ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
https://doi.org/10.17559/TV-20210318071726
Preliminary communication

Adaptive Sliding Mode Control of Permanent Magnet Direct-Drive Wind Turbine

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Abstract: The damping coefficient of permanent magnet direct-drive (PMDD) wind turbine is unmeasurable. To solve the problem, this paper attempts to design a sliding mode control (SMC) strategy that adapts to the speed of PMDD wind turbine. Firstly, the authors analyzed the features of wind turbines, and the nonlinear dynamic structural features of permanent magnet synchronous machine (PMSM). Next, the parameter adaptive law was designed based on Lyapunov stability theory, and backstepping control was combined with SMC into a comprehensive control strategy that regulates the speed of wind turbines. Simulation results show that the proposed strategy can compensate for the disturbance of uncertain parameters, and ensure the frequency stability of the wind turbine.

Keywords: backstepping; large-scale direct-drive wind power system; parameter uncertainty; Sliding Mode Control (SMC)

1 INTRODUCTION

The permanent magnet direct-drive (PMDD) wind turbine has a simple mechanical transmission structure, for the rotor adopts the permanent magnet structure, the generator is directly connected to the wind turbine, and the step-up gearbox is eliminated. The simple structure improves the utilization rate of wind energy, and reduces the cost of operation and maintenance. As a result, the PMDD wind turbine has become a favorite among designers of large-scale variable speed constant frequency wind turbines [1-4].

The permanent magnet synchronous wind turbine is a PMDD generator set composed of a permanent magnet synchronous machine (PMSM) driven by a wind turbine. This nonlinear, complex object has multiple variables, a strong coupling effect, and variable parameters. Due to the large inertia of large-scale wind turbines, the increasing grid-connection of wind power makes it more and more difficult to realize fast and stable control of the power system.

The traditional variable speed constant frequency controller only considers the change of wind speed. When the load and wind speed change simultaneously, the variable speed constant frequency controller cannot easily track the variation of generator parameters, external disturbances, and other uncertainties [5]. To address the nonlinearity and uncertain parameters, many nonlinear control methods have been applied to regulate the speed of wind turbines [6, 7].

The existing nonlinear models and control strategies for PMDD wind turbines fail to consider the sudden increase in large inertia load or the uncertainty of generator parameters. These uncertain factors will affect the effect of the designed controllers. To ensure the safety of PMDD synchronous generator and the effectiveness of its controller, it is urgently needed to fully consider the uncertainty of generator structure and parameters in controller design.

The adaptive sliding mode backstepping control combines backstepping control, adaptive control, and sliding mode control (SMD), and relies on the SMC with a norm-type switching function to compensate for the influence of uncertainties on the system. This SMC greatly reduces the numerous derivatives in the traditional adaptive backstepping control, and thus simplifies the entire controller [8, 9].

In this paper, the operating model of the PMDD synchronous wind turbine is thoroughly analyzed. Considering unmeasured factors like wind speed, load, and damping coefficient, an affine nonlinear model was established for the PMDD wind power system, and the nonlinear speed control was realized for large-scale PMDD wind power system based on adaptive SMC. The proposed control strategy can solve the uncertainty in parameters and structure of permanent magnet synchronous wind turbine, suppress load disturbance, and improve the dynamic accuracy of the wind turbine speed control system, thereby enhancing the frequency stability of the wind power generation system [10].

2 MATHEMATICAL MODEL OF PMDD WIND POWER SYSTEM

2.1 Wind Turbine Features and its Mathematical Model

Fig. 1 shows the grid-connected structure of a wind turbine. The converter is composed of an inverter and a rectifier. The generator-side includes the speed control of the PMSM, and the generator-side voltage control. This article only aims to design the speed controller.

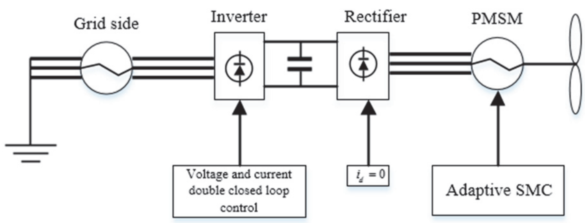


Figure 1 The grid-connected structure of a wind turbine

The wind turbine, as the core of the entire wind power system, has three important parameters: tip speed ratio, blade pitch angle, and power coefficient. Under a constant wind speed v, the wind energy utilization coefficient determines the amount of wind energy converted by the wind turbine:

$$C_p\left(\lambda, \beta\right) = 0.5176\left(\frac{116}{\delta} - 0.4\beta - 5\right)e^{\frac{-21}{\delta}} + 0.0068\lambda \quad (1)$$

where, $\lambda = \frac{\omega r}{v}$, $\frac{1}{\delta} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$.

where, $C_p(\lambda, \beta)$ is the function of the blade tip speed ratio λ and the pitch angle β; ω is the blade angular velocity; r is the radius of the wind wheel of the wind turbine, δ is related to λ and β.

When the aerodynamic features are normal, the aerodynamic performance of the wind turbine depends on the tip speed ratio and the blade pitch angle. The starting torque T of the wind turbine can be expressed as:

$$T = \frac{P}{\omega} = \frac{\rho \pi R^2 v^3 C_p\left(\lambda, \beta\right)}{2\omega} \quad (2)$$

where, P is the mechanical output power of the wind turbine; ρ is the air density.

2.2 Mathematical Model of PMSM

It is assumed that the air gap magnetic field of the motor is sinusoidally distributed, the magnetic circuit is not saturated, and the core eddy current and hysteresis loss are so small as to be negligible. Under the d-q axis coordinate system, the state space of the PMSM can be expressed as [11]:

$$\begin{bmatrix} i_d \\ i_q \\ \omega_m \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L} & P\omega_m & 0 \\ -P\omega_m & -\frac{R_s}{L} & \frac{2P\psi_f}{L} \\ 0 & -\frac{3P\psi_f}{2J} & -\frac{B}{J} \end{bmatrix} = \begin{bmatrix} i_d \\ i_q \\ \omega_m \end{bmatrix} + \begin{bmatrix} -\frac{u_d}{L} \\ -\frac{u_q}{L} \\ \frac{T}{J} \end{bmatrix} \quad (3)$$

where, u_d, u_q, i_d, i_q, L_d and L_q are the d-axis component and q-axis component of stator voltage, stator current, and stator inductance, respectively ($L_d = L_q = L$); R_s is the stator armature resistance; ω_r is the rotor angular velocity; ψ_f is the flux linkage of the permanent magnet rotor; J is the moment of inertia of the electronic rotor; B is the friction damping coefficient of the system; ω_m is the rotor angular velocity; P is the number of pole pairs ($\omega_r = P\omega_m$).

Adopting the vector control strategy, i.e., $i_d = 0$, Eq. (3) can be transformed into:

$$\begin{cases} \dot{i}_d = \frac{1}{L}\left[P\psi_f \omega_m - R_s i_q - u_q\right] \\ \dot{\omega}_m = \frac{1}{J}\left[-\frac{3P\psi_f i_q}{2} + T - B\omega_m\right] \end{cases} \quad (4)$$

In order to transform the Eq. (4) into an affine nonlinear mathematical model, let $x_1 = \omega_m - \omega_{ref}$ and $x_2 = \dot{x}_1 = \dot{\omega}_m$ be the state variables, and $u = u_q$ be the controlled quantity of the system. The control objective is to design the controller u to make the speed track the expected speed.

Then, we have:

$$\dot{x}_1 = x_2;$$
$$\dot{x}_1 = \left(\frac{B^2}{J^2} - \frac{3P^2\psi_f^{\ 2}}{2J^2}\right)x_1 + \left(\frac{3P\psi_f R_s}{2JL} + \frac{3BP\psi_f}{2J^2}\right)i_q + \quad (5)$$
$$+\frac{3P\psi_f}{2JL}u + \left(\frac{B^2}{J^2} - \frac{3P^2\psi_f^{\ 2}}{2JL}\right)\omega_{ref} + \frac{1}{J}\dot{T} - \frac{BT}{J}$$

The damping coefficient B, which cannot be accurately measured in practice, was viewed as an uncertain parameter. Thus, all terms containing damping coefficient B are uncertain. The uncertain parameters can be recorded as:

$$\theta_1 = \frac{B^2}{J^2} - \frac{3P^2\psi_f^{\ 2}}{2J^2};\ \theta_2 = \frac{3P\psi_f R_s}{2JL} + \frac{3BP\psi_f}{2J^2};$$
$$\theta_3 = \frac{B^2}{J^2} - \frac{3P^2\psi_f^{\ 2}}{2JL};\ \theta_4 = \frac{BT}{J^2};\ A = \frac{3P\psi_f}{2JL};\ C = \frac{1}{J}$$

Sorting the parameters, the mathematical model of the wind turbine can be described as:

$$\begin{cases} \dot{x}_1 = x_2; \\ \dot{x}_2 = \theta_1 x_1 + \theta_1 i_q + \\ +Au + \theta_3\omega_{ref} - \theta_4 T - CT \end{cases} \quad (6)$$

3 DESIGN OF ADAPTIVE SMC STRATEGY

Based on the Eq. (6), this section designs an adaptive SMC strategy by selecting the error sliding surface, and defining the adaptive control law for uncertain parameters to realize Lyapunov stability.

The error sliding surface can be defined as:

$$\begin{cases} s_1 = x_1 \\ s_2 = x_2 - x_{2d} \end{cases} \quad (7)$$

where, x_{2d} is the virtual controlled quantity. Taking the derivative of s_1:

$$\dot{s}_1 = \dot{x}_1 = x_2 = s_2 + x_{2d} \quad (8)$$

where, s_1 and s_2 are error sliding mode surfaces, the design goal is to eventually make $s_1 = 0$, $s_2 = 0$. Since s_2 is related to state variable ω_m, it can be viewed as an uncertain term to facilitate further analysis. Besides, a hypothesis was made to simplify the design of the control system:

Hypothesis 1. Suppose $\left\|s_2\right\| \le \alpha_1$, where α_1 is an unknown but bounded normal number.

The virtual controlled quantity of x_{2d} was taken as:

$$x_{2d} = -\left[K_1 + \varphi_1(|s_1|)\right]s_1 - \frac{\overline{\alpha_1} c_1 s_1}{\left(s_1^2 + \varepsilon_1^2\right)^{\frac{1}{2}}} \tag{9}$$

where, $\varepsilon_1 > 0$, $K_1 > 0$, $c_1 > 1$, $\varphi_1(|s_1|) = \tau_1 s_1^2$ with $\tau_1 > 0$, $\overline{\alpha_1}$ is the estimated value of α_1. Let $\tilde{\alpha} = \alpha - \overline{\alpha_1}$ be the estimation error of α_1. Then, the adaptive law of $\overline{\alpha_1}$ can be defined as:

$$\dot{\overline{\alpha_1}} = \frac{\rho_1 c_1 s_1^2}{\left(s_1^2 + \varepsilon_1^2\right)^{\frac{1}{2}}}, \rho_1 > 0 \tag{10}$$

The Lyapunov function of the first order subsystem can be defined as:

$$V_1 = \frac{1}{2}s_1^2 + \frac{1}{2\rho_1}\tilde{\alpha}_1^2 \tag{11}$$

Then, we have:

$$\begin{aligned} \dot{V}_1 &= s_1 \dot{s}_1 - \frac{1}{\rho_1}\tilde{\alpha}\dot{\overline{\alpha}} = -\left[K_1 + \varphi_1(|s_1|)\right]s_1^2 + s_1 s_2 - \\ &-\left(\overline{\alpha_1} + \tilde{\alpha}_1\right)\frac{c_1 s_1^2}{\left(s_1^2 + \varepsilon_1^2\right)^{\frac{1}{2}}} \le -\left[K_1 + \varphi_1(|s_1|)\right]s_1^2 + \\ &+\alpha_1\|s_1\| - \alpha_1\frac{c_1 s_1^2}{\left(s_1^2 + \varepsilon_1^2\right)^{\frac{1}{2}}} \end{aligned} \tag{12}$$

If the sliding surface s_1 satisfies $\|s_1\| \le \frac{c_1 s_1^2}{\left(s_1^2 + \varepsilon_1^2\right)^{\frac{1}{2}}}$, then $\dot{V}_1 \le -\left[K_1 + \varphi_1(|s_1|)\right]s_1^2 \le 0$. This means s_1 is ultimately bounded and stable, under the action of the virtual controlled quantity x_{2d}.

According to the error sliding surface defined by Eq. (7), the derivative of s_2 can be obtained as:

$$\begin{aligned} \dot{s}_2 &= \dot{x}_2 - x_{2d} = \theta_1 x_1 + \dot{\theta}_2 i_q + \theta_3\omega_{ref} - \\ &-\theta_4 T + C\dot{T} + Au_q - \dot{x}_{2d} \end{aligned} \tag{13}$$

Direct calculation of $\dot{x}_{2d}$ in Eq. (13) would be too complicated, and might result in overestimation of coefficients. To avoid this phenomenon, this paper designs an adaptive SMC strategy, and makes the following hypothesis about $\dot{x}_{2d}$:

Hypothesis 2. Suppose $\left\|\dot{x}_{2d}\right\| \le \alpha_2$, where α_2 is an unknown but bounded normal number.

The uncertain terms of $\theta_i (i = 1, 2, 3, 4)$ in the system call for adaptive compensation. $\overline{\theta_i}\,(i = 1, 2, 3, 4)$ is the estimated value of $\theta_i (i = 1, 2, 3, 4)$, with $\tilde{\theta}_i\,(i = 1, 2, 3, 4)$ being the estimation error:" $\tilde{\theta}_i = \theta_i - \overline{\theta_i}$. Substituting the error formula into Eq. (13):

$$\begin{aligned} \dot{s}_2 &= \left(\overline{\theta_i} + \tilde{\theta}_i\right)x_1 + \left(\overline{\theta_2} + \tilde{\theta}_2\right)i_q + \\ &\left(\overline{\theta_3} + \tilde{\theta}_3\right)\omega_{ref} - \left(\overline{\theta_4} + \tilde{\theta}_4\right) + Au_q - \dot{x}_{2d} \end{aligned} \tag{14}$$

The Lyapunov function of system (6) can be defined as:

$$V_2 = V_1 + \frac{1}{2}\left(s_2^2 + \frac{1}{\varsigma_1}\tilde{\theta}_1^2 + \frac{1}{\varsigma_2}\tilde{\theta}_2^2 + \frac{1}{\varsigma_3}\tilde{\theta}_3^2 + \frac{1}{\varsigma_4}\tilde{\theta}_4^2\right) \tag{15}$$

where, $\varsigma_i (i = 1, 2, 3, 4)$ is the adaptive parameters to be designed. Combining Eq. (12), Eq. (14) and Eq. (15):

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + s_2\dot{s}_2 + \frac{1}{\varsigma_1}\tilde{\theta}_1\left(\dot{\theta}_1 - \dot{\overline{\theta}}_1\right) + \frac{1}{\varsigma_2}\tilde{\theta}_2\left(\dot{\theta}_2 - \dot{\overline{\theta}}_2\right) + \\ &+\frac{1}{\varsigma_3}\tilde{\theta}_3\left(\dot{\theta}_3 - \dot{\overline{\theta}}_3\right) + \frac{1}{\varsigma_4}\tilde{\theta}_4\left(\dot{\theta}_4 - \dot{\overline{\theta}}_4\right) = -\left[K_1 + \varphi_1(|s_1|)\right]s_1^2 + \\ &+s_2\left(\overline{\theta}_1 x_1 + \overline{\theta}_2 i_q + \overline{\theta}_3\omega_{ref} - \overline{\theta}_4 T + C\dot{T} + Au_q - \dot{x}_{2d}\right) - \\ &-\frac{1}{\varsigma_1}\tilde{\theta}_1\left(\dot{\overline{\theta}}_1 - \varsigma_1 x_1 s_2\right) - \frac{1}{\varsigma_2}\tilde{\theta}_2\left(\dot{\overline{\theta}}_2 - \varsigma_2 i_q s_2\right) - \\ &-\frac{1}{\varsigma_3}\tilde{\theta}_3\left(\dot{\overline{\theta}}_3 - \varsigma_3\omega_{ref} s_2\right) - \frac{1}{\varsigma_4}\tilde{\theta}_4\left(\dot{\overline{\theta}}_4 - \varsigma_4 s_2\right) \end{aligned} \tag{16}$$

The control law and parameter adaptive law can be respectively selected as:

$$\begin{aligned} u &= \frac{s_2}{A}\left[\overline{\theta}_1 x_1 + \overline{\theta}_3 i_q + \overline{\theta}_3\omega_{ref} - \overline{\theta}_4 T + \right. \\ &\left. C\dot{T} - \alpha_2 + K_2 + \phi_2(|s_2|)\right] \end{aligned} \tag{17}$$

$$\begin{cases} \dot{\overline{\theta}}_1 = \varsigma_1 x_1 s_2 \\ \dot{\overline{\theta}}_2 = \varsigma_2 i_q s_2 \\ \dot{\overline{\theta}}_3 = \varsigma_3\omega_{ref} s_2 \\ \dot{\overline{\theta}}_4 = \varsigma_4 T s_2 \end{cases} \tag{18}$$

such that:

$$\dot{V}_2 = -\left[K_1 + \varphi_1(|s_1|)\right]s_1^2 - \left[K_2 + \varphi_2(|s_2|)\right]s_2^2 \le 0 \tag{19}$$

4 SIMULATION ANALYSIS

Due to the stochasticity of the wind speed, the PMSM speed is irregular and nonlinear, making the output power unstable. However, the load change is not random, but stable over a period of time. Thus, it is critical to choose a control strategy to stabilize wind turbine speed, and guarantee the stability of power generation.

This paper sets up a simulation platform on MATLAB/Simulink, and implements adaptive SMC of the speed of PMDD wind turbine, using the vector control method with i_d = 0. During the simulation, the PMSM parameters were configured as follows: number of pole pairs p = 8; stator inductance L = 0.334 H; stator resistance R = 0.97 Ω; flux linkage ψ = 0.5 wb; moment of inertia J = 0.2 kgm^2.

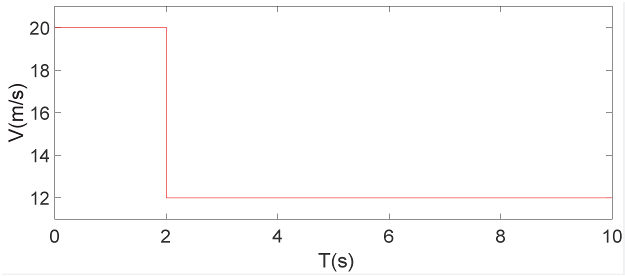


Figure 2 Wind speed curve

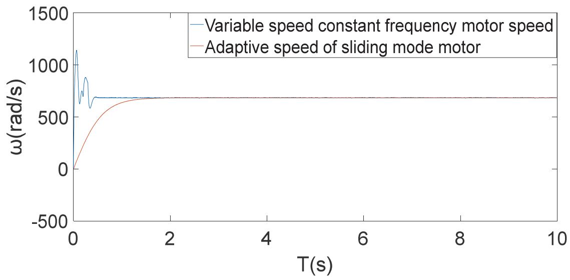


Figure 3 Motor speeds under adatpive SMC and variable speed contant frequency control

The simulation conditions were set as follows: grid-side voltage U = 380 V; sampling cycle T_s = 5 μs; simulation time 10 s; coefficients c_1 = 3, ρ_1 = 1.5, ε_1 = 2 and K_1 = 1; reference speed ω_{ref} = 700 rad/s; initial load torque T_L = 0 Nm (at time 0 s, load torque changes to $TL1$ = 7 Ns); initial wind speed 20 m/s (at time 0 s, wind speed changes to 12 m/s); simulation coefficients: ξ_1 = 1, ξ_2 = 2, ξ_3 = 2, ξ_4 = 1, K_2 = 10 and α_2 = 100. The simulation results are displayed in Fig. 2 to Fig. 8.

As shown in Fig. 2 and Fig. 3, the load torque of the system changed to 7 Nm at time 0 s, and the wind speed of the PMSM dropped from 20 m/s to 12 m/s at that time. The falling wind speed and growing load caused the PMSM to accelerate at 0 s.

From Fig. 3 and Fig. 4, it is inferred that, under adaptive SMC, the PMSM speed slowly climbed up to 680 rad/s, while that under variable speed constant frequency control suddenly increased, before stabilizing at 680 rad/s after correcting the large overshoot. Thus, the adaptive SMC is obviously superior to variable speed constant frequency control in speed regulation.

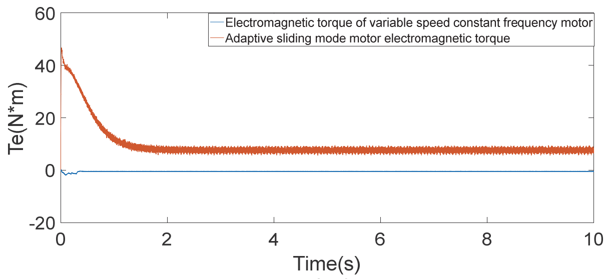
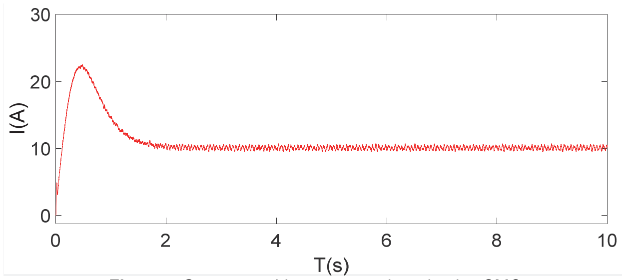


Figure 4 Motor torques under adaptive SMC and variable speed constant frequency control



Figrue 5 Generator-side current under adaptive SMC

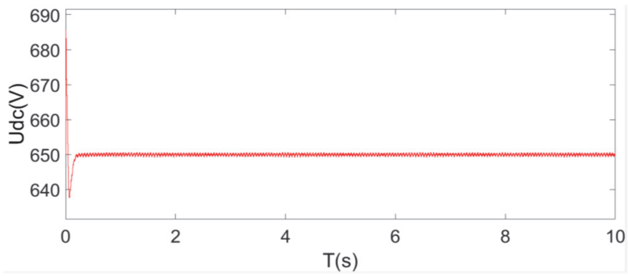


Figure 6 Rectifier-side direct current voltage

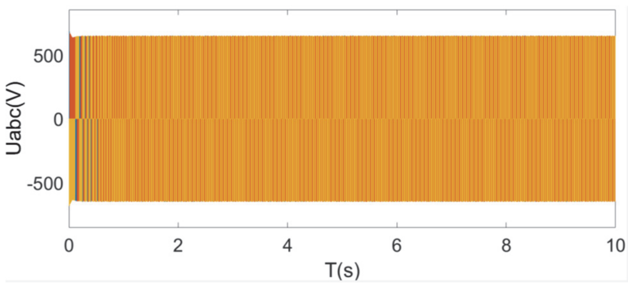


Figure 7 Generator-side three-phase voltage

Due to the load increase, the PMSM had a torque of −0.5 Nm under variable speed constant frequency control. In this case, the turbine output cannot meet the load demand. By contrast, the PMSM's electromagnetic torque under adaptive SMC changed greatly at the beginning, but slowly declined at 1s, and eventually stabilized at 5 Nm. The PMSM almost realized full power operation, meeting the load demand.

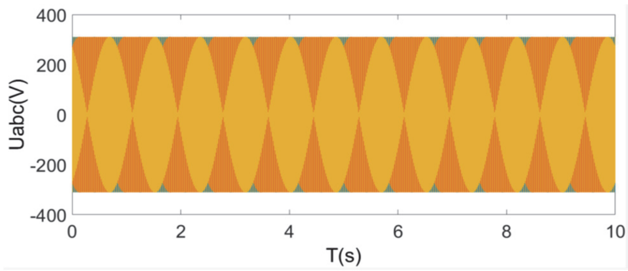


Figure 8 Grid-side three-phase voltage

During the operation, no overshoot occurred to the PMSM speed under adaptive SMC, i.e., the system speed was always on the rise. This favors the stable operation and power generation of the PMSM, and ensures the service life of the generator. On the contrary, the PMSM speed under variable speed constant frequency control suffered from overshoot, despite reaching the stable level in a short time. The temporary overshoot undermines the power generation frequency and quality of output power. The unreliable power thus generated is the so-called garbage power, which could produce high-order harmonics, posing a serious threat to grid safety and reliability. Besides, the garbage power also increases the load on inverter and other devices, and might shorten their service life.

From Fig. 6 to Fig. 8, it can be seen that, under adaptive SMC, the grid-side voltage and generator-side voltage were both stable, meeting the operation requirements for the grid.

To sum up, the proposed adaptive SMC outperforms the traditional variable speed constant frequency control.

5 CONCLUSIONS

To solve the unmeasurable damping coefficient of PMDD wind power system, this paper designs an adaptive SMC strategy based on the Lyapunov stability theory. Under the proposed control strategy, the PMSM in the wind power system can operate at a suitable speed, despite the simultaneous changes of wind speed and load torque. Simulation results show that the proposed adaptive SMC strategy is highly effective and strongly robust.

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