International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok / Virtual
Paper ID: 0626

Maximum Power Point Control of Wind Turbine with Practical Prescribed Time Stability

Lei Wang*, Fangjun Jin, Longge Ji

College of Automation, Chongqing University, Chongqing,400044, PR China

ABSTRACT

For a wind turbine (WT), the maximum power point tracking (MPPT) is always required to ensure its operational reliability and increase its annual production capacity. However, it is difficult to quickly and accurately track the maximum power point since the parameter uncertainty and external disturbances, which ultimately leads to a decrease in annual power generation. In this paper, a new type of practical prescribed time controller with fault-tolerant performance is proposed to ensure the reliable operation of WT and quickly capture the maximum wind energy. First, we construct a time varying bounded performance function embedded with convergence speed and tracking accuracy that can be preset by designer, and then use this function to perform error conversion. Based on this, the problem is transformed into a new one with the bounds of the conversion error variable aiming to improve the systems fault tolerance and robustness. Finally, through FAST and simulink joint simulation, the effectiveness of the control scheme is verified.

Keywords: Wind turbine, maximum power point tracking, fault-tolerant control, practical prescribed time stability.

NONMENCLATURE

Abbreviations

WT	Wind turbine
MPPT	Maximum power point tracking
UUB	Uniformly ultimately bounded

1. INTRODUCTION

Wind energy has received widespread attention over the past decades worldwide, helping to stabilize global energy-related CO_2-emissions. WT and wind industries grow rapidly in the past years. In 2019, the wind industry enjoys a rapid growth with installations of 60.4GW, and the industry is still far from reaching a high level of growth rate [1].

It is widely known that the WT is controlled to operate in three different religions [4], which is bounded by the cut-in speed v_{in} and cut-out speed v_{out}. Specifically, in religion 2 where the WT operated between the v_{in} and rated wind speed. To extract more power from the fluctuating wind below the rated wind speed, the MPPT control unit is essential to the WT system. Considering the operating reliability of the unit and the economics of power generation, the designed MPPT controller should ensure that the wind turbine can quickly and stably capture the maximum wind energy after startup, and ensure that the wind turbine has good anti-disturbance and fault tolerance performance during stable operation. Numbers of control methods have studied and applied in this field, such as sliding mode control [3], robust adaptive control [2], fault-tolerant control [5]. However, they features low tracking speed and highly dependent on the system parameters. A hot spot of current control is the practical prescribed time control [6], which can ensure that the error converges to a given accuracy within a given time. Because of the appealing features such as stronger robustness against uncertainties, faster convergence rate, and quicker disturbance rejection, practical prescribed time method is very attractive for applied in MPPT control of WT.

By analyzing the structure and aerodynamic characteristics of the WT, this paper converts the maximum power tracking problem into a generator speed tracking problem, then a practical prescribed time MPPT scheme with fault-tolerant performance is proposed for the WT to improve the systems fault tolerance and robustness. The rest of this paper is organized as follows: The modeling process for the

Selection and peer-review under responsibility of the scientific committee of the 12th Int. Conf. on Applied Energy (ICAE2020).

considered WT system is given in the section 2. A new MPPT control method is proposed in the section 3, and the analysis on the system performance is elaborated.

2. SYSTEM MODELING

A PMSG-based WT system is considered in this study. The schematic of the two-mass model [7] is presented in Fig 1.

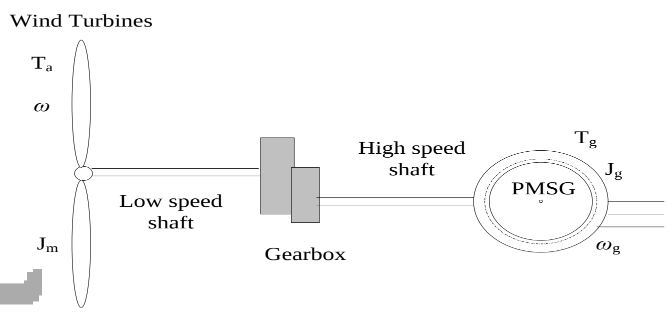


Fig 1 Two-mass model of WT

Actually, considering a multi-mass model such as three-mass and six-mass, one might find that the model has flexibility in both low-speed and high-speed shafts in the existing literature. Although the three-mass model may be more suitable for accurate harmonic evaluation of WT, the representation of shaft and blade flexibility increases the order of the model. Therefore, the three-mass model was reduced to an accceptable two-mass model. The study concluded that the six-mass model also can be transformed to a two-mass model for the transient stability analysis of WT with reasonable accuracy. Two reasons for choosing the two-mass model are that the general model can be greatly simplified for control scheme design, and the work proposed here is to solve the maximum wind energy capture problem, in which the average wind speed is regarded as a constant. Therefore, it is sufficient to use a two-mass model.

The aerodynamic model of WT can be obtained as

$$\begin{cases} P_a = \dfrac{1}{2}\rho\pi R^2 v^3 C_p(\lambda,\beta) \\ \lambda = \dfrac{R\omega}{v} \end{cases} \tag{1}$$

where ρ is the air density, R is the rotor radius, v is the wind speed, $C_p(\lambda,\beta)$ is the wind energy utilization coefficient, which is a nonlinear function of the blade tip speed ratio λ and the pitch angle β.

The aerodynamic torque output by the wind turbine shaft can be expressed as

$$T_a = K_a\omega^2 \tag{2}$$

where K_a is the operating state coefficient of the wind turbine, which can be further expressed as

$$K_a = \frac{1}{2}\rho\pi R^5 \frac{C_p(\lambda,\beta)}{\lambda^3} \tag{3}$$

where the coefficient $C_p(\lambda,\beta)$ is defined as follows:

$$C_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_0} - c_3\beta - c_4\right)\exp\left(\frac{-c_5}{\lambda_0}\right) + c_6\lambda \tag{4}$$

$$\frac{1}{\lambda_0} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3+1} \tag{5}$$

$$\omega_d = \frac{\lambda_{opt} R}{v} \tag{6}$$

which imply that maximum power can be ensured in religion 2 and the wind energy utilization coefficient C_p reaches its maximum if the proper generator torque T_g selected to ensure $\omega \to \omega_d$.

To sum up, the generator speed ω follows the change of the wind speed v and stabilizes at the optimal generator speed ω_d, then the MPPT maximum power tracking operation of the wind power system is realized.

From Fig 1, the dynamics of the proposed WT model is derived as

$$J\dot{\omega} = T_a - r_g T_g - B\omega + d(.) \tag{7}$$

where J is the total moment of inertia of the wind turbine; B is the total damping coefficient of the transmission system; T_g is generator torque; r_g is the gear ratio between the low-speed shaft and the high-speed shaft; $d(\cdot)$ represents all disturbance torques and external noises.

It is worth mentioning that this paper considers the fact that the parameters of the WT cannot be fully obtained or the uncertainties appear in the practical working conditions, such as the system parameter changes caused by the aging of the parts, so the system parameters will not appear in the controller, but only for system stability analysis. To facilitate the design of the controller, three assumptions are made :

1) $d(\cdot)$ in (7) is bounded and there exists an unknown constant $D > 0$ such that $|d(\cdot)| < D$.
2) The function K_a in (3) is also bounded and there exists an unknown constant $\bar{K}_a > 0$ such that $|K_a| < \bar{K}_a$.
3) The first derivative $\dot{\omega}_d$ of ω_d is bounded, that is,

there is an unknown constant $\sigma > 0$ such that $|\dot{\omega}_d| < \sigma$.

3. MPPT CONTROLLER DESIGN

In this paper, the MPPT control problem can be described as according to the system dynamics model equation (7), the control law T_g is designed so that the wind turbine can ensure that the actual generator speed ω follows the optimal generator speed ω_d within a finite time. Moreover, the tracking error does not exceed the given boundary.

The tracking speed of the generator and reference is obtained as

$$e = \omega - \omega_d \tag{8}$$

Integrated with (8), the derivative of e is expressed as

$$\dot{e} = \frac{1}{J}(-B\omega + K_a\omega^2 - J\dot{\omega}_d + d(.) - r_g T_g) \tag{9}$$

To achieve that the tracking error e can converge to a compact set without exceeding a preset boundary, a finite-time boundary function is introduced,

$$\psi(t) = \begin{cases} (\frac{T-t}{T})^2 e^{-\eta t}(\psi_0 - \varepsilon) + \varepsilon, t \le T \\ \varepsilon \qquad\qquad\qquad\qquad\quad ,t > T \end{cases} \tag{10}$$

where T, ε, ψ_0 and η are positive constants that can be set in advance by the designer.

Then, we introduce the following transformation on the tracking error e,

$$\xi = \frac{e}{\psi^2 - e^2} \tag{11}$$

It can be concluded that if ξ is bounded under the initial condition that $e(0) < \psi_0$, then $|e| < \psi$ holds for all $t \ge 0$.

Such proofs by contradiction. Since $|e(0)| \le \psi_0$ $-\psi < e(0) < \psi$ naturally holds. Suppose that $e(t) \le -\psi$ or $e(t) \ge \psi$ for $t = t_1$, from the intermediate value theorem of continuous functions, there exists a time instant $0 < t_2 < t_1$ such that $e(t_2) = -\psi(t_2)$ or $e(t_2) = \psi(t_2)$, resulting $\xi(t_2) = \infty$, which leads to a contradiction for the boundedness of ξ. Therefore, it is concluded that $-\psi < e(t) < \psi$ for all $t \in [0, \infty)$. This completes the proof.

It is obvious that the constraint on $e(t)$ in (8) is satisfied if we are able to keep $\xi(t)$ bounded for $t \in [0, \infty)$. Differentiating (11) with respect to time, we have

$$\dot{\xi} = \varpi\dot{e} + \varphi \tag{12}$$

where

$$\varpi = \frac{e^2 + \psi^2}{(\psi^2 - e^2)^2} \tag{13}$$

$$\varphi = \frac{-2e\psi\dot{\psi}}{(\psi^2 - e^2)^2} \tag{14}$$

Let $a = r_g / J$, $b = 1/r_g$, $u = T_g$ and combine (9) and (12), we have,

$$\dot{\xi} = ab\varpi(-B\omega + K_a\omega^2 - J\dot{\omega}_d + d) - a\varpi u + \varphi \tag{15}$$

Take the time derivative of $\frac{1}{2}\xi^2$, we have

$$\begin{aligned} \xi\dot{\xi} &= ab\xi\varpi(-B\omega + K_a\omega^2 - J\dot{\omega}_d + d) - a\xi\varpi u + \xi\varphi \\ &= ab\xi\varpi\Delta + \xi\varphi - a\xi\varpi u \end{aligned} \tag{16}$$

where

$$\Delta = -B\omega + K_a\omega^2 - J\dot{\omega}_d + d(.) \tag{17}$$

$$\begin{aligned} |\Delta| &\le |B\omega| + |K_a\omega^2| + |J\dot{\omega}_d| + D \\ &\le \max\{|B|, |K_a|, J\sigma + D\} \cdot (\omega + \omega^2 + 1) \\ &= \tau\phi \end{aligned} \tag{18}$$

where $\tau = \max\{|B|, |K_a|, J\sigma + D\}$ is an unknown constant and $\phi = (\omega + \omega^2 + 1)$.

With the young's inequality, one can easy to obtain that

$$ab\xi\varpi\Delta \le a\xi^2\varpi^2\phi^2 + \frac{1}{4}ab^2\tau^2 \tag{19}$$

$$\xi\varphi \le a\xi^2\varphi^2 + \frac{1}{4a} \tag{20}$$

Hence the actual control is constructed as

$$u = \xi\varpi\phi^2 + \frac{\xi}{\varpi}\varphi^2 + k\frac{\xi}{\varpi} \tag{21}$$

Consider the following Lyapunov function candidate

$$V = \frac{1}{2}\xi^2 \tag{22}$$

Integrating with (16), (19), (20) and (21), it follows that

$$\begin{aligned} \dot{V} &\le -ka\xi^2 + \frac{1}{4}ab^2\tau^2 + \frac{1}{4a} \\ &\le -\bar{k}V + c_0 \end{aligned} \tag{23}$$

where $\bar{k} = ka,\ c_0 = \frac{1}{4}ab^2\tau^2 + \frac{1}{4a}$.

It is readily known from (23) that the signals of the closed-loop system is UUB. Alternatively, the $|e| < \psi$ holds for all $t \geq 0$, which means that the tracking error will not exceed the preset boundary.

4. SIMULATION RESULTS

In order to verify the validity and correctness of the proposed finite-time control method, a simulation on 1MW wind turbine model was carried out using Matlab/Simulink. Detailed system parameters can refer to [7]. The designed controller parameters are chosen as: $T = 5$, $\psi_0 = 5$, $\varepsilon = 0.01$, $\eta = 1$, $k = 10$.

The natural continuous wind with turbulence was introduced in this simulation to verify the dynamic performance of the controller under actual working conditions. We use Turbsim software to simulate the continuous turbulent winds with effective speed being 9m/s, as shown in Fig 2. Four-stage simulation of $80s$ is performed.

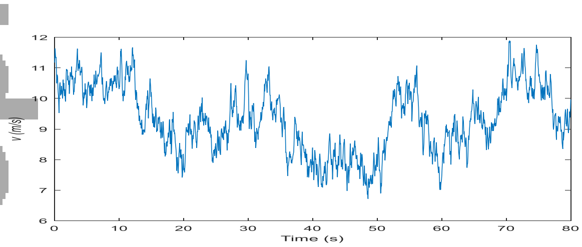


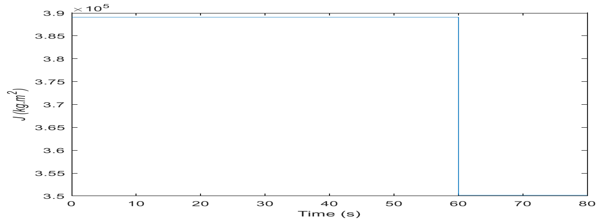
Fig 2 Natural continuous turbulent wind

The first stage at $0 \sim 20\ s$ shows the fast-tracking performance simulation of the system. The initial generator speed of the WT is selected as $\omega(0) = 3.56\ rad/s$, the electromagnetic torque is selected as $T_g(0) = 0$, the additional disturbance torque $d(0) = 0$.

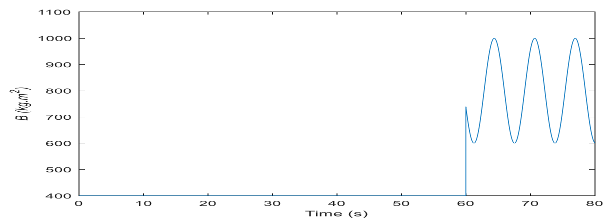
The second stage shows the anti-interference ability of the system in the MPPT stable operation state, the external disturbances torque d changes at $t = 40\ s$, i.e. $d = 35000(2 + \sin(t))$ and the simulation is $20 \sim 40$ s.

The third stage tests the fault-tolerant capability of the proposed controller. The actuator fault occurs at $t = 40\ s$, i.e. $u^* = 0.5u + 100$, where u^* is the actual control input and the simulation time is $40 \sim 60\ s$.

The fourth stage tests the maximum wind energy capture capability under the perturbation of model parameters. The model parameters change at $t = 60\ s$ i.e. $B = (2 + 0.5\sin(t))B_0$, $J = 0.9J_0$, where J_0 and B_0 are the original initial value of the total moment inertia J and the total damping coefficient B.

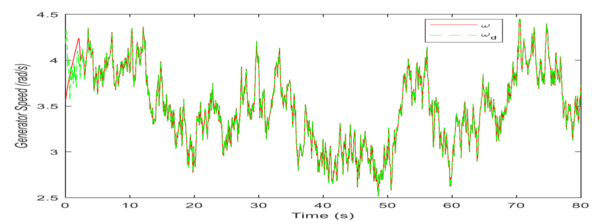


(a)

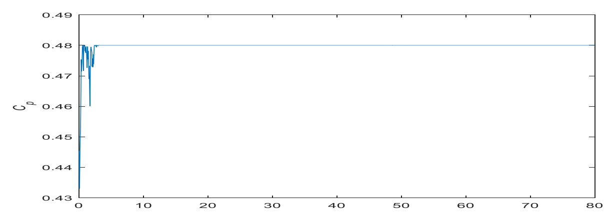


(b)

Fig 3 The perturbation of model parameters



(a)



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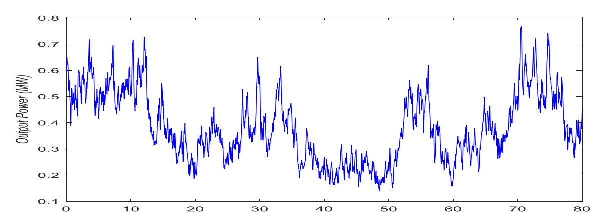
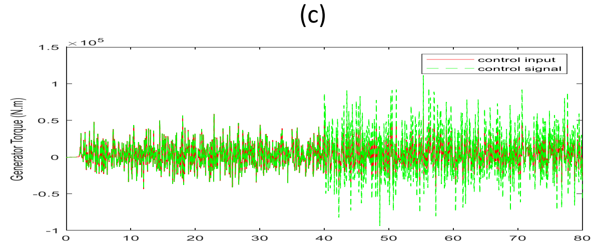


(c)



(d)

Fig 4 MPPT performance under natural continuous turbulent wind

From Fig 3 and Fig 4, it can be seen that the system can fast tracking in terms of transient performance. The tracking error can converge to a small area of zero $\Omega = \{e \| e| < \varepsilon = 0.01\}$ within a set $T = 5\ s$, resulting C_p also quickly approaches its maximum. Theoretically, T and ε can be set arbitrarily in advance by the designer. In terms of steady-state performance, we can see that the system has good anti-disturbance and fault tolerance performance. Because of the tracking error is continuous and always within the preset boundary, the WT generator speed can still track the expected generator speed and C_p can maintain its maximum value without sudden changes or jitter after that a disturbance is added at $t = 20\,\mathrm{s}$ and the actuator failure occurs at $t = 40\ s$. Even when the model parameter changes suddenly at $t = 60\ s$, it can be seen that C_p is still at its maximum value, namely the wind turbine can always capture the maximum wind energy. The simulation results show that the proposed controller can guarantee the maximum wind energy utilization rate of the system under natural continuous wind speed when the system is affected by the random strong uncertainty of the aerodynamic torque T_a caused by the natural continuous wind, model parameter perturbation, large disturbance and actuator failure.

5. CONCLUSION

In this study, a MPPT controller is proposed to address the problem of precise tracking the optimal generator speed in finite time for the WT. The MPPT scheme plays an important role during the power generation process. Based on the finite time boundary performance function, an improved fault-tolerant MPPT strategy is proposed. By analyzing the simulation results, we can conclude that the proposed controller does not only guarantee the steady-state performance of the MPPT operation but also realizes the excellent dynamic performance considering the WT parameter uncertainty and unknown disturbances. Moreover, the proposed controller exhibit superior fault-tolerant capability. The tracking error can converge to a given accuracy range within a given time and then it is always within the preset boundary regardless of whether there is disturbance, actuator failure or sudden change in system parameters. Therefore, the WT can quickly, safely and reliably capture wind energy to achieve maximum energy conversion, thereby increasing annual power generation.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China (NO.51875058),Central University Frontier Discipline Special Project(NO. 20 19CDQYZDH025), Chongqing Basic Science and Front ier Technology Research Special(NO.CSTC2018jcyjAX0 414)and Chongqing Municipal Education Commission Science and Technology Research Project (NO. KJQ N20180118).

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