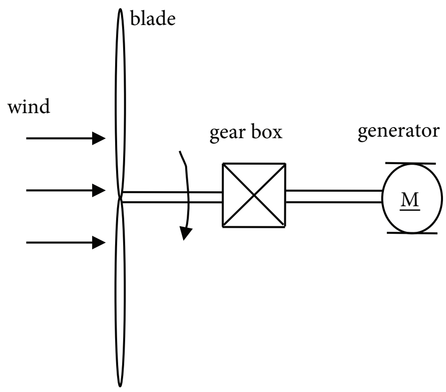


Figure 2: The block diagram of energy conversion of wind turbine.

of turbine rotor, ρ is the air density, R is the radius of turbine rotor, v is the wind speed, $C_p(\lambda, \beta)$ is the conversion coefficient of wind energy, J_r is the rotational inertia of turbine rotor, T_l is the torque of low speed shaft, λ is the tip-speed ratio, and β is the pitch angle.

The shaft power of wind turbine is proportional to the cube of wind speed known from (1) so that the output power will be strongly affected when wind speed increases. Therefore, in order to keep output power at constant, power conversion coefficient will be decreased when wind speed is over the rated value. In addition, known from (3) and (4), power conversion coefficient is controlled by rotor speed of turbine rotor and pitch angle of wind turbine when wind speed is changing. After the output power of wind turbine is over the rated value, rotor speed of electric generator is constant. Consequently, adjusting pitch angle is a main method for controlling the output power. On the other hand, based on (1), it is known that output power can also be maintained at the rated value by adjusting torque.

Due to the fact, this paper focuses on algorithms of adjusting power. In order to simplify the model of the drive train, the system structure is assumed to be rigid that will not affect researching wind turbine system. The relationship between low speed shaft and high speed shaft can be expressed in [12]

$$k = \frac{\omega_g}{\omega_r} = \frac{T_l}{T_h} \tag{5}$$

where k is the gear ratio of the drive train, ω_g is the angular speed of high speed shaft, and T_h is the torque of high speed shaft.

In high speed section of the drive train, the relationship can be expressed in [17]

$$J_g \dot{\omega}_g = T_h - T_e \tag{6}$$

where J_g is the rotational inertia of electric generator and T_e is the torque of electric generator.

The relationship can be gained from (5) as follows:

$$T_l = kT_h \tag{7}$$

$$\omega_g = k\omega_r \tag{8}$$

The relationship can be acquired based on (6) as

$$T_h = J_g \dot{\omega}_g + T_e \tag{9}$$

Substituting (7), (8), and (9) into (2), the relationship can be further written as

$$\dot{\omega}_r \left(J_r + k^2 J_g\right) = T_r - kT_e \tag{10}$$

Controlling the pitch angle of variable pitch wind turbine is to maintain output power at nominal value when wind speed is over the rated value. Pitch system can be expressed approximately as a first-order inertia system in [17]

$$\dot{\beta} = \frac{1}{\tau}\left(\beta_1 - \beta\right) \tag{11}$$

where β is the pitch angle, τ is the time constant, and β_1 is the desired pitch angle. When wind speed is changing, the desired pitch angle is the output value of controller. Therefore, the real-time pitch angle can be calculated by using integral algorithm based on (11).

According to double-fed generator equivalent circuit, stator equation, and rotor equation, the expression of electromagnetic torque can be expressed in

$$\begin{aligned} T_{em} = {} & \frac{-3spx_m^2 r_2}{\omega_1 c^2} U_1^2 + \frac{3px_m^2 r_1}{\omega_1 c^2} U_2^2 \\ & + \frac{3px_m}{\omega_1 c^2} \left[\left(r_1 r_2 + sx_{2\sigma} x_{1\sigma} + sx_m^2 \right) \sin \alpha_{12} \right. \\ & \left. - \left(sx_{2\sigma} r_1 - x_{1\sigma} r_2 \right) \cos \alpha_{12} \right] U_1 U_2 \end{aligned} \tag{12}$$

where $c = \sqrt{(r_1 r_2 - sx_{2\sigma} x_{1\sigma} + sx_m^2)^2 + (sx_{2\sigma} r_1 + x_{1\sigma} r_2)^2}$, p is the pole pairs, ω_1 is the synchronous angular velocity, s is the slip rate, U_1 is the stator voltage, U_2 is the rotor voltage, α_{12} is the phase difference between stator and rotor, r_1 is the stator winding resistance, $x_{1\sigma}$ is the leakage reactance, r_2 is the rotor winding resistance calculated to stator, $x_{2\sigma}$ is the leakage calculated to stator side, and x_m is the excitation reactance.

The electromagnetic power of doubly fed motor can be expressed in

$$\begin{aligned} P_e = T_{em} \Omega_1 = T_{em} \frac{\omega_1}{p} = {} & \frac{-3sx_m^2 r_2}{c^2} U_1^2 + \frac{3x_m^2 r_1}{c^2} U_2^2 \\ & + \frac{3x_m}{c^2} \left[\left(r_1 r_2 + sx_{2\sigma} x_{1\sigma} + sx_m^2 \right) \sin \alpha_{12} \right. \\ & \left. - \left(sx_{2\sigma} r_1 - x_{1\sigma} r_2 \right) \cos \alpha_{12} \right] U_1 U_2 \end{aligned} \tag{13}$$

where Ω_1 is the generator synchronous mechanical angular velocity.

3. Feedforward Feedback Controller Based on Feedback Linearization with Sliding Mode and Fuzzy Self-Tuning PID

Known from (3), the energy conversion coefficient $C_p(\lambda, \beta)$ is nonlinear function including λ and β. Therefore, the shaft

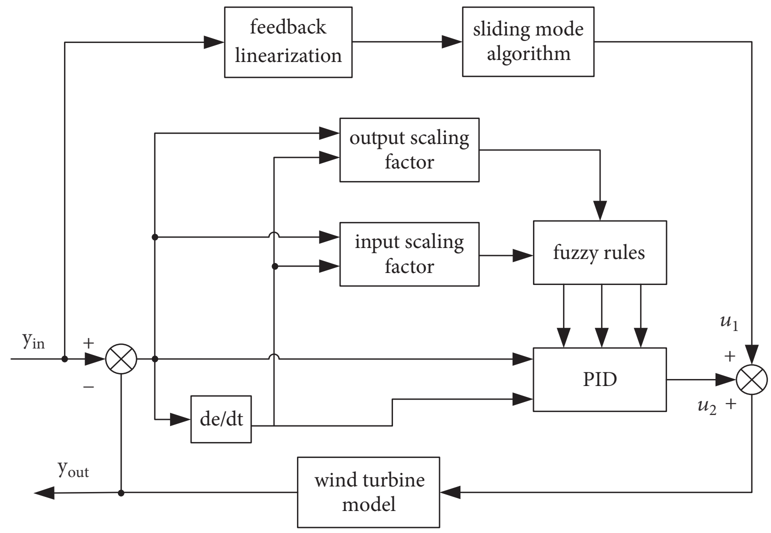


Figure 3: The system control structure of wind turbine.

power expression of wind turbine is nonlinear. As wind turbine system model is a typical nonlinear system, the controller designed based on linear system is not the best choice. However, nonlinear controller is a better idea. In this paper, we propose a novel feedforward feedback algorithm, whose feedback section is fuzzy self-tuning PID algorithm and its feedforward section is feedback linearization algorithm. However, feedback linearization control needs an accurate system model and it is subject to parameter variation. Consequently, its application is limited. As sliding mode control is not affected by parameter variation of system and disturbances, robustness of system can be improved by combining sliding mode method with feedback linearization algorithm. The chart that describes this algorithm is shown in Figure 3. Differential equations of wind turbine can be acquired from Section 2 as follows:

$$\dot{\omega}_r \left(J_r + k^2 J_g\right) = \frac{1}{2\omega_r} \rho \pi R^2 v^3 C_p (\lambda, \beta) - kT_g$$
$$\dot{\beta} = \frac{1}{\tau} (\beta_1 - \beta) \tag{14}$$

Assuming state variables $x_1 = \omega_r$, $x_2 = \beta$, control input $u = \beta_1$, state equations can be given as

$$\dot{x_1} = \frac{1}{J_r + k^2 J_g} \left(\frac{1}{2x_1} \rho \pi R^2 v^3 C_p (\lambda, x_2) - kT_g \right)$$
$$\dot{x_2} = \frac{1}{\tau} (u - x_2) \tag{15}$$

Then output equation can be expressed as follows.

$$y = x_1 \tag{16}$$

3.1. Fuzzy Self-Tuning PID Algorithm. Due to the nonlinearity and time-varying characteristics of the wind turbine, the conventional PID cannot meet the control requirements. The fuzzy algorithm transforms input values by fuzzifier and makes a judgment based on fuzzy rules, which can control the more complex systems [28–32]. In this paper, we use the fuzzy algorithm to adjust the parameters of the PID controller in the feedback control loop to improve the control performance of the controller.

Generator velocity will be a constant when wind speed is overrated value. As drivetrain is considered stiffness, wind turbine velocity is also a constant. However, the velocity will fluctuate in a very small range for there are random disturbances. Accordingly, we select wind turbine velocity as reference variable. When pitching, the input variables of the fuzzy controller are the wind turbine velocity errors and the error changing rates. The output variables are the proportion, integral, and differential gains of the PID controller. Error and error changing rate corresponding to the fuzzy domain are taken as {−3, −2, −1, 0, +1, +2, +3}. Fuzzy rules are the key of fuzzy control. Not only the correctness of fuzzy control rules directly affects the performance of the controller but their number is also an important factor to measure controller performance. Therefore, we define seven fuzzy subsets and the language variables are {negative big, negative middle, negative small, zero, positive small, positive middle, positive big}, expressed as NB, NM, NS, Z, PS, PM, and PB, respectively. These language variables cannot only clearly express universe but the control rule number is appropriate. Fuzzy rules are shown in Tables 1–3. They can be further described as follows:

If e is NB and ec is NB, then output is PB.
If e is NB and ec is NM, then output is PB.
If e is NB and ec is NS, then output is PM.

The membership function determines the sensitivity of the fuzzy control performance. If the membership function changes more smoothly, the stability of the controller is better. On the other hand, if the membership function is steeper, then the controller has high sensitivity. Therefore, when the

Table 1: The fuzzy rules of K_P.

		e						
		NB	NM	NS	Z	PS	PM	PB
	NB	PB	PB	PM	PM	PS	Z	Z
	NM	PB	PB	PM	PS	PS	Z	NS
	NS	PM	PM	PM	PS	Z	NS	NS
ec	Z	PM	PM	PS	Z	NS	NM	NM
	PS	PS	PS	Z	NS	NS	NM	NM
	PM	PS	Z	NS	NM	NM	NM	NB
	PB	Z	Z	NM	NM	NM	NB	NB

Table 2: The fuzzy rules of K_I.

		e						
		NB	NM	NS	Z	PS	PM	PB
	NB	NB	NB	NM	NM	NS	Z	Z
	NM	NB	NB	NM	NS	NS	Z	Z
	NS	NB	NM	NS	NS	Z	PS	PS
ec	Z	NM	NM	NS	Z	PS	PM	PM
	PS	NM	NS	Z	PS	PS	PM	PB
	PM	Z	Z	PS	PS	PM	PB	PB
	PB	Z	Z	PS	PM	PM	PB	PB

Table 3: The fuzzy rules of K_D.

		e						
		NB	NM	NS	Z	PS	PM	PB
	NB	PS	NS	NB	NB	NB	NM	PM
	NM	PS	NS	NB	NM	NM	NS	Z
	NS	Z	NS	NM	NM	NS	NS	Z
ec	Z	Z	NS	NS	NS	NS	NS	Z
	PS	Z	Z	Z	Z	Z	Z	Z
	PM	PB	PS	PS	PS	PS	PS	PB
	PB	PB	PM	PM	PM	PS	PS	PB

error and error rate of change are large, Gaussian membership function with smooth change is selected, which makes the system change smoothly and have good robustness. When the error and error changing rate are both small, the triangular membership function with high sensitivity is proposed to improve the system response. The diagram of fuzzy system with two-input three-output is shown in Figure 4. Parameters of fuzzy controller are shown in Table 5.

e is the error and ec is the error changing rate. The output of PID controller is as follows.

$$u_1 = K_P\left(e(t) + \frac{1}{T_I}\int e(t)\,dt + T_D\frac{de(t)}{dt}\right) \quad (17)$$

where u_1 is the output of PID controller, K_P is the proportional coefficient, $e(t)$ is the error, T_I is the integral coefficient, and T_D is the differential coefficient.

3.2. Variable Universe Theory. Fuzzy PID controllers exhibit good control performance. Nevertheless, when input variables change a lot, the control accuracy needs to be further

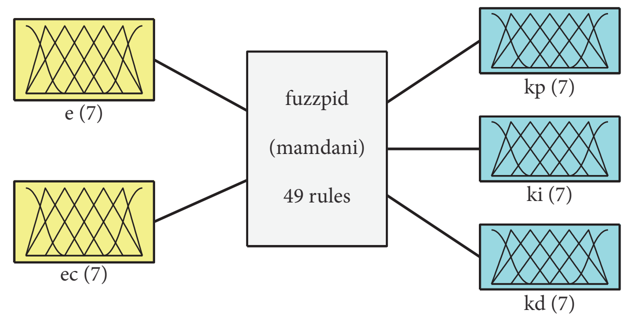


Figure 4: The fuzzy system structure.

improved. The idea of variable universe is to make any input can correspond to the entire input universe by adding a scaling factor without increasing the fuzzy rules based on the changes of the input [33]. If the original basic universe is adopted, control accuracy is not ideal. Furthermore, when the control error becomes smaller, its corresponding rules can be reduced. However, the rules corresponding to the input can be increased by adjusting scaling factor if the variable universe method is implemented. In other words, the corresponding rule density is increased. Therefore, the control accuracy is improved. The key of the variable universe approach is to determine the scaling factor, which should meet the following requirements.

(1) Duality: for $(\forall x \in X)$, $\alpha(x) = -\alpha(-x)$ is a necessary condition.

(2) Avoid zero: $\alpha(0) = \varepsilon$.

(3) Monotonicity: $\alpha(x)$ is strictly monotonically increasing from 0 to E.

(4) Coordination: $\forall x \in X$, $x \le \alpha(x)E$.

(5) Regularity: $\alpha(\pm E) = 1$.

Thereby, the universe scaling factors are expressed in

$$\alpha(x) = \left(\frac{|x|}{E}\right)^{\mu} + \varepsilon \quad (18)$$

$$\eta(x) = \left(\frac{|x|}{E}\right)^{\mu_1}\left(\frac{|y|}{EC}\right)^{\mu_2} + \varepsilon \quad (19)$$

where $\alpha(x)$ is the scaling factor of the input universe, $\eta(x)$ is the scaling factor of the output universe, x is the error, y is the error rate of change, E is the value of the error universe, EC is the value of the error changing rate universe, μ, μ_1, and μ_2 are constants from 0 to 1, and ε is a full small positive number.

The process of changing universe is shown in Figure 5.

3.3. Design of Feedback Linearization of Nonlinear Model for Wind Turbine. Feedback linearization algorithm is to add a nonlinear compensation part in control input variables. Then a new equivalent controlled system can be gained. The original system is transformed into linear form. As feedback linearization algorithm is based on strict mathematical derivation and control input is expressed in output equation,

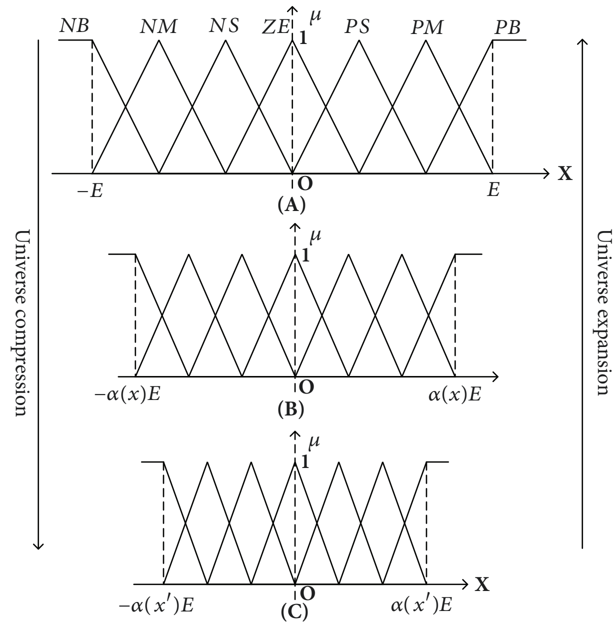


Figure 5: The diagram of changing universe process.

the nonlinear system model can be linearized by designing appropriate control rules. Therefore, control performance of system can be improved distinctly.

The affine nonlinear models of single input single output are expressed as [13]

$$\begin{aligned} \dot{x} &= f(x) + g(x)u \\ y &= h(x) \end{aligned} \tag{20}$$

where $x = [x_1, x_2 \cdots x_n]^T$ are the n-dimensional state vectors, $f(x)$ and $g(x)$ are the fully smooth vector fields in R^n, $u \in R$, $y \in R$, and $h(x)$ is the fully smooth nonlinear function.

The expression can be gained as follows based on (15), (16), and (20):

$$\begin{aligned} f(x) &= \begin{bmatrix} f_1(x) \\ f_2(x) \end{bmatrix} \\ &= \begin{bmatrix} \dfrac{1}{J_r + k^2 J_g}\left(\dfrac{1}{2x_1}\rho\pi R^2 v^3 C_p(\lambda, x_2) - kT_g\right) \\ -\dfrac{1}{\tau}x_2 \end{bmatrix} \end{aligned} \tag{21}$$

$$g(x) = \begin{bmatrix} 0 \\ \dfrac{1}{\tau} \end{bmatrix} \tag{22}$$

$$h(x) = x_1 \tag{23}$$

Known from (23), there is no direct relationship between the output equation and the control input. Therefore, derivative of time for output equation must be implemented as

$$\begin{aligned} \dot{y} &= \frac{dh(x)}{dt} = \frac{\partial h(x)}{\partial x}\frac{\partial x}{\partial t} \\ &= \frac{\partial h(x)}{\partial x}[f(x) + g(x)u] \\ &= \frac{\partial h(x)}{\partial x}f(x) + \frac{\partial h(x)}{\partial x}g(x)u \end{aligned} \tag{24}$$

$$\frac{\partial h(x)}{\partial x} = [1 \quad 0] \tag{25}$$

Equations (26) and (27) can be gained based on (25).

$$\frac{\partial h(x)}{\partial x}f(x) = L_f h(x) = f_1(x) \tag{26}$$

$$\frac{\partial h(x)}{\partial x}g(x) = L_g h(x) = 0 \tag{27}$$

Substituting (26) and (27) into (24), it is seen that $\dot{y}$ does not include u. Then, derivative of time for (24) will be continued.

$$\begin{aligned} \ddot{y} &= \frac{\partial L_f h(x)}{\partial x}\frac{\partial x}{\partial t} = \frac{\partial L_f h(x)}{\partial x}[f(x) + g(x)u] \\ &= L_f^2 h(x) + L_g L_f h(x) u \end{aligned} \tag{28}$$

In (28)

$$\begin{aligned} L_f^2 h(x) &= \frac{\partial L_f h(x)}{\partial x}f(x) \\ &= \begin{bmatrix} \dfrac{\partial f_1(x)}{\partial x_1} & \dfrac{\partial f_1(x)}{\partial x_2} \end{bmatrix}\begin{bmatrix} f_1(x) \\ f_2(x) \end{bmatrix} \\ &= \frac{\partial f_1(x)}{\partial x_1}f_1(x) + \frac{\partial f_1(x)}{\partial x_2}f_2(x) \end{aligned} \tag{29}$$

$$\begin{aligned} L_g L_f h(x) &= \frac{\partial L_f h(x)}{\partial x}g(x) \\ &= \begin{bmatrix} \dfrac{\partial f_1(x)}{\partial x_1} & \dfrac{\partial f_1(x)}{\partial x_2} \end{bmatrix}\begin{bmatrix} 0 \\ \dfrac{1}{\tau} \end{bmatrix} = \frac{\partial f_1(x)}{\partial x_2}\frac{1}{\tau} \end{aligned} \tag{30}$$

Therefore,

$$L_g L_f h(x) \neq 0 \tag{31}$$

From now on, input variable u is expressed in $\ddot{y}$, and the condition for meeting feedback linearization is gained.

3.4. Input-Output Feedback Linearization Based Sliding Mode Control. Both linear controller and nonlinear controller are usually adopted to control nonlinear system. However, linear controller can only control linear system well. In nonlinear system, if linear controller is used, nonlinear model will be usually linearized. Sliding mode control is a nonlinear

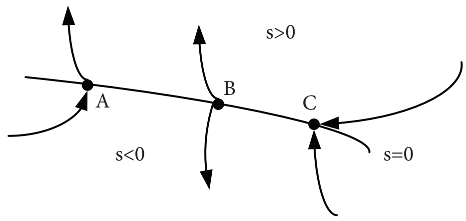


Figure 6: The schematic diagram of sliding mode hypersurface.

algorithm and it can continuously adjust itself based on real-time state variables during dynamic process for system to track the state trajectory of sliding mode [34, 35]. In this paper, we propose sliding mode algorithm to enhance the robustness of feedback linearization.

Assume that there exists a system as follows.

$$\dot{x} = f(x) \quad x \in R^n \tag{32}$$

In its state space, there is a hypersurface $s(x) = s(x_1, x_2, \cdots, x_n) = 0$, depicted in Figure 6.

The state space is divided into two parts $s > 0$ and $s < 0$ in hypersurface. In switching surface $s = 0$, the point in system will be close to termination point when it is near switching surface.

If all points are termination points in a special field in the switching surface, once the points move to this area, to which they will be attracted; it is called sliding mode area. The movement of system in sliding mode area is called sliding mode action.

As the moving point is termination point in sliding mode area, the expression can be gained as follows when the point moves to a place near the sliding mode surface.

In other words,

$$\lim_{s\to 0^+} \dot{s} \le 0 \le \lim_{s\to 0^-} \dot{s} \tag{33}$$

The other expression is formulated as

$$\lim_{s\to 0} s\,\dot{s} \le 0 \tag{34}$$

Assume that a function is given by

$$v(x_1, x_2, \cdots, x_n) = [s(x_1, x_2, \cdots x_n)]^2 \tag{35}$$

The derivative of time for (35) can be expressed as follows.

$$\frac{ds^2}{dt} = 2s\,\dot{s} \tag{36}$$

According to (34), (36) is negative semidefinite form. Therefore, (35) is a Lyapunov function of system. Then, the system is stable when $s = 0$.

According to these analyses above, system performance can be improved by combining sliding mode control with feedback linear algorithm because of stable advantage of sliding mode control. To gain good tracking performance, the error between reference and output is defined as

$$e = y_{in} - y \tag{37}$$

where y_{in} is the ideal tracked object and y is the control output.

Then, sliding function can be obtained as follows.

$$s(x,t) = \mathbf{ce} \tag{38}$$

where

$$\mathbf{c} = [c \quad 1] \tag{39}$$

$$c > 0 \tag{40}$$

$$\mathbf{e} = [e \quad \dot{e}]^T \tag{41}$$

According to the discussed study for wind turbine in 3.3, the control rule can be designed as

$$u_2 = \frac{1}{(\partial f_1(x)/\partial x_2)(1/\tau)} \left(v - \left(\frac{\partial f_1(x)}{\partial x_1} f_1(x) + \frac{\partial f_1(x)}{\partial x_2} f_2(x) \right) + \eta\,\mathrm{sgn}(s) \right) \tag{42}$$

where v is the aided term, $\eta \ge 0$, and $\mathrm{sgn}(s)$ is the sign function, which is formulated by

$$\mathrm{sgn}(s) = \begin{cases} 1 & s > 0 \\ -1 & s < 0 \end{cases} \tag{43}$$

Simulation results show that there is large fluctuation in output power and rotor speed when using sign function. In order to reduce the fluctuation, saturation function is implemented to replace sign function. Saturation function is defined as follows. Results are shown in Figures 7(a)–7(d) and Figures 8(a)–8(d).

$$sat(s) = \begin{cases} 1 & s > \delta \\ \dfrac{s}{\delta} & |s| \le \delta \\ -1 & s < -\delta \end{cases} \tag{44}$$

Up to now, the final control law can be expressed based on (17) and (42) as follows.

$$u = u_1 + u_2 \tag{45}$$

4. Simulation Results and Analyses

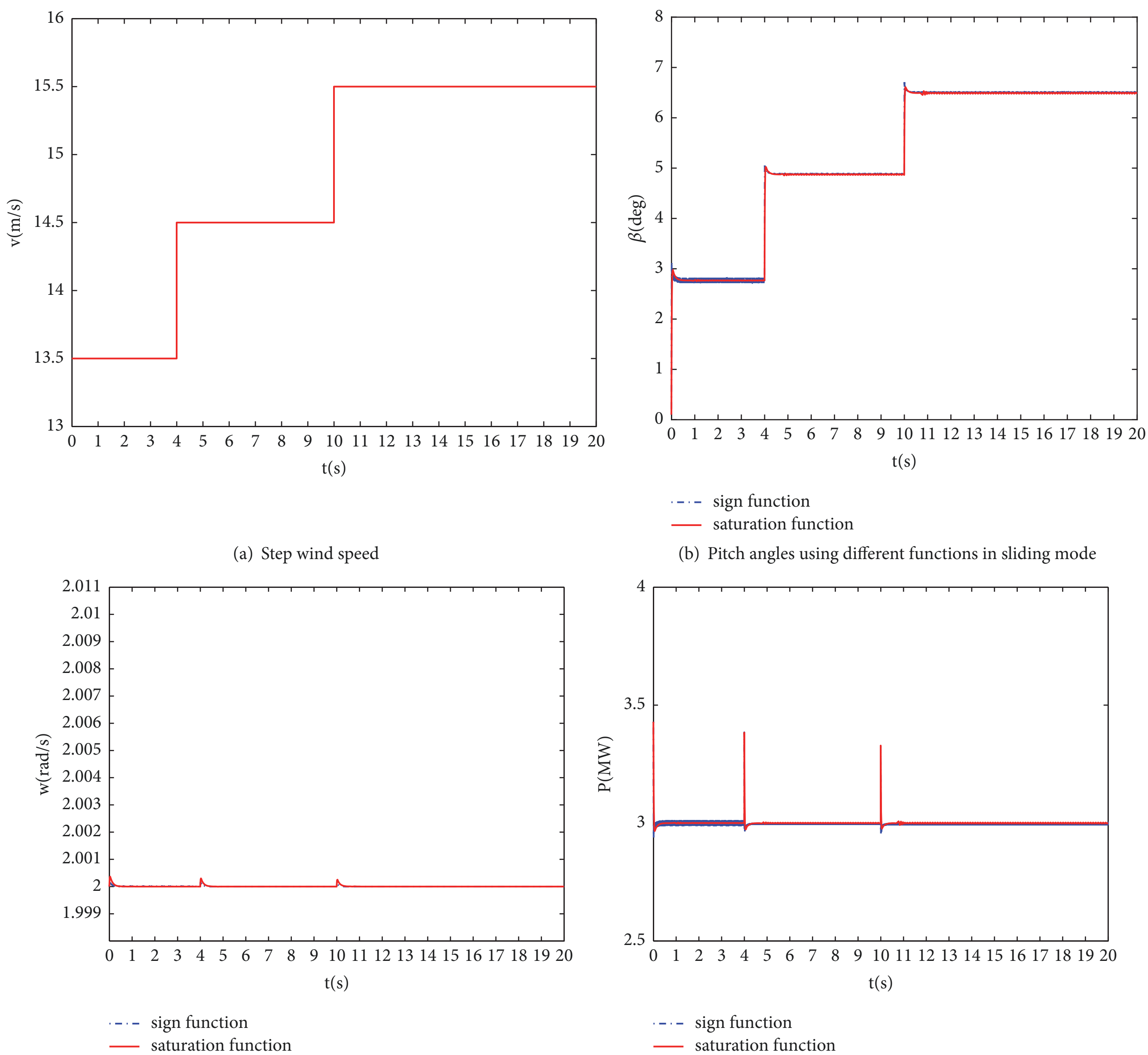
Simulation experiments based on a MW scale wind turbine are carried out to verify the effectiveness of the proposed algorithm, in which parameters are depicted in Table 4. The controller parameters are shown in Table 5.

The simulation experiments for wind turbine pitching control are implemented using step wind and random wind. Step speed is shown in Figure 7(a) and random wind is depicted in Figure 8(a).

Firstly, Figures 7(b)–7(d) and Figures 8(b)–8(d) depict the control results when using sign function and saturation function. The results show that there are little differences in

TABLE 4: The parameters of the wind turbine.

Symbols	Parameters	Values
P_{rated}	Rated output power	3000KW
V_{rated}	Rated wind speed	12m/s
R	The Radius of the turbine rotor	47.5m
J_r	The inertia moment of the turbine rotor	6250000kg·m^2
J_g	The inertia moment of the generator	15kg·m^2
k	Drive ratio	80
τ	Time constant	0.2
r_1	Stator winding resistance	0.0148Ω
r_2	Rotor winding resistance calculated to stator	0.0370Ω
$x_{1\sigma}$	Leakage reactance	0.0727Ω
$x_{2\sigma}$	Leakage calculated to stator side	0.0863Ω
x_m	Excitation reactance	2.0000Ω

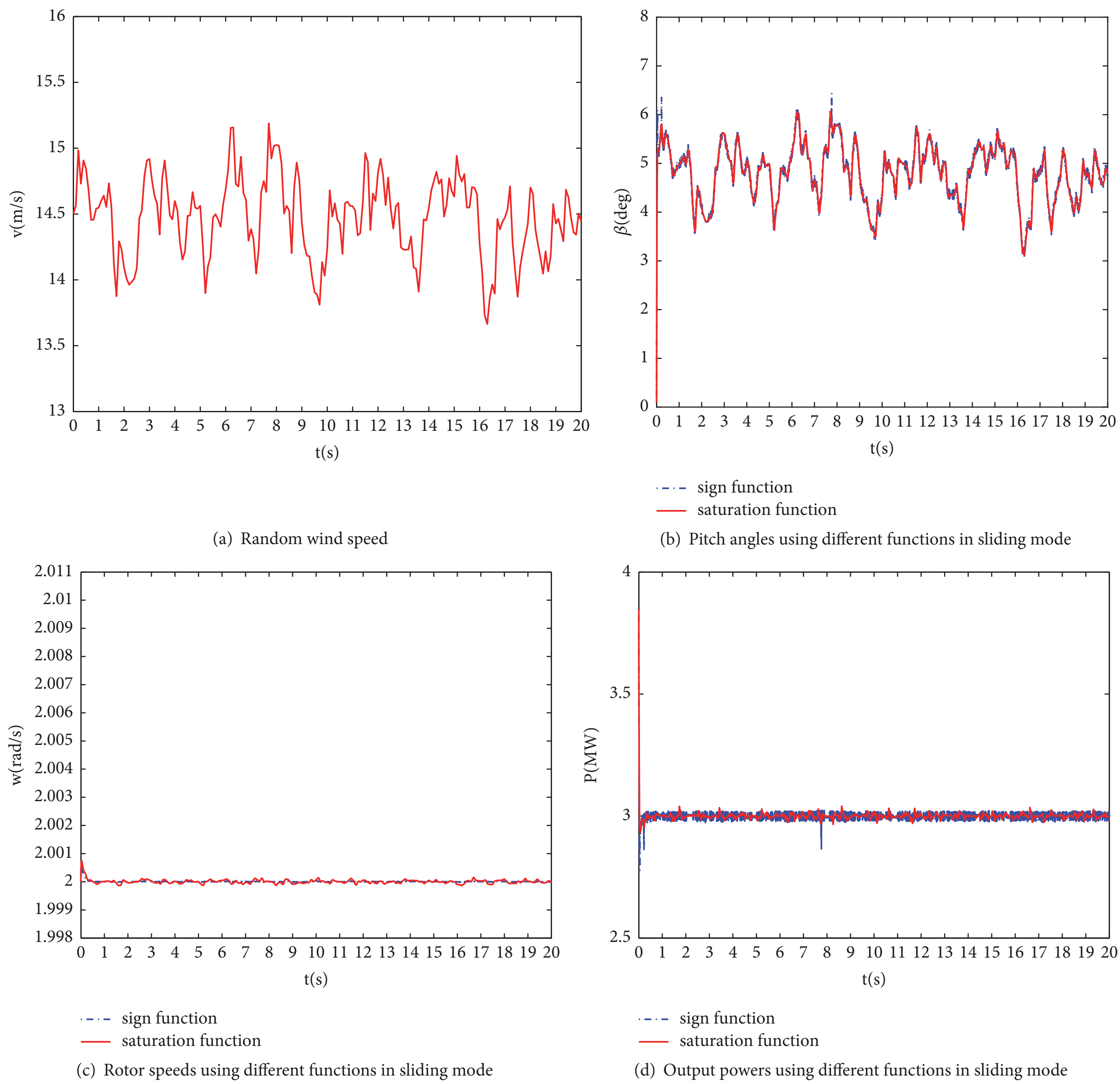


(a) Step wind speed
(b) Pitch angles using different functions in sliding mode
(c) Rotor speeds using different functions in sliding mode
(d) Output powers using different functions in sliding mode

FIGURE 7: (a) Step wind speed; (b) pitch angles using different functions in sliding mode; (c) rotor speeds using different functions in sliding mode; (d) output powers using different functions in sliding mode.

Table 5: The parameters of the proposed controller.

Symbols	Parameters	Values
c	Constant defined in sliding mode algorithm	10
e_range	The universe of rotor deviation	[-0.003 0.003]
ec_range	The universe of rotor deviation changing rate	[-0.008 0.008]
K_P_range	The universe of proportionality coefficent	[-0.3 0.3]
K_I_range	The universe of integral coefficient	[-0.06 0.06]
K_D_range	The universe of differential coefficient	[-3 3]
E	The value of the error universe	0.003
EC	The value of the error changing rate universe	0.008
μ	The coefficient of universe scaling factor	0.9
μ_1	The coefficient of universe scaling factor	0.9
μ_2	The coefficient of universe scaling factor	0.4
ε	A full small positive number	0.00001



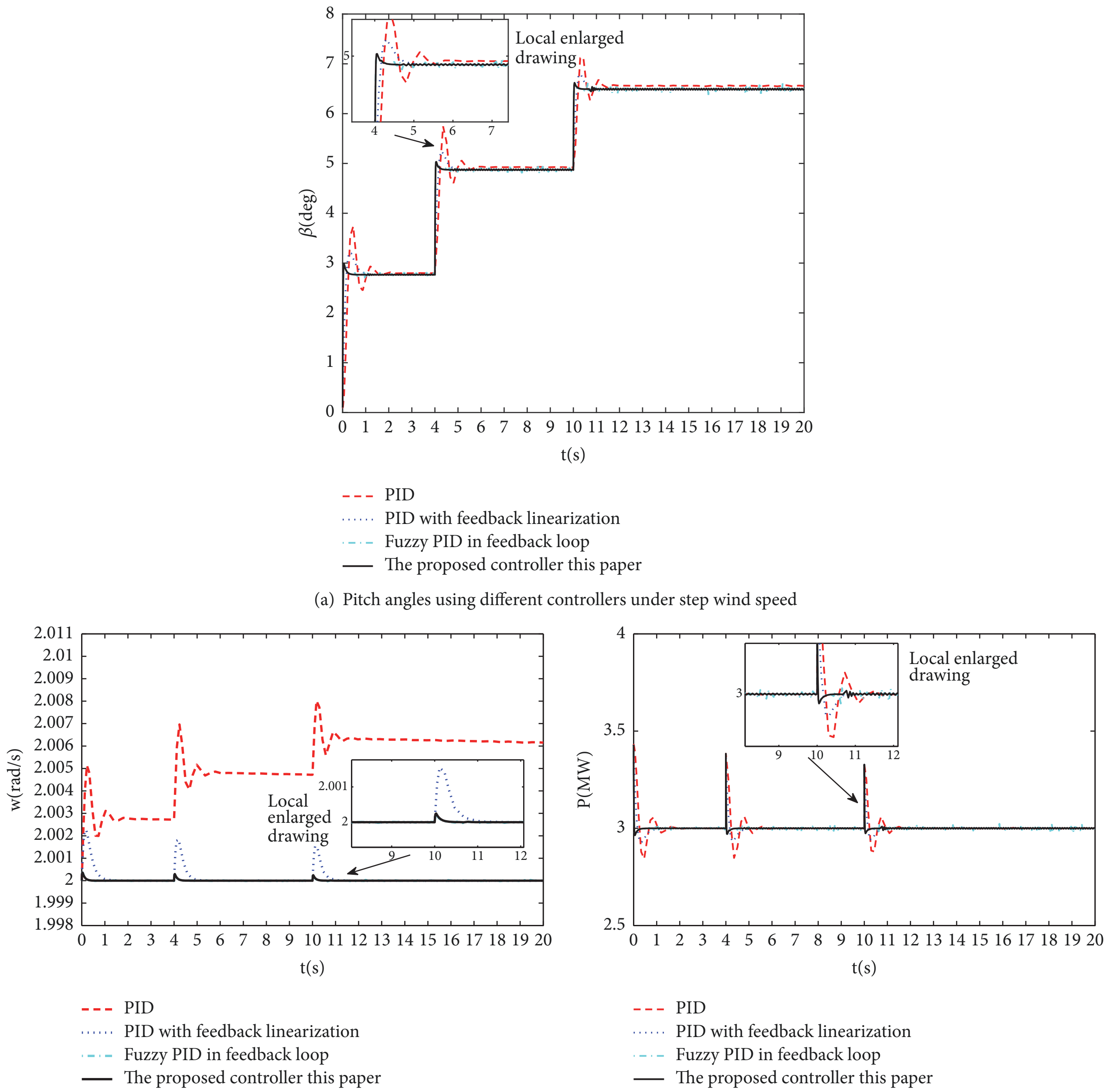
(a) Random wind speed

(b) Pitch angles using different functions in sliding mode

(c) Rotor speeds using different functions in sliding mode

(d) Output powers using different functions in sliding mode

Figure 8: (a) Random wind speed; (b) pitch angles using different functions in sliding mode; (c) rotor speeds using different functions in sliding mode; (d) output powers using different functions in sliding mode.



(a) Pitch angles using different controllers under step wind speed

(b) Rotor speed using different controllers under step wind speed

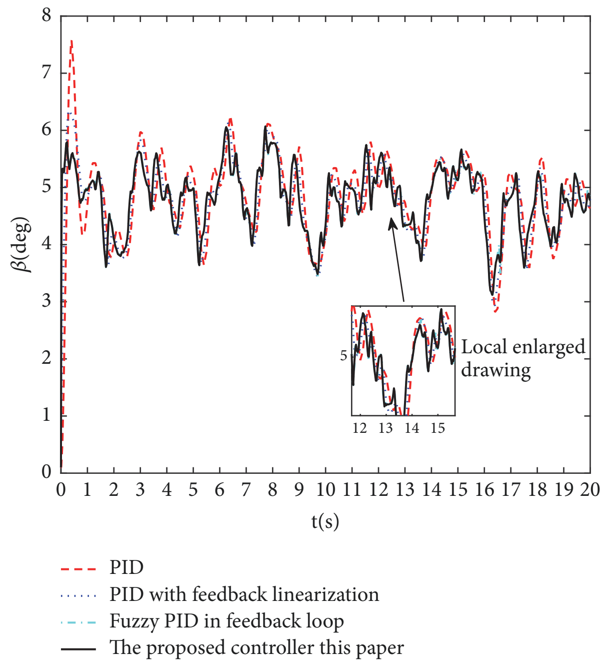
(c) output power using different controllers under step wind speed

Figure 9: (a) Pitch angles using different controllers under step wind speed; (b) rotor speed using different controllers under step wind speed; and (c) output power using different controllers under step wind speed.

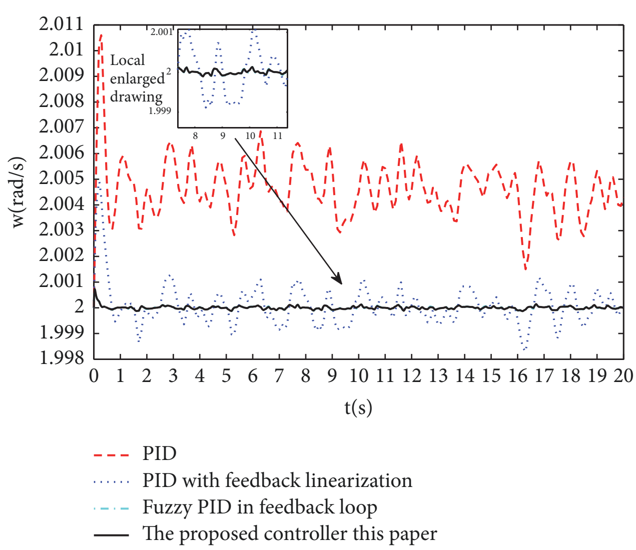
the control when implementing the two different functions under the step wind speed. However, under random wind speed, the control performance of the saturation function adjusting output power is significantly better than that of the sign function in Figure 8(d).

Comparisons are further studied among which there are conventional PID algorithm, feedforward feedback control combining PID with feedback linearization algorithm, feedforward feedback control based on fuzzy self-tuning PID with feedback linearization with sliding mode control (called fuzzy PID in feedback loop in Figures 9(a)–9(c) and Figures 10(a)–10(c)), and the proposed controller in this paper. Results are depicted in Figures 9(a)–9(c) and Figures 10(a)–10(c). The wind speed is changed continuously to further validate pitching control algorithms, which is depicted in Figure 8(a).

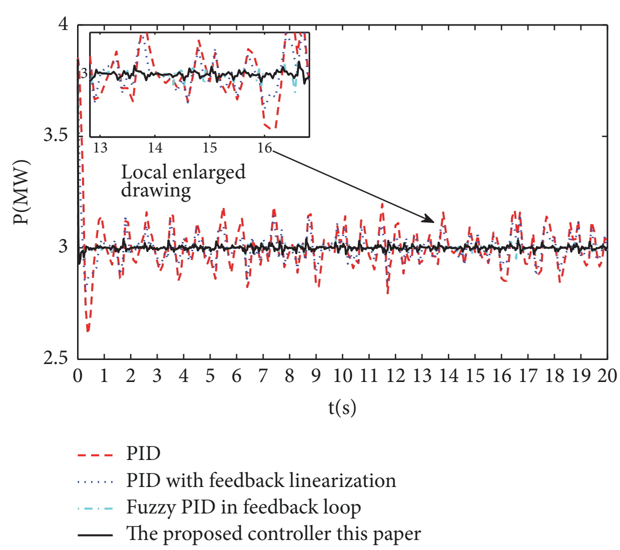
At the initial moment, control outputs fluctuate strongly, which are caused by initial values of states. However, if fluctuations are in acceptable ranges of the physical structure of the wind turbine, the initial responses will not affect the evaluation for the controller. In Figure 7(a), at $t = 4$ and $t = 10$, step wind speed occurs. As the wind speeds exceed the



(a) Pitch angles using different controllers under random wind speed



(b) Rotor speed using different controllers under random wind speed



(c) Output power using different controllers under random wind speed

Figure 10: (a) Pitch angles using different controllers under random wind speed; (b) rotor speed using different controllers under random wind speed; and (c) output power using different controllers under random wind speed.

rated value, pitch angles need to be adjusted to keep output power at constant.

In Figure 9(a), the overshoot of the pitch angle is greater, while oscillation time is longer when adopting the conventional PID controller. Although rotor speed also converges at the rated value, steady-state errors cannot be eliminated, which is approved in rotor speed chart depicted in Figure 9(b). The rotor speeds of wind turbine are maintained at constant when wind speed exceeds the rated value. Due to the steady-state errors of the pitch angle, rotor speeds have deviations. These results show that single linear PID controller cannot track target well for wind turbine exhibits strongly nonlinear features.

To address this problem, we design a PID controller combining with feedback linearization theory. The PID controller is feedback control, while feedback linearization is proposed as feedforward control. Feedback control can keep the system stable. However, the feedback control is hysteric. Only when the deviation occurs, the controller is implemented to eliminate it. Nevertheless, feedforward can produce a control variable in advance. Thus, the final outputs of the two controllers are proposed as the input of the wind turbine system so that tracking accuracy of controller can be enhanced.

Figures 9(a)–9(c) demonstrate that the control performance of feedforward feedback controller based on combining PID algorithm with feedback linearization algorithm is clearly superior to conventional PID controller, in which the overshoot of pitch angle is smaller and adjusting time of oscillating is shorter, and furthermore the steady-state deviation is eliminated, which is also shown both in the rotor speed diagram and in the output power diagram. To further improve control performance, sliding mode control is combined with feedback linear algorithm in feedforward loop, while the fuzzy self-tuning algorithm is used to adjust the parameters of the PID controller in feedback loop. Furthermore, in order to decrease the effect when input variable and output variable change a lot, variable universe approach is proposed to optimize fuzzy rules. Known from the results, the deficiencies of controller produced by system construct and parameters variation can be overcome. From Figures 9(a)–9(c), it is shown that the performance of the controller we propose in this paper is the best among the four controllers, whose overshoot is the least, while it rapidly converges to constant without steady-state errors. Although continuous step speed can evaluate controller performance, it still exhibits limitation.

In order to further verify the effectiveness and universality of the proposed controller in this paper, we further adopt random wind speed. Figure 8(a) depicts random wind speed. Figures 10(a)–10(c) show the control results of the pitch angle, rotor speed of turbine, and output power produced by four different control algorithms under random wind speed. The results are reasonable, which are the same as those produced by step wind speed. Therefore, the control algorithm we propose in this paper is the best among the described four algorithms and it can keep the output power at the rated value when wind speed exceeds the nominal velocity.

5. Conclusions

In this research a novel pitch control strategy for large variable speed variable pitch wind turbines is studied, aiming at maintaining the output power at constant so that the energy quality is improved. Known from the results, as the sliding mode theory is combined with feedback linearization algorithm in feedforward loop, the uncertainty of model and time-varying of system parameters are overcome. Furthermore, with setting a control variable in advance, the overshoot can be decreased when wind speed is varying. On the other hand, in feedback loop, as variable universe fuzzy algorithm is employed to optimize the parameters of the conventional PID controller, the tracking performance of the feedback controller is enhanced. Meanwhile, instead of sign function, saturation function is implemented to decrease oscillation of sliding mode algorithm and thus the fluctuations of output power and rotor speed of wind turbine are mitigated. Both control accuracy and robustness using the proposed algorithm are the best among four different controllers. Another, in future, we plan to supply fuzzy predictive adaptive algorithm in power control to further improve system performance.

Data Availability

The data used to support the findings of this study are currently under embargo, while the research findings are commercialized. Requests for data, 6 months after publication of this article, will be considered by the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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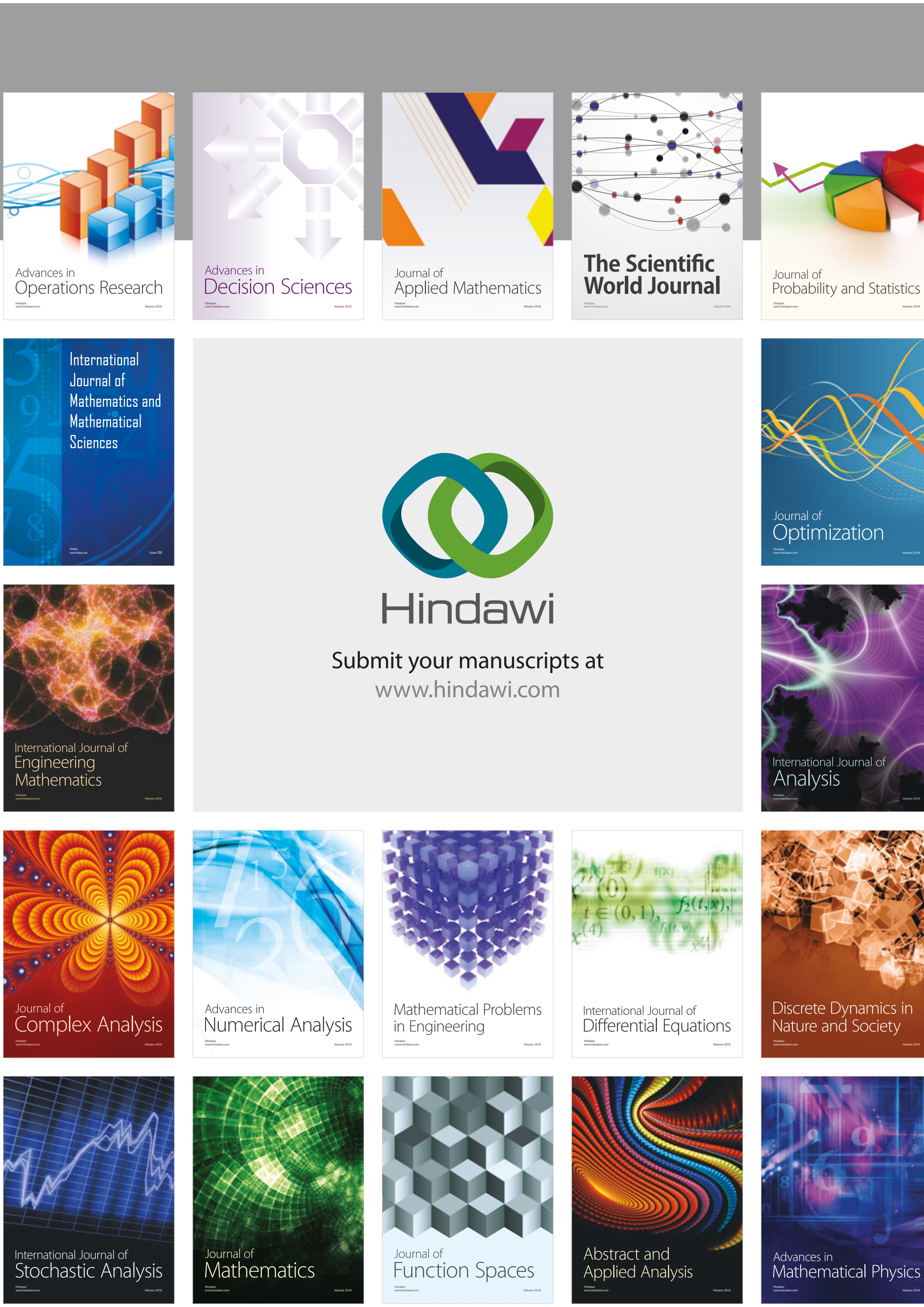

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