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Chattering Free Sliding Mode Pitch Control of PMSG Wind Turbine

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Abstract: Due to the stochastic nature of wind speed, nonlinearity and time-variable parameters of the system, the power generated by wind turbines appears to be unsteady at high speed region. To improve the dynamic performance in the operation region of constant power output, a Chattering Free sliding-mode variable structure pitch controller for wind turbine is proposed based on the analyses of system dynamic models, and a new support vector machine (SVM)-based reaching law for reducing the chattering caused by the sign function is presented. A pitch control system mode for the wind turbine system with permanent magnet synchronous generator (PMSG) is built and simulations are performed. The simulation results show that the proposed strategy has many advantages, such as strong ability for eliminating chattering, robust to the parameters variation and fast response.

1. INTRODUCTION

No gear box, high power density and high reliability are the main advantages for direct-drive PMSG wind turbines, which have become one of mainstream type (Semken, R. S. et al., 2012) for large grid-connected wind turbines. Pitch system, as a key part of variable-speed constant-frequency wind turbine system, its main control purpose is to keep power generated by wind turbines constant above rated wind speed, reduce fatigue load and prolong the service life of wind turbines. Also, the reliability, stability and efficient operation are the key considering factors for pitch control due to the big torque and low speed characteristics of direct-drive PMSG wind turbines, time-delay of pitch actuator and speed limit of pitch angle. For pitch control of wind turbine systems with PMSG, the PI control scheme is widely used (Yin, M. et al., 2007), but it shows a limited performance, especially against uncertainties.

The sliding mode variable structure control (SMC) has advantages of strong robustness, rapid response, simple design, and is easy to be realized, which has drawn much attention and has been widely used in many application (Zhang, C. F. et al,2012). In recent years, a sliding mode pitch control scheme has been presented (Wang, B., & Qin, S., 2010). The main problem of this method is that high frequency chattering is produced while the state trajectory reaches to the sliding mode surface, and even leads to system instability. To overcome this problem, some improvement work has been made, e.g, a high order sliding mode controller was introduced to reduce the chattering (Beltran, B. et al. 2009). With the development of intelligent control methods, fuzzy logic(Ha, Q. P. et al, 2001), neural network (Huang, S. J. et al, 2003) and least squares support vector machine(Li, J. N. et al., 2013) were also introduced to the sliding mode variable structure control systems. A sliding mode variable structure pitch controller using RBF neural network was proposed (Qin, B. et al., 2013), and the results show that the controller has strong adaptability, good robustness and dynamic performance. However, the fuzzy rules of fuzzy controllers are depended on the designers' experience. Meanwhile, the neural network's structure and its parameters are difficult to be determined and sometimes overfitting problems may occur.

Support Vector Machine is a new learning machine which is based on statistical learning theory and structural risk minimization principle (Vapnik, V. N.1999). Compared with neural networks, it has no local minimum problem, no curse of dimensionality and has strong generalization ability. Moreover, its model complexity can be designed automatically (Smola, A., & Schölkopf, B.2004).

In this work, a chattering free sliding mode variable structure pitch control of PMSG wind turbines based on SVM was proposed. To reduce system chattering, a new reaching law is introduced, which makes the sliding errors converge to zero quickly and keep the system state movement on the sliding surface. The simulation results from a wind turbine system are provided to demonstrate the effectiveness of the proposed methods.

The remaining parts of this paper are organized as follows. In Section 2 the wind turbine model is built. In section 3 the proposed pitch controller is discussed. Simulation results of a 2M wind turbine is given to verify the controller performance in section 4. Finally, conclusion is given in Section 5.

2. WIND TURBINE SYSTEM MODEL

The structure of direct-drive PMSG wind turbines system is shown in Figure 1. The generator speed is controlled by the electromagnetic torque of the machine control unit, and maximum wind power tracking is carried out under the rated wind speed. The objective of pitch control above rated wind speed is to control pitch and regulate rotor speed to the rated speed set point. To account for variations in wind speed, the pitch control response must be fast.

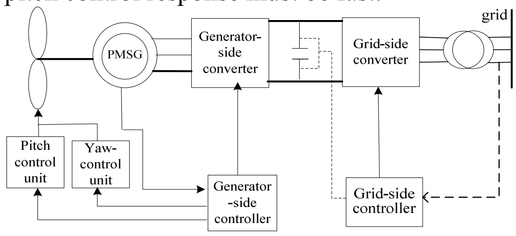

Fig.1. Structure of direct-drive PMSG wind turbines

2.1 Aerodynamic characteristics

According to Batz's law, all power can't be absorbed by wind turbines while converting wind energy into mechanical energy. Power available in wind is given by,

$$p_w = \frac{1}{2}\rho s_w v^3 \tag{1}$$

Where ρ —air density

s_w —swept area

v —wind speed

Power produced by wind turbine rotor is given by,

$$p_o = p_w C_p(\lambda,\beta) = \frac{1}{2}\rho s_w v^3 C_p(\lambda,\beta) \tag{2}$$

Where $C_p(\lambda,\beta)$ is power coefficient, β is blade pitch angle.

According to literature (Abdin, E. S., & Xu, W., 2000) and the type of wind turbine, C_p is given by

$$C_p = (0.44-0.0167\beta)\sin[\frac{\pi(\lambda-3)}{15-0.3\beta}] - 0.00184(\lambda-3)\beta \tag{3}$$

$C_p(\lambda,\beta)$ is a function of the tip-speed ratio λ, as well as the blade pitch angle β. The nonlinear relationship between C_p and β 、 λ is shown in Figure 2.

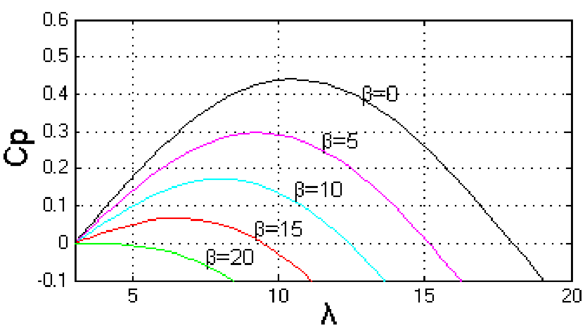

Fig. 2. Wind turbine power coefficient

According to formula (3) and Fig. 2:

1) C_p is maximized for a tip-speed ratio value λ_{opt} when $\beta = 0$, and C_p decreases significantly with the increase of β .

2) For constant pitch angle, $C_{p\max}$ is unique.

The above two points provide a theoretical basis for pitch angle control. With the change in wind speed, the power coefficient values can be adjusted by pitch angle, and the output power can be kept steady near the power rating.

2.2 PMSG mathematical model

According to axes transformation, the mathematical model of PMSG based on rotor flux in the rotor reference frame can be written as (*dq* axes):

$$\begin{cases} \dfrac{di_d}{dt} = -\dfrac{R_a}{L} i_d + \omega_e i_q + \dfrac{1}{L_d} u_d \\ \dfrac{di_q}{dt} = -\dfrac{R_a}{L} i_q - \omega_e (i_d + \dfrac{1}{L}\lambda_0) + \dfrac{1}{L} u_q \end{cases} \tag{4}$$

Where i_d and i_q are the d-axis and q-axis currents respectively; L_d and L_q are the d-axis and q-axis inductances of PMSG respectively; R_a is the stator resistance; ω_e is the rotor electrical angular speed, $\omega_e = N_p \omega_g$; N_p is the number of pole pairs; λ_0 is the permanent magnetic flux; u_d and u_q are components of *dq* axes of u_g .

Assuming the stator inductance of d-axis is equal to q-axis, so the electromagnetic torque can be obtained from the following formula:

$$T_e = 1.5 N_p i_q \lambda_0 \tag{5}$$

Assuming that the mechanical transmission efficiency is constant throughout the speed range, and some assumptions are simplified for the structural characteristics. Then, the dynamic model of transmission system can be expressed by a first-order formula:

$$J\dot{\omega}_g = T_\omega - T_e - B\omega_g \tag{6}$$

Where T_ω is pneumatic torque; T_e is electromagnetic torque; B is friction coefficient; ω is wind rotor speed; J is rotor movement of inertia.

2.3 Variable pitch actuator model

The hydraulic device and the motor drive system are two types of actuators which are often used by variable pitch system. As well, the blades of MW wind turbine generally weigh several tons and their moment of inertia is very large, therefore, the variable pitch actuator model can be simplified by one order inertial link. Its structure is shown in Fig. 3:

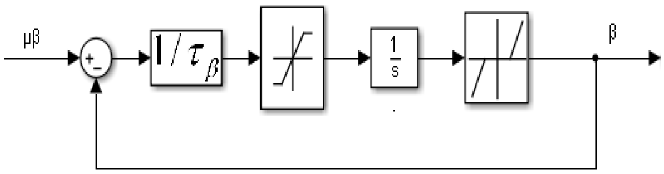

Fig.3. Structure of variable pitch actuator

The dynamic model of variable pitch actuator can be described as:

$$\tau_\beta \dot{\beta} = \mu_\beta - \beta \tag{7}$$

Where τ_β is the response time constant of pitch angle; β is the actual pitch angle; u_β is a given pitch angle.

3. CHATTERING FREE SMC PITCH CONTROL DESIGN

According to the mathematical model of the variable pitch system mentioned before, and combined with SVM, a chattering free SMC pitch control system of PMSG wind turbine is proposed, which is shown in Fig. 4.

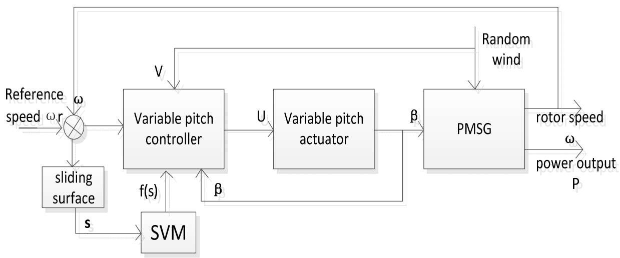

Fig.4. SMC pitch control system of PMSG wind turbine

3.1 Variable structure pitch control

The variable structure control system can be divided into two parts (Gao, W.B., 1990):

(1) Determine the switching function, so-called switching surface, which can make the sliding mode system have asymptotical stability with good quality, and represents the ideal dynamic characteristics of the system.

(2) Design the sliding mode control law to satisfy Lyapunov stability requirements, which makes the approach movement (non-sliding mode) reach the switch surface in a limited time, and form the sliding mode band on the switching surface.

The torque of wind turbines is given by:

$$T_w = \frac{P_\omega}{\omega_\omega} = \frac{1}{2\omega_\omega}\rho s_\omega v^3 C_p(\lambda, \beta) \tag{8}$$

When tip-speed ratio is optimal, and power coefficient is maximum, then

$$\begin{aligned} p_{\omega,opt} &= \frac{1}{2}\rho s_\omega c_{p\max}\left(\frac{R}{\lambda_{opt}}\right)\omega_\omega^3 \\ &= \frac{1}{2}\rho s_\omega c_{p\max}\left(\frac{R}{\lambda_{opt}}\right)^3\left(\frac{\omega_e}{N_p}\right)^3 = K\omega_e^3 \end{aligned} \tag{9}$$

$$T_{e,opt} = \frac{N_p P_{e,opt}}{\omega_e} = N_p K \omega_e^2 \tag{10}$$

$$K = \frac{1}{2N_p^2}\rho s_\omega c_{p\max}\left(\frac{R}{\lambda_{opt}}\right)^3$$

Here ω_e is rotor speed, N_p is pole-pairs.

Assuming that the torque controller works well, namely the electromagnetic torque can be obtained by (10). Then the transmission system dynamic model (6) can be rewritten as:

$$\begin{aligned} \dot{\omega}_e &= \frac{N_p}{J}\left(\frac{P_\omega}{\omega_\omega} + T_e - B\frac{\omega_e}{N_p}\right) \\ &= \frac{N_p}{J}\left(\frac{1}{2}\cdot\frac{\rho s_\omega V^3 C_p(\beta,\lambda) N_p}{\omega_e} - N_p K \omega_e^2 - B\frac{\omega_e}{N_p}\right) \end{aligned} \tag{11}$$

This is a nonlinear function related to three variables V, β, ω_e. Let Approximations ignoring the high error values of a Taylor series for equation (11) at the working point $(V_{opt}, \beta_{opt}, u_{opt})$ of constant power operation be made and α', ϕ', γ' are given by

$$\alpha' = \frac{\partial f}{\partial \omega}\Big|_{opt}, \varphi' = \frac{\partial f}{\partial V}\Big|_{opt}, \gamma' = \frac{\partial f}{\partial \beta}\Big|_{opt}$$

Meanwhile, (7) is substituted into (11), and then formula (12) can be obtained

$$\begin{aligned} \ddot{\omega}_e &= \alpha'\cdot\dot{\omega}_e + \phi'\cdot\dot{V} + \gamma'\cdot\dot{\beta} \\ &= \alpha'\cdot\dot{\omega}_g + \phi'\cdot\dot{V} + \gamma'\cdot\frac{u_\beta - \beta}{\tau_\beta} \\ &= \alpha\cdot\dot{\omega}_g + \phi\cdot\dot{V} + \gamma\cdot(u_\beta - \beta) \end{aligned} \tag{12}$$

Here suppose that $x_1 = \omega_e - \omega_{er}, x_2 = \dot{x}_1 = \dot{\omega}_e$, ω_{er} is the optimal rated speed of the rotors, so formula (13) can be obtained

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \alpha x_2 + \phi\dot{v} + \gamma(u_\beta - \beta) \end{aligned} \tag{13}$$

Where u_β is the input of pitch angle control, the rotor electromagnetic speed ω_e is output of the linear equation of the drive system.

A sliding mode surface equation is given by：

$$s = c_1 x_1 + x_2 \tag{14}$$

The stability of generator power output is achieved by sliding mode control, which can make the rotor electromagnetic speed steadily transfer to optimal rating. According to (13), the sliding mode controller (SMC) is designed as:

$$\mu_\beta = \beta - \frac{1}{\gamma}[c_1 x_2 + \alpha x_2 + \phi \dot{v} - k_\beta \operatorname{sgn}(s)] \tag{15}$$

Where the stability condition satisfies such requirement: $s(x)\dot{s}(x) < 0$

Considering the digital controller is used in pitch control, formula (15) can be discretized with zero-order holder and be rewritten as

$$\begin{aligned} \mu_\beta(k) = \beta(k) - \frac{1}{\gamma}[\bar{c}_1 x_2(k) + \bar{\alpha} x_2(k) \\ + \bar{\phi}(v(k+1) - v(k)) - k_\beta \operatorname{sgn}(s(k))] \end{aligned} \tag{16}$$

Where $\bar{c}_1$, $\bar{\alpha}$, $\bar{\varphi}$ are the coefficient functions after discretization.

3.2 Support Vector Machine Regression

Consider a given training set $\{(x_k, y_k)\}_{k=1}^N$, where $x_k \in R^n$ and $y_k \in R$. The SVM model is given by:

$$f(x) = w^T \phi(x) + b \tag{17}$$

Where $\phi(x)$ denotes the higher dimensional feature maps. *w* is weight vector, and *b* means bias.

The SVM regression is formulated as minimization of the structural and empirical risks:

$$R_{SVMs} = \frac{1}{2}\|w\|^2 + C\frac{1}{n}\sum_{i=1}^{n} L_\varepsilon(y_i - f(x_i)) \tag{18}$$

$$L_\varepsilon(x, y, f) = |y - f(x)|_\varepsilon = \max(0, |y - f(x)| - \varepsilon) \tag{19}$$

Where *C* is regularization constant determining the trade-off between the empirical risk and the regularized term. $L_\varepsilon(x, y, f)$ is ε-insensitive loss function. By introduction of the positive slack variables and after kernel substitution the dual objective function can be solved using sequential minimal optimization. Then, the SVM regression is obtained:

$$f(x) = \sum_{i=1}^{N} (\alpha_i - \alpha_i^*) K(x_i, x) + b \tag{20}$$

Where $K(x_i, x_j)$ represents kernel function and *K* satisfies Mercer's condition: $K(x_i, x_j) = \varphi(x_i)^T \varphi(x_j)$. Here the radial basis function is used:

$$K(x, x_i) = \exp(-|x - x_i|^2 / \sigma^2) \tag{21}$$

Given a new input point *x*, the estimated function $f(x)$ can be predicted by (20).

3.3 Chattering free sliding mode pitch control based on SVM

A series of serious chattering problems are caused by the sign function in formula (16), which leads to big load to the wind turbine and fluctuation of output power. So a chattering free sliding mode pitch control method for PMSG wind turbine based on support vector machine (SVM-SMC) is proposed in this section.

In Conventional sliding mode pitch control (15), the general reaching law is shown as:

$$\dot{s} = -\varepsilon \operatorname{sgn}(s) - as, \quad \varepsilon > 0, a > 0 \tag{22}$$

And from formula (22), formula (23) can be obtained

$$\begin{aligned} \frac{s(k+1) - s(k)}{T} &= -\varepsilon \operatorname{sgn}(s(k)) - as(k) \\ s(k+1) &= (1 - aT)s(k) - \varepsilon T \operatorname{sgn}(s) \end{aligned} \tag{23}$$

The ideal sliding mode control requires $s(k+1) \to 0$, hence, formula (24) is derived (Li, J. N. et al., 2013)

$$\begin{aligned} (1 - aT)s(k) - \varepsilon T \operatorname{sgn}(s(k)) \to 0 \\ \operatorname{sgn}(s(k)) \to (1 - aT)s(k)/(\varepsilon T) \end{aligned} \tag{24}$$

Also, a new reaching law and conditions based on support vector machine are derived:

Here assume that enough training samples are got $\{(s_m, f(s_m))\}_{m=1}^N$. For simplicity, *f(g)* is used to denote the output of SVM $f(s_m) = (1 - aT)s_m/(\varepsilon T)$ .N represents the number of samples. Hence, the estimated function based on training samples can be described as follows:

$$f(s_k) = \sum_{m=1}^{N} (\alpha_m - \alpha_m^*) K(s_m, s_k) + b \tag{25}$$

$$f(s_k) = \frac{(1 - aT)}{\varepsilon T}\tilde{s}_k \to \frac{(1 - aT)}{\varepsilon T} s_k \tag{26}$$

Where *s(k)* is a new point, $\tilde{s}_k$ is estimated value of input of s_k , denoting estimated error $|s_k - \tilde{s}_k| \le \Delta$.

Based on the aforementioned model (24) and (26), the reaching law based on SVM is rewritten as:

$$s(k+1) = (1 - aT)s(k) - \varepsilon T f(s(k)) \tag{27}$$

If the reaching conditions ($|s(k+1)| < |s(k)|$) are satisfied, the system states can converge to the sliding surface and the following inequality is obtained

$$\begin{aligned}|s(k+1)| &= |(1-aT)s(k)-\varepsilon Tf(s(k))| \\ &= |(1-aT)(s(k)-\tilde{s}(k))| \le (1-aT)\Delta \\ &\le |s(k)|\end{aligned} \tag{28}$$

According to the inequality (28), if the estimated error satisfies the inequality (29), the reaching condition can be obtained directly.

$$\Delta < \frac{|s(k)|}{1-aT} \tag{29}$$

So the inequality can be satisfied if an appropriate parameter a is chosen, and then the output of SVM can be used to replace the sign function in the sliding mode controller.
From the above, the control law can be rewritten as:

$$\begin{aligned}\mu_\beta(k) = \beta(k) - \frac{1}{\gamma}[\bar{c}_1 x_2(k) + \bar{\alpha} x_2(k) \\ + \bar{\phi}(v(k+1) - v(k)) - k_\beta f(s(k))]\end{aligned} \tag{30}$$

4. SIMULATION RESULTS

Simulink/SimPowerSystems model about a pitch control system of 2MW direct drive PMSG wind turbine is built and simulations are performed to verify the control methods proposed in this paper. The main parameters of wind turbine are shown in Table1.

Table 1. Wind Turbine Generation Unit Parameters List

Turbine radius	35m	number of pole pairs	30
Number of blades	3	rated torque	940kN•m
wind rotor moment of inertia	411185 kg•m^2	Wind rotor rated speed	9~22.5r/m
motor moment of inertia	18905.7 kg•m^2	generator maximum speed	29r/m
rated power	2000kw	rated wind speed	13m/s
stator resistance	R_a=6.7e$^{-3}\Omega$	cut in /cut out wind speed	3m/s25 m/s
d, q-axis inductance	L_d=2.7 mH L_q=2.7 mH	air density	1.25kg/m^3

The random wind speed model established by Risø National Laboratory (Denmark based KAMA (Kaimal) spectrum) is used in this paper, which is shown in Figure. 5. The basic speed is 15m / s and the turbulence intensity is 12%. Simulation results are shown in figure 6-9.

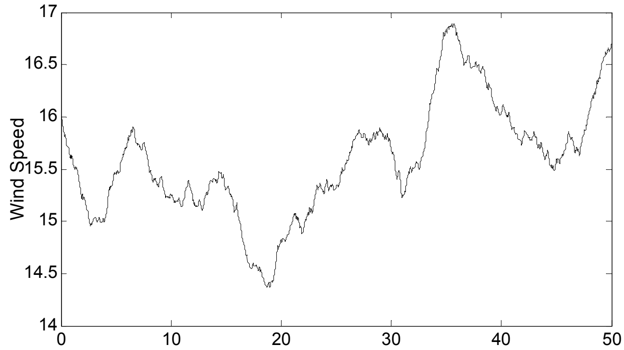

Fig.5. Radom wind curve (15 m/s)

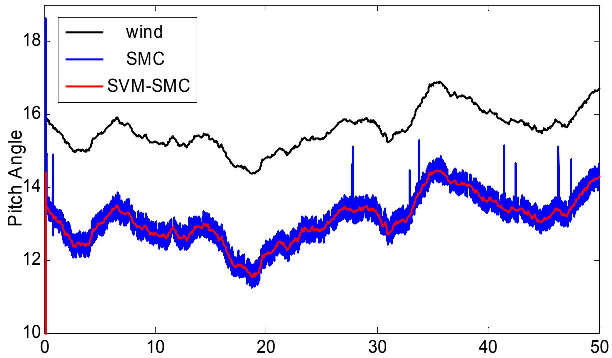

Fig.6. Curve of pitch angle

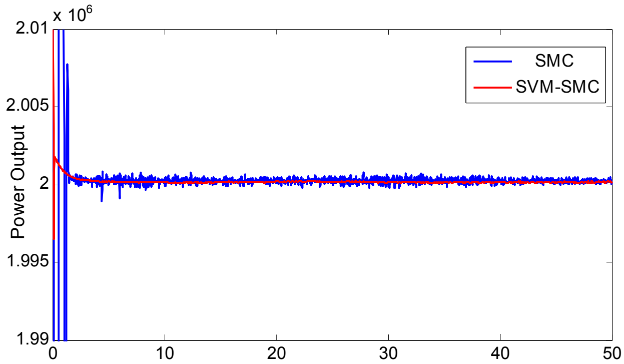

Fig.7. Curve of output power of the generator

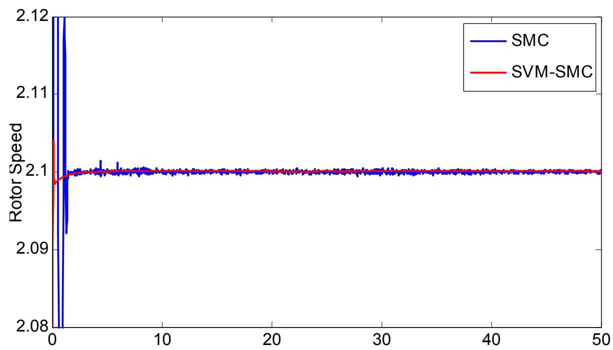

Fig.8. Curve of wind turbine speed

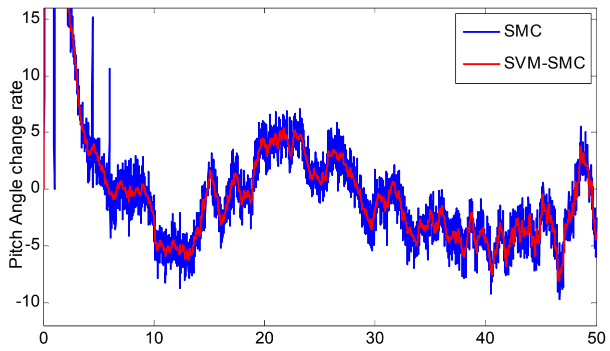

Fig.9. Curve of pitch angle velocity change

We can see from Figure. 6-8 that the SMC method introduced in this paper can keep the power output steady near the rated power when the wind speed changes. However, the chattering occurs due to the rapid switching control in pitch angle. As well, there exits 1~2 seconds shocks and pitch angle peaks. Compared with the SMC, the SVM-SMC method can reduce chattering obviously. It also has higher accuracy, and almost no shocks under variable wind speed.

We can also see from Figure. 9 that the pitch angle change rate under SVM-SMC is relatively smooth, and the movement of actuators of pitch angle is accurate and smooth. Therefore, steady power output can be achieved with this control method and the pitch angle change rate is smaller than that of the SMC. Moreover, the pitch actuator fatigue is effectively reduced and the life of wind turbine is extended.

5. CONCLUSION

In this paper, in order to reduce fatigue load and get good response, a chattering free sliding mode pitch control strategy for PMSG wind turbine based on SVM is proposed, in which a new reaching law is introduced. So the sliding errors converge to zero quickly and the chattering is weakened. The simulation results show that the proposed strategy has rapid response and strong robustness performance under the stochastic wind speed. It combines with the advantages of sliding mode control and support vector machine regression. Also, it effectively reduces chattering, adjusts the pitch angle smoothly without frequent action, prolongs the life of wind turbines, and satisfies the pitch control requirements.

ACKNOWLEDGEMENTS

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