Energy Proceedings
Vol 54, 2025
ISSN 2004-2965

Research on Full-Power Preset Time Control Algorithm of Wind Turbines for Gobi Desert Environments#

Li Zhang[1], Lei Wang[1*]

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

(Corresponding Author: leiwang08@cqu.edu.cn)

ABSTRACT

Wind turbines located in the Gobi Desert and other arid regions are subject to extreme environmental conditions, including frequent sandstorms and significant temperature fluctuations. These factors complicate maintenance and elevate operational costs, necessitating enhanced adaptability and performance in wind turbine controllers. Traditional controllers, which rely on linearized models, often require extensive adjustments and may deliver suboptimal performance. This study introduces a novel collective pitch controller for output power regulation and an independent pitch controller for reducing structural loads. By integrating these controllers into a robust, nonlinear system model, we developed a full-power preset time controller specifically tailored for the challenging conditions of the Gobi Desert. The proposed controller significantly enhances output power stability and reduces turbine loads. Comparative analysis with a gain-scheduled proportional-integral controller demonstrates the superior performance of our proposed solution.

Keywords: Renewable Energy, Onshore Wind Turbines, Preset Time Control, Power Control, Load Shedding Control

NONMENCLATURE

Abbreviations	
WT	Wind Turbine
PPT	Practical Preset Time

1. INTRODUCTION

Offshore WTs play a crucial role in sustainable energy development, yet onshore turbines offer advantages such as simpler design, lower construction costs, and easier installation, making them highly competitive. However, many onshore turbines are located in remote desert areas where they are exposed to extreme conditions, including high ground temperatures, significant temperature differences, and strong winds laden with sand. Ensuring the long-term stable operation of these turbines under such conditions is a critical challenge. The control strategy for WTs, particularly the pitch control system, is vital for stable power output, high wind energy utilization, reliable start and stop performance, and overall system durability[1].

While significant research has focused on pitch control, there are ongoing challenges. For example, Chu et al. designed a disturbance suppression controller that achieves stable output power without relying on an accurate mathematical model, proving effective even in the presence of interference[2]. Li Jianshen proposed a dual multivariable, model-free, adaptive fault-tolerant independent pitch control strategy, which demonstrated robustness against various actuator faults[3]. However, the nonlinear and interdependent nature of WT systems poses additional challenges. This paper addresses these challenges by developing a full-power control algorithm based on practical preset time (PPT) control, combining collective and independent pitch control to achieve more stable output power and reduced turbine loads.

2. FULL POWER CONTROL SYSTEM MODEL

This study treats collective and independent pitch control as two independent control loops, modeling them accordingly. Linearization around specific operating points (wind speed and rotor speed) is conducted using FAST software, resulting in the following state equation model:

$$\dot{x} = A(t)x + B_d(t)\delta + B(t)u \tag{2-1}$$

Where $\dot{x}$ is the system state, $B_d(t) = \beta_1, \beta_2, \beta_3$ represents the pitch angles, and δ is the wind disturbance input; the matrix A, B_d, B depend on the selected operating point. The nonlinear system operating above rated wind speed is described as:

$$\dot{x} = f(x) + g(x)u \tag{2-2}$$

in which, $f(x) = A(t)x + B_d(t)\delta$, $g(x) = B(t)$. This paper considers the WT operating above the rated

This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

wind speed, that is, $f(x)$ and $g(x)$ are both unknown and bounded.

Given the minimal coupling between collective and independent pitch control, they are designed as separate control loops to achieve the specific objectives of each loop. The control scheme is shown in Figure 1.

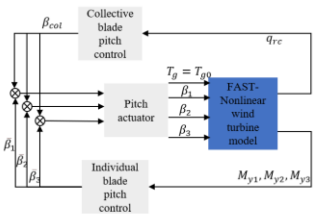

Fig. 1. Pitch Control Loop Program

2.1 Collective pitch control model

To stabilize the output power at the rated value P_0, the rotor displacement q_{rc} and rotor speed ω are selected as state quantities, and the input is the collective pitch angle β_{col}. the system model can be obtained as follows:

$$\begin{aligned} \dot{x}_c &= f(x_c) + g_c u_c \\ y_c &= x_c \end{aligned} \tag{2-3}$$

In which, $x_c = [q_{rc}, \omega]^T, u_c = \beta_{col}$

In the excess state, the generator torque is $T_g = T_{g_0}$, and the speed error $e_\omega = \omega - \omega_r$ is used as the feedback signal. When the pitch controller is designed so that $e_\omega = 0$, the output power is $P_{out} = T_{gr}\omega_r = P_0$. The rotor speed is obtained as:

$$\omega_r = \frac{P_0}{NT_{g0}} \tag{2-4}$$

The expected value of the collective pitch control model output is $y_{Cr} = [0, \omega_r]^T$. Therefore, the above system belongs to a single-input multiple-output under-driven system.

2.2 Independent pitch control model

The bending angle of the blade is selected as the state quantity, the pitch angle is selected as the input quantity of the controller, and the blade root load is selected as the output quantity, that is, $x_I = [\delta_1, \delta_2, \delta_3]^T$, $u_I = [\bar{\beta}_1, \bar{\beta}_2, \bar{\beta}_3]^T$, $y_I = [M_{y_1}, M_{y_2}, M_{y_3}]^T$, then the system model is:

$$\begin{aligned} \dot{x}_I &= f_I(x_I) + g_I u_I \\ y_I &= [M_{y_1}, M_{y_2}, M_{y_3}]^T \end{aligned} \tag{2-5}$$

Taking the azimuth angle of each blade as Ψ, applying Coleman transformation:

$$x_{Ic} = Tx_I \tag{2-6}$$

Where $x_{Ic} = [q_{tilt}, q_{yaw}]$, q_{tilt}, q_{yaw} are the tilt and yaw components of the blade bending direction, respectively, and T is the Coleman transformation matrix:

$$T = \frac{2}{3}\begin{bmatrix} cos\psi & cos(\psi + 2\pi / 3) & cos(\psi + 4\pi / 3) \\ sin\psi & sin(\psi + 2\pi / 3) & sin(\psi + 4\pi / 3) \end{bmatrix} \tag{2-7}$$

So, the independent pitch model can be written as:

$$\begin{aligned} \dot{x}_{Ic} &= f_{Ic}(x_{Ic}) + g_{Ic}(x_{Ic})u_{Ic} \\ y_{Io} &= [M_{tilit}, M_{yaw}] = h_{Ic}(x_{Ic}) + l_{Ic}(x_{Ic})u_{Ic} \end{aligned} \tag{2-8}$$

Among them, y_{IO} is the output of the system, M_{tilt} and M_{yaw} are the tilt moment and yaw moment respectively, $u_{Ic} = [\beta_{yaw}, \beta_{tilt}]^T$ is the control input, β_{yaw} and β_{tilt} are the yaw and tilt components of the pitch angle respectively. Finally, the actual three pitch angles are obtained through the inverse Coleman transform:

$$\begin{aligned} &[\bar{\beta}_1, \bar{\beta}_2, \bar{\beta}_3]^T \\ &= \begin{bmatrix} \cos\varphi & \sin\varphi \\ cos(\psi + 2\pi / 3) & sin(\psi + 2\pi / 3) \\ cos(\psi + 4\pi / 3) & sin(\psi + 4\pi / 3) \end{bmatrix} [\beta_{yaw}, \beta_{tilt}]^T \end{aligned} \tag{2-9}$$

3. DESIGN OF FULL POWER CONTROLLER BASED ON PRACTICAL PRESET TIME CONTROL

WTs are highly nonlinear systems with significant uncertainties. Traditional controllers, designed based on linearization, require frequent adjustments as operating points change, leading to increased workload. This paper proposes a PPT-based robust controller that maintains high performance across the entire operating domain, reducing the need for frequent adjustments[4].

3.1 Problem Assumptions

From the uncertainty nonlinear system of the full power control system is:

$$\begin{aligned} \dot{x} &= f(x) + g(x)u + \Delta d \\ y &= h(x) \end{aligned} \tag{3-1}$$

In which, Δd is the unknown disturbance bounded, y is the system output. The control objective is that all intermediate variables of the closed-loop system are bounded and when $t \geq T$, the tracking error $|e(t)| = |y(t) - y_d(t)| < \varepsilon, (\varepsilon > 0)$.

The dynamic model for the derivative of tracking error is:

$$\dot{e} = a(x) + b(x)u + d \tag{3-2}$$

In which

$$a(x) = \frac{\partial h}{\partial t} + \frac{\partial h}{\partial x} f(x) - \dot{y}_d$$
$$b(x) = \frac{\partial h}{\partial x} g(x)$$
$$d = \frac{\partial h}{\partial x} \Delta d$$
(3-3)

The controller design assumes the following:

(1) There exists an unknown constant a_0 and a known function $\varphi(x)$, such that $a(x) \leq a_0\varphi(x)$.

(2) $b(x)$ is a positive function and there exists an unknown constant $b_1 < b_2$, and $0 < b_1 < b(x) < b_2$;

(3) The disturbance d is bounded by a constant D, such that $|d| < D$;

To realize the PPT control in this paper, the PPT boundary function is defined.

(1) The time-varying function $\rho(t)$ is a continuous non-increasing function, and $\rho(0) = \rho_0$, $\rho(T) = \varepsilon$;

(2) $\dot{\rho}(T) = 0$, for all $t > T$, $\rho(T) = \varepsilon$;

Combining the above two conditions, the PPT function is:

$$\rho(t) = \begin{cases} \left(\frac{T-t}{T}\right)^2 (\rho_0 - \varepsilon) + \varepsilon, 0 \leq t < T \\ \varepsilon, t \geq T \end{cases}$$
(3-4)

Where T is the adjustment time, ε is the tracking accuracy. To facilitate the design of the controller, this paper gives the critical lemma.

Lemma 1: Define the error variable $h = e / (\rho^2 - e^2)$. If the controller u is designed to make h bounded when the initial value is $|e(0)| < \rho_0$, then $-\rho(t) < e(t) < \rho(t)$ exists at any time.

Proof: Assume that when $t = t_1$, $e(t) \leq -\rho$ a or $e(t) \geq \rho$, define $r = e / \rho$, then $r(t_1) \leq -1$ or $r(t_1) \geq 1$, because $|e(0)| < \rho_0$, that is, $-1 < r_1(0) < 1$. According to the middle value theorem, there must exist t_2, such that $r(t_2) = 1$ or $r(t_2) = -1$, which contradicts the boundedness of h. Therefore, when $t \in [0, \infty)$, $-1 < r(t) < 1$, that is, $-\rho(t) < e(t) < \rho(t)$ holds.

3.2 Controller Design

If the controller tracks the error $-\rho(t) < e(t) < \rho(t)$, then the control objective of PPT is established, as shown in Figure 2.

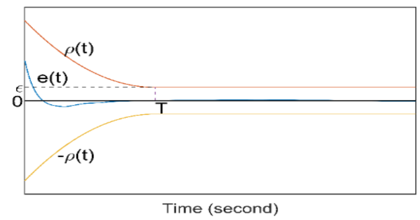

Fig. 2 Schematic diagram of PPT tracking error

The PPT control aims to ensure that the tracking error remains within a predefined boundary and converges within a preset time. The error variable is transformed, and a Lyapunov-based controller is designed to ensure system stability and bounded tracking error.

$$h = \frac{e}{\rho^2 - e^2}$$
(3-5)

Taking the derivative to h:

$$\dot{h} = \varphi + \varpi(a + d + bu) \quad (3\text{-}6)$$

In which

$$\varpi = \frac{e^2 + \rho^2}{(\rho^2 - e^2)^2}$$
$$\varphi = \frac{-2e\rho\dot{\rho}}{(\rho^2 - e^2)^2}$$
(3-7)

Select the Lyapunov function V as:

$$V = \frac{1}{2}h^2$$
(3-8)

The derivative of V is:

$$\dot{V} = h\dot{h} = h\varphi + h\varpi(a + d + bu) \quad (3\text{-}9)$$

Combining assumptions 1-3:

$$h\varphi \leq b_1 h^2 \varphi^2 + \frac{1}{4b_1}$$
$$h\varpi a \leq |h\varpi| a_0 \phi \leq b_1 \phi^2 h^2 \varpi^2 + \frac{a_0^2}{4b_1}$$
$$h\varpi d \leq b_1 h^2 \varpi^2 + \frac{D^2}{4b_1}$$
(3-10)

Combining formula (3-9,3-10):

$$\dot{V} \leq h\varpi bu + b_1 h^2 \varpi^2 \left(\frac{\varphi^2}{\varpi^2} + \phi^2 + 1\right) + \frac{1 + a_0^2 + D^2}{4b_1}$$
(3-11)

Therefore, the controller u is designed as:

$$u = -h\frac{\varphi^2}{\varpi} - h\varpi\phi^2 - h\varpi - k\frac{h}{\varpi} \quad (3\text{-}12)$$

Where, the control gain k is a positive constant. Combining formula (3-11,3-12):

$$\dot{V} \leq -2kb_1 V + \frac{1 + a_0^2 + D^2}{4b_1}$$
(3-13)

Proof: For any initial condition, V is bounded, that is, $V \in L_\infty$, and $h \in L_\infty$ is also bounded; because the controller u is function of h and ρ, so $u \in L_\infty$ and the closed-loop system is stable; according to Lemma 1, $-\rho(t) < e(t) < \rho(t)$ is bounded at any time, so the tracking error not only has the preset performance $|e| < \rho$, but also can converge to the given error range $\Omega = \{e \in R: |e| < \varepsilon\}$ within the preset time.

At the same time, to apply PPT control to the full power control system of WTs, pitch control is used as a process of tracking the expected signal so that the tracking error converges within a certain period and ensures that the tracking error does not exceed the given boundary value. Therefore, the tracking error's convergence determines the system's final control effect. The purpose of collective pitch control is to stabilize the output power. To meet the PPT control requirements, the tracking error is [5]:

$$e_1 = \omega - \omega_{d1} \tag{3-14}$$

In the independent pitch control loop, the control target is to reduce the blade root load, so the expected output signal of the independent pitch control system is 0, and the tracking error is:

$$\begin{aligned} e_2 &= M_{tilt} \\ e_3 &= M_{yaw} \end{aligned} \tag{3-15}$$

Where, M_{tilt}, M_{yaw} is the pitch moment and yaw moment. In summary, the tracking error signal is expressed as:

$$e = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \omega - \omega_{d1} \\ M_{tilt} \\ M_{yaw} \end{bmatrix} \tag{3-16}$$

The corresponding error dynamic model is:

$$\dot{e} = a(\cdot) + b(\cdot)u + d \tag{3-17}$$

Where $a(\cdot)$ and $b(\cdot)$ are collective pitch and independent pitch system models, and are unknown bounded functions. The input preset time controller u is:

$$u = \left[\beta_{col}, \beta_{yaw}, \beta_{tilt}\right]^T = [u_1, u_2, u_3]^T \tag{3-18}$$

4. SIMULATION AND ANALYSIS

In order to verify the effectiveness of the designed control algorithm in adjusting the output power and reducing the structural load during the full power operation of the WT, this paper uses FAST-Matlab/Simulink to build a platform and perform simulation analysis. The controller parameters are shown in Table 1. To further demonstrate the effectiveness of the designed controller, the enhanced baseline controller is compared with this controller, and the time domain simulation results of the two controllers are given.

Table1 Controller parameters

parameters	δ	ρ_0	T	ε	k
$\beta_{col}(u_1)$	1e-4	15	60	1.7	10
$\beta_{yaw}(u_2)$	-	1e4	60	0.5e4	1e-5
$\beta_{tilt}(u_3)$	-	1e4	60	0.5e4	1e-5

To validate the effectiveness of the proposed control algorithm, simulations were conducted using FAST-Matlab/Simulink. A 5MW WT was used as the test subject, with wind speeds exceeding the rated 11.4 m/s. The performance of the proposed controller was compared with a traditional gain-scheduled proportional-integral (GSPI) controller. The results from Figures 3-5 show that the proposed PPT controller significantly reduces output power fluctuations and rotor speed errors, while also providing smoother pitch control inputs, thereby reducing actuator fatigue.

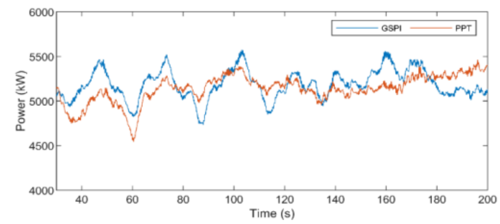

Fig. 3 Output power comparison

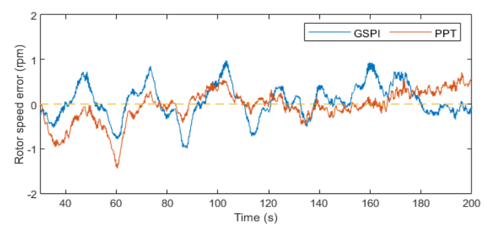

Fig. 4 Rotor speed error

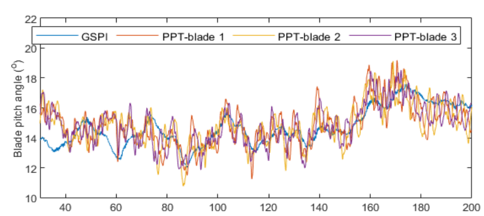

Fig. 5 Blade pitch angle

To analyze the load reduction performance of the controller, this paper analyzes the load on the blades under the two controllers. As shown in Figure 6-9. It can be seen from the figure that the independent variable pitch control method based on PPT has small fluctuations in blade bending moment, flapping moment, pitching moment, and yaw moment, which can effectively reduce the blade root load and reduce the risk of blade breakage.

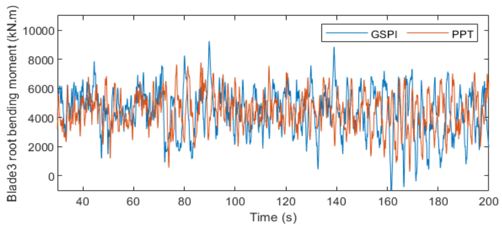

Fig. 6 Blade3 root bending moment

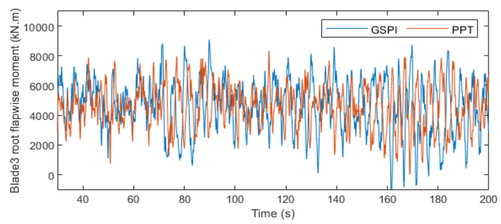

Fig. 7 Blade3 root flapwise moment

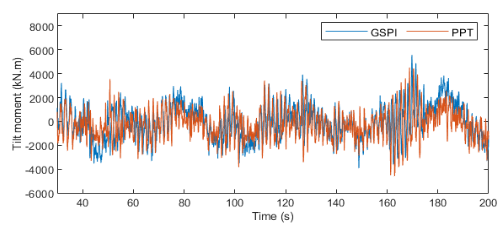

Fig. 8 Tilt moment

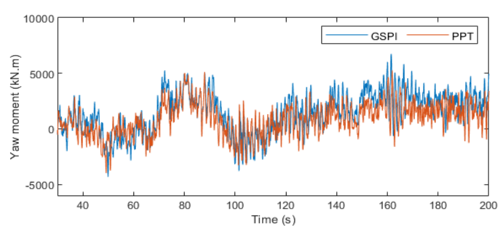

Fig. 9 Yaw moment

5. CONCLUSIONS

This study presents a WT pitch control scheme suitable for the harsh desert environment, incorporating both collective and independent pitch control strategies. The proposed PPT-based controller demonstrates superior performance in power regulation and structural load reduction compared to traditional controllers, offering significant benefits for the stable operation of WTs in challenging conditions.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China (NO.51875058), Central University Frontier Discipline Special Project (NO.ZYYD2024CG13)，Special Fund Project for Central Guidance of Local Science and Technology Development：

Intelligent control technology and application of wind turbines based on multi-source information fusion (ZYYD2024CG13)

REFERENCE

[1] Tian X, Liao H, Fan S. Simulation and research on a fuzzy adaptive PID controller for a wind power generation system with variable pitch[J]. Industrial Control Computer, 2020, 33(04):28-30.

[2] Chu H, Li W. Research on disturbance suppression in variable speed and pitch wind power generation systems[J]. Journal of Nanjing Normal University (Engineering and Technology Edition), 2019, 19(03):66-71.

[3] Li J. Research on model-free adaptive control for wind turbine pitch systems[D]. Beijing Jiaotong University, 2023. DOI:10.26944/d.cnki.gbfju.2022.000098.

[4] Zhao K, Song Y, Wang Y. Regular error feedback based adaptive practical prescribed time tracking control of normal-form nonaffine systems[J]. Journal of the Franklin Institute, 2019, 356:2759-2779.

[5] Zhang C, Plestan F. Individual/collective blade pitch control of floating wind turbine based on adaptive second order sliding mode[J]. Ocean Engineering, 2021, 228:1709-1720.