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Maximum Power Point Tracking Control of Wind Turbine Based on Prescribed Performance Function Method

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ABSTRACT

The stability of maximum power point tracking (MPPT) of wind turbine(WT) system will be affected by the disturbance of external environment. The response speed, accuracy, and stability of the controller directly affect the efficiency and power generation of WT. In this paper, a novel robust adaptive controller with prescribed performance is designed to achieve MPPT. Robustness of the controller is used to overcome the effects of instantaneous variation characteristics of wind and disturbances on the stability of the WT system. Considering the uncertainty of the precise parameters of the WT system in the actual operation process, the adaptive algorithm is used to estimate the system parameters. In additional, the prescribed performance function is applied to MPPT to ensure the tracking speed and accuracy. The simulation results show the effectiveness of the controller in natural continuous turbulent wind speed.

Keywords: Maximum power point tracking, prescribed performance function, robust adaptive control, wind turbine.

NONMENCLATURE

Abbreviations	
MPPT	Maximum power point tracking
WT	wind turbine
SMC	Sliding mode control

1. INTRODUCTION

In order to solve the problem of traditional energy shortage and environmental pollution, renewable energy becomes the key alternatives[1]. As one of renewable energy, wind power has achieved a compound annual growth rate of 24% since 2013 and has become the largest and fastest-growing energy in the world. In the past 2019, the total installed capacity of global offshore wind power has exceeded 29 GW, and it is estimated that 205 GW will be added by 2030[2]. According to the IEA wind power market forecast report, wind power will account for 15-18% of global electricity in 2050[3]. Compared with other renewable energy industries, the wind power industry has a broader development trend.

The power control of WT is mainly divided into MPPT control and constant power control. Specifically,the MPPT control plays a key role in capturing wind energy below the rated wind speed. The response speed, accuracy, and stability of the controller directly affect the efficiency and power generation of WT. In the practical application, the MPPT control problem is described as adjusting the electromagnetic torque, so that the actual angular speed ω can track the expected angular speed ω_r and the power coefficient C_p can quickly reach the maximum value. At present, many control algorithms are used in MPPT control of WT. The optimal tip speed ratio method[4] is sensitive to changes in turbulent wind. The problems of the optimal torque tracking control[5] are the slow response speed and poor efficiency of the controller. The traditional nonlinear PI control is used to realize the MPPT[6], but it has poor performance for fast-changing wind. Due to Sliding mode control (SMC)has strong robustness in dealing with nonlinearity, parameter uncertainty, and disturbance, the SMC is applied to the WT[7]. However, other methods are needed to eliminate the chattering phenomenon in SMC. A super-twisting algorithm is applied to WT[8], which can capture wind energy in a finite time without chattering, but it is too conservative for the disturbance. In[9], a multivariable adaptive exceeding approach is proposed for MPPT control, but when the disturbance exists, the power coefficient C_p will change suddenly.

In this paper, a new controller is designed to ensure the response speed, accuracy and stability of WT's MPPT control. The controller has the following advantages:

1)The prescribed performance function is used in the controller design process to ensure that the tracking error converges to the preset arbitrary small interval; 2) The exact parameters of the WT need not be known; 3) The designed controller has good fault tolerance and anti-disturbance ability; 4) In the case of rapid changes in wind speed, the power coefficient C_p and tip speed ratio λ can remains at the optimal value.

2. SYSTEM MODEL

According to Betz theory, the effective power captured by the WT is

$$P_a = \frac{1}{2}\rho\pi R^2 v^3 C_p = T_a\omega \tag{1}$$

where ρ is the air density, R is the radius of the wind wheel, C_p is the power coefficient, which is a nonlinear function of the blade tip speed ratio λ and pitch angle β. Because it is the MPPT control of the WT in the low wind speed area, the pitch angle $\beta = 0$. The power coefficient C_p is

$$\begin{aligned} C_p &= c_1\left(\frac{c_2}{\lambda_i} - c_3\right)\exp\left(\frac{-c_4}{\lambda_i}\right) + c_5\lambda \\ \frac{1}{\lambda_i} &= \frac{1}{\lambda} - 0.035 \end{aligned} \tag{2}$$

The λ is defined as

$$\lambda = \frac{R\omega}{v} \tag{3}$$

where ω is the rotor angular speed.

The aerodynamic torque is defined as

$$\begin{cases} T_a = K_l\omega^2 \\ K_l = \dfrac{1}{2}\rho\pi R^5 \dfrac{C_p}{\lambda^3} \end{cases} \tag{4}$$

The drive-train system model is shown in Fig 1. Without considering the stiffness of the drive-train system, it can be described by the following single mass model

$$\begin{cases} J\dot{\omega} = T_a - T_g - B\omega \\ J = J_r + n_g^2 J_g \\ B = B_r + n_g^2 B_g \end{cases} \tag{5}$$

where J_r and J_g are the moment of inertia of the WT and generator respectively; B_r and B_g are damping coefficients of low-speed shaft and high-speed shaft, respectively; T_g is the equivalent electromagnetic torque on the low-speed shaft of WT.

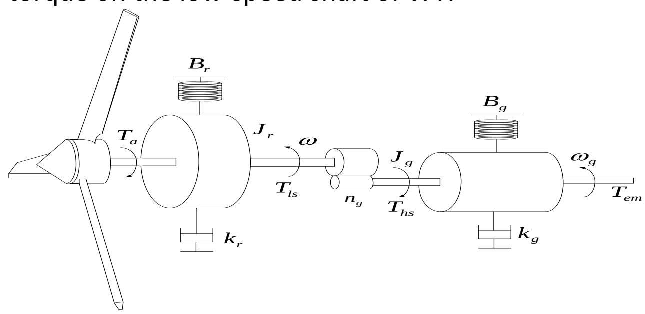

Fig 1 Drive-train system model

Considering the unknown disturbance d, equation (5) is transformed into

$$J\dot{\omega} = T_a - T_g - B\omega + d \tag{6}$$

In this paper, the tracking of angular speed is considered when the actuator faults, so modeling actuation failures as

$$T_g = lu + \theta \tag{7}$$

where l reflecting the effectiveness of the actuator, θ is the uncertain partition of the control input.

3. MPPT CONTROLLER DESIGN

In the practical application, the MPPT control problem of WT system can be described as: by adjusting the torque T_g, the actual angular speed ω can quickly and accurately tracking the optimal angular speed ω_r. The expected angular speed ω_r is

$$\omega_r = \frac{\lambda_{opt} v}{R} \tag{8}$$

where λ_{opt} is the optimal tip speed ratio.

3.1 Controller design

Define the tracking error as

$$z = \omega - \omega_r \tag{9}$$

Derivation of (9)and combining equation (6)

$$\dot{z} = a(-B\omega + k_l\omega^2 - J\dot{\omega}_r + d - T_g) \tag{10}$$

where $a = 1/J$.

To proceed, the following assumptions are shown as follows,

1) There is an unknown constant $\bar{d}>0$ such that $|d|<\bar{d}$.
2) The function of K_l in (4) is bounded, that is, there exists an unknown positive constant $\bar{K}_l$ such that $|K_l|<\bar{K}_l$.
3) The derivative of ω_r is bounded, and there have an unknown positive constant υ such that $|\dot{\omega}_r|<\upsilon$.

In order to keep the tracking error z in the preset error range, the following prescribed performance function is adopted,

$$y(t)=y_0e^{-\tau t}+\varepsilon \tag{11}$$

where y_0, τ and δ are positive constants.

Design the control signal u as

$$u=c_0yr+\hat{\theta}\phi\varphi^2 \tag{12}$$

where c_0 is a design parameter, $r=z/y$. The adaptive updating laws are as follows,

$$\dot{\hat{\theta}}=\phi^2\varphi^2-\hat{\theta} \tag{13}$$

where

$$\phi=\frac{r}{y(\delta-r^2)} \tag{14}$$

$$\varphi=(\omega+\omega^2+|r\dot{y}|+1) \tag{15}$$

Before the stability proves, the following important inequalities are given

$$\ln\left(\frac{\delta}{\delta-f^2}\right)\le\frac{f^2}{\delta-f^2} \tag{16}$$

where f is a function satisfying $-\sqrt{\delta}<f<\sqrt{\delta}$, $0<\delta\le 1$.

3.2 Stability Analysis

Candidate Lyapunov function

$$V=\frac{1}{2}\ln\left(\frac{\delta}{\delta-r^2}\right)+\frac{1}{2}an_g\tilde{\theta}^2 \tag{17}$$

where

$$\tilde{\theta}=\theta^2-\hat{\theta} \tag{18}$$

$$\theta=\max\{B,|K_l|,J\upsilon+D,J\} \tag{19}$$

By combining (14),(17) and (18), it follows that

$$\dot{V}=a(\phi\varpi-n_g\phi u)+an_g\tilde{\theta}(-\dot{\hat{\theta}}) \tag{20}$$

where

$$\varpi=-B\omega+K_l\omega^2-J\dot{\omega}_d+d-Jr\dot{y} \tag{21}$$

$$\begin{aligned}|\varpi|&\le\max\{B,|K_l|,J\upsilon+\bar{d},J\}\cdot(\omega+\omega^2+|r\dot{y}|+1)\\&=\theta\varphi\end{aligned} \tag{22}$$

Using Young's inequality, we can obtain that

$$\phi\varpi\le n_g\theta^2\phi^2\varphi^2+\frac{1}{4n_g} \tag{23}$$

$$\begin{aligned}an_g\tilde{\theta}\hat{\theta}&=an_g\tilde{\theta}(\theta^2-\tilde{\theta})\\&\le-\frac{1}{2}an_g\tilde{\theta}^2+\frac{1}{2}an_g\theta^4\end{aligned} \tag{24}$$

Combine (12),(21),(23)and(24), we have

$$\begin{aligned}\dot{V}&\le-ac_0\frac{r^2}{\delta-r^2}-an_g\tilde{\theta}\dot{\hat{\theta}}+\frac{a}{4n_g}\\&\le-ac_0\frac{r^2}{\delta-r^2}-\frac{1}{2}an_g\tilde{\theta}^2+\frac{1}{2}an_g\theta^4+\frac{a}{4n_g}\\&\le-cV+\sigma\end{aligned} \tag{25}$$

where $c=\min\{ac_0,1\}$, $\sigma=\frac{1}{2}an_g\theta^4+\frac{a}{4n_g}$.

From the formula (25), we can see that the system is ultimately uniformly bounded. Therefore, all intermediate signals are bounded, which means that the denominator $(\delta-r^2)$ of the first term in the formula (17) can only be greater than zero. Further, we get $-\sqrt{\delta}y<z<\sqrt{\delta}y$, indicating that the tracking error will not exceed the preset boundary, and the maximum overshoot is less than $\sqrt{\delta}$.

4. SIMULATION VERIFICATION

In order to prove the effectiveness of the controller in practical application, a 1MW WT[10] system model is established by Matlab/Simulink. The natural turbulence wind speed model with duration of 100s was selected, as shown in Fig 2. The main parameters of the WT are shown in Table 1. The controller parameters are chosen as $y_0=\tau=5$ $\varepsilon=0.01$, $\delta=1$.

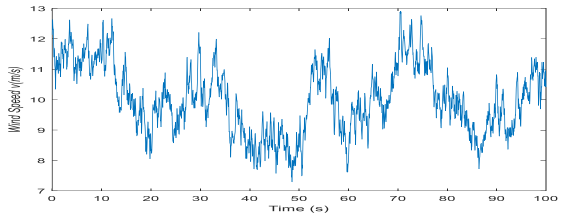

Fig 2 Turbulent wind speed v

The actuator fault occurs at $t = 40s$,i.e.,

$$T_g = \begin{cases} u & \text{t<40s} \\ 0.55u + 1000 & \text{t} \geq 40\text{s} \end{cases} \quad (26)$$

Table 1 WT parameters

parameter	value	parameter	value
R	$21.64m$	λ_{opt}	8.1
ρ	$1.293kg/m^3$	$C_{p\max}$	0.48
J_r	$325000kg.m^2$	n_g	43.165
J_g	$34.4kg.m^2$	T_{gN}	$200kN.m$
B_r	$27.36N.m/rad/s$	$T_{g\max}$	$320kN.m$
B_g	$0.2N.m/rad/s$		

In order to verify the influence of system parameter uncertainty, J_r^* and B_r^* are set as time-varying parameters in the whole simulation process.

$$\begin{cases} J_r^* = J_r(1 + 0.5\sin(t) + 0.5\sin(\pi t)) \\ B_r^* = B_r(1 + \sin(t) + \sin(\pi t)) \end{cases} \quad (27)$$

The simulation analysis is divided into four stages.

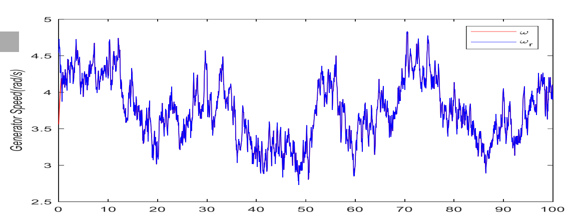

Fig 3 Angular speed tracking curve ω

A . $0 < t < 20s$

From Fig 3 to Fig 6 show that the angular speed ω almost tracks the expected angular speed ω_r in $t = 2s$, the tracking error converges to a small area of zero $|z| < \varepsilon = 0.01$, the power coefficient C_p reaches the maximum power coefficient $C_{p\max}$, and the tip speed ratio λ reaches the theoretical optimal value λ_{opt} , which proved that the proposed controller has a fast response speed and high tracking accuracy, WT can extract more wind energy.

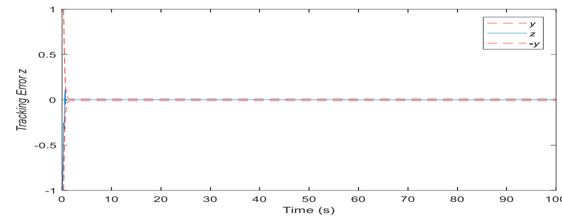

Fig 4 Angular speed tracking error z

B. $20 \leq t < 40s$

A time-varying disturbance d lasting for $20s$ is used at $t = 20s$, where $d = 30000\sin(t) + 100$. Fig 3 and Fig 4 show that ω it still tracks ω_r closely in the presence of disturbance. C_p and λ keep the optimal value unchanged in Fig 5 and Fig 6. The results show that the control system has strong robustness and low sensitivity to disturbance and fast changing turbulent wind.

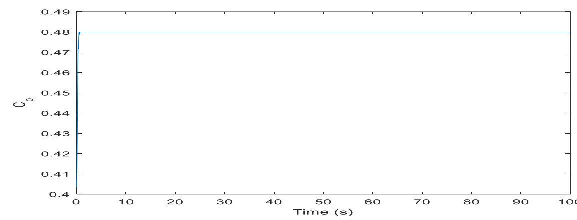

Fig 5 Power coefficient C_p

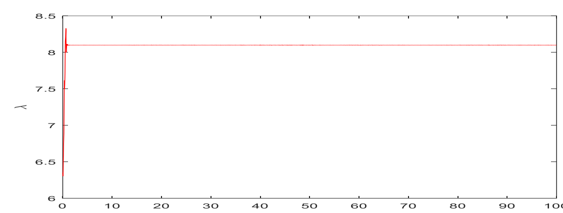

Fig 6 Tip speed ratio λ

C. $40 \leq t < 60s$

After $40s$, there is an actuator fault with the duration of $20s$. The effectiveness of the actuator l=0.65, uncertain partition of the control θ=1000 . It can be seen clearly in Fig7 that the actuator failure occurred at $t = 40s$, but there is no sudden oscillation in C_p and λ curves, moreover, the angular speed tracking error does not exceed the prescribed performance boundary in Fig 4, which proved that the controller has good fault tolerance performance.

D. $t \geq 60s$

In order to verify the ability of the controller to deal with actuator faults and disturbances at the same time. After time $t = 60s$, the disturbance and actuator fault exist simultaneously. Fig 4 shows that the tracking error can still be in a very small range and there is no oscillation in Fig 5 and Fig 6. The results show that the controller has good fault tolerance and anti-interference performance.

From Fig7, the generator torque T_g does not exceed the rated torque T_{gN} during the whole process. Fig 8 shows the output power p.

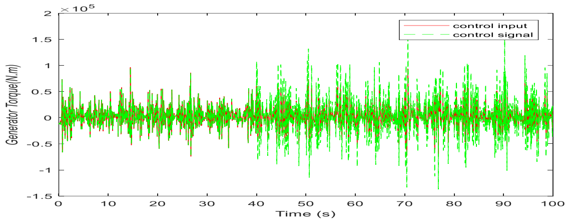

Fig 7 Generator torque T_g

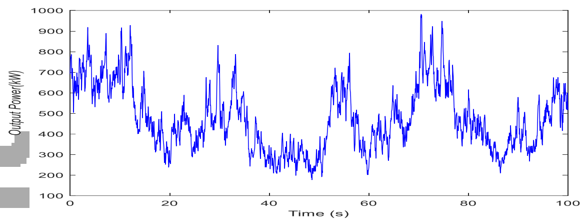

Fig 8 Output power p

5. CONCLUSION

In this paper, a MPPT control scheme has been proposed for WT with prescribed performance. Prescribed performance function is applied to the MPPT controller to ensure that the tracking error is always within the given range. Then, the adaptive algorithm is used to realize the fast and effective compensation of the unknown precise parameters of the WT system, which reflects the good engineering practicability. In additional, the controller has strong fault-tolerant performance and anti-disturbance ability, in the presence of actuator fault and external disturbance, the value of C_p and λ is basically kept at the optimal value and the sudden oscillations does not exist. Furthermore, the peak value of MPPT is not affected by the change of wind speed, so that the WT can capture more wind energy. The simulation results show the effectiveness of the MPPT controller.

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