

# Research on Maximum Power Point Tracking Strategy for Direct-Drive Permanent Magnet Synchronous Wind Turbine Generators Based on Double Closed-Loop Control

Gangqiang Zhou<sup>1</sup>, Zhenkai Ma<sup>1</sup>, Xiaoqiang Guo<sup>1</sup>, Zhongchen Shi<sup>2</sup>

<sup>1</sup>Xinjiang University of Technology and Vocational Education, Kashgar 844000, China

<sup>2</sup>State Grid Hetian Power Supply Company, Hetian 848000, China

**Copyright:** © 2026 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

**Abstract:** To maximize the efficiency of wind energy utilization, a maximum power point tracking (MPPT) strategy based on optimal torque control is adopted to realize the control of the permanent magnet synchronous wind power generation system. First, the structure of the permanent magnet direct-drive wind power system and the basic principle of MPPT are elaborated, and the optimal power-speed relationship is derived. A system model composed of a wind turbine, permanent magnet synchronous generator (PMSG), uncontrolled rectifier, and boost step-up chopper circuit is constructed. To verify the effectiveness of the strategy, a system simulation model is built on the MATLAB/Simulink platform. Simulation results show that when the wind speed is constant, the DC-side voltage can be stabilized. When the wind speed increases or decreases, the control strategy can track the maximum power point of wind energy according to the wind speed change, maintaining the wind energy utilization coefficient at a high level.

**Keywords:** MATLAB; Maximum Power Point Tracking (MPPT); Permanent Magnet Synchronous Generator (PMSG)

**Online publication:** April 21, 2026

## 1. Introduction

The rapid development of global industry and the negative impacts of traditional energy sources have led to the transformation of the energy structure towards a clean, low-carbon, and sustainable direction, which has become a common strategic choice for countries around the world. Wind energy, with its significant advantages such as large reserves, wide distribution, and high technical maturity, has become a key force leading the global energy revolution and achieving the goals of “carbon peaking and carbon neutrality”. The wind power generation system based on the permanent magnet synchronous generator (PMSG) accounts for a large proportion of the global wind power market due to its technical maturity and corresponding economic advantages<sup>[1]</sup>.

Wind power generation is characterized by randomness, intermittency, and volatility. Maximizing the acquisition of electrical energy from unstable wind resources is the main method to improve the efficiency

and market competitiveness of wind power generation at this stage. The core essence of variable-speed wind turbines lies in realizing maximum power point tracking (MPPT) control. Its goal is to dynamically adjust the electromagnetic torque of the generator to change its speed when the wind speed changes, thereby stabilizing the tip-speed ratio of the wind rotor at the optimal value <sup>[2]</sup>.

This study focuses on the maximum power tracking strategy of the dual-PMSG wind power generation system and carries out research relying on the powerful modeling and simulation platform MATLAB/Simulink. The effectiveness of the control strategy is verified by setting scenarios of stable wind speed and gradual wind speed.

## 2. Structure and principle of permanent magnet synchronous direct-drive wind power system

The permanent magnet synchronous direct-drive wind power system includes a permanent magnet synchronous direct-drive wind turbine generator, a rectifier circuit, and a chopper circuit. The rectifier converts the alternating current (AC) with varying frequency and amplitude generated by the PMSG into direct current (DC). The DC chopper circuit boosts the DC voltage.

The permanent magnet synchronous generator is the core device for converting wind energy into electrical energy. The kinetic energy of wind energy can be expressed as:

$$E = \frac{1}{2}mv^2$$

where E represents the kinetic energy of flowing air, m is the mass of air, and v is the air flow velocity. Let the density of air be  $\tilde{\rho}$ , the cross-sectional area of the wind-facing surface of the permanent magnet synchronous generator be S, and the volume be V; then:

$$m = \rho V = \rho sv$$

$$E = \frac{1}{2}\rho Sv^3$$

Assume  $S_1$  is the cross-sectional area when air enters the wind turbine, and  $S_2$  is the cross-sectional area when air exits the wind turbine.  $v$ ,  $v_1$ , and  $v_2$  respectively represent the flow velocities of air when passing through the cross-sectional areas S,  $S_1$ , and  $S_2$  the average cross-section of the wind turbine. Assuming air is an incompressible fluid, the volume flow rate of air passing through the wind turbine per unit time is  $S_1v_1 = S_2v_2 = Sv$ .

According to the momentum theorem, the force exerted on the wind turbine blades and the power absorbed by the wind turbine can be calculated.

$$F = mv_1 - mv_2 = \rho Sv(v_1 - v_2)$$

$$P = Fv = \rho Sv^2(v_1 - v_2)$$

The reduction in kinetic energy  $\Delta E$  of air after flowing through the wind turbine blades can be calculated as:

$$\Delta E = \frac{1}{2}m(v_1^2 - v_2^2) = \frac{1}{2}\rho Sv(v_1^2 - v_2^2)$$

Without considering other energy losses, the kinetic energy lost by the gas is the energy absorbed by the

wind turbine blades:

$$P = \frac{1}{2} \rho S v (v_1^2 - v_2^2) = \frac{1}{4} \rho S (v_1^2 - v_2^2) (v_1 + v_2)$$

where  $v_1 - v_2$  is the average velocity of air when passing through the wind turbine.

By taking the first derivative of power with respect to time to find the maximum value, when  $v_2 = 1/3v_1$ , there is a maximum value  $P$ . Substituting into the above formula, the maximum power is obtained:

$$P = \frac{8}{27} \rho S v_1^3$$

From the above formula, the maximum wind energy utilization efficiency can be  $C_{p\max}$  expressed as:

$$C_{p\max} = \frac{P_{\max}}{P} = \frac{\frac{8}{27} \rho S v_1^3}{\frac{1}{2} \rho S v_1^3} = \frac{16}{27} \approx 0.593$$

The maximum wind energy utilization coefficient calculated in the formula is the maximum value under ideal conditions. In actual situations, it is lower than this value due to factors such as friction and electromagnetic losses.

### 3. Working principle of maximum power point tracking strategy

Compared with other methods, the hill-climbing search method shows significant advantages in application: first, the control structure is simple, without the need for complex mathematical operations; second, the algorithm only requires electrical power signals, without the need for additional wind speed sensors, which helps reduce the hardware cost of the system; third, it is insensitive to changes in system aerodynamic parameters and has strong robustness. Given the above advantages, this study chooses the hill-climbing search method as the core to construct the maximum power tracking module of the PMSG system<sup>[3]</sup>.

#### 3.1. Implementation process of maximum power point tracking

The hill-climbing search method, also known as the “perturb and observe method”, is a closed-loop feedback-based maximum power point tracking method. This method applies periodic small perturbations to the control variable, observes changes in the system output power, and then dynamically adjusts the direction of subsequent perturbations to make the system gradually converge to the maximum power point (MPPT). The specific implementation can be divided into the following three steps:

- (1) Applying Perturbation: Apply a fixed-step perturbation to the control variable. In the direct-drive permanent magnet synchronous wind power generation system, the generator speed or converter reference torque/current is usually used as the control variable, which is slightly adjusted in one direction in each control cycle.
- (2) Power Detection: After the perturbation is applied, wait for the system to stabilize briefly, then measure the real-time electromagnetic power output by the wind turbine. This power is generally calculated through the measured values of the DC-side voltage and current of the generator.
- (3) Direction Decision: Compare the current power with the power at the previous moment. If the power increases, maintain the current perturbation direction; if the power decreases, reverse the perturbation direction. Through continuous iteration, the system finally achieves dynamic stability near the maximum

power point.

### 3.2. Control principle and process

To ensure that the permanent magnet synchronous motor can quickly and smoothly track the maximum power point of wind speed changes and achieve efficient capture of wind energy, a double closed-loop control strategy is designed. The outer loop of the control strategy is responsible for speed regulation. Its given input is the speed command ( $\omega_{ref}$ ) generated by the hill-climbing search method. The core of this algorithm is to search for the optimal speed corresponding to the maximum power point by fine-tuning the speed and observing changes in the output electrical power. The speed feedback signal ( $\omega$ ) is the measured value of the actual generator speed. The PI controller of the outer loop calculates the error ( $\omega_{ref} - \omega$ ) between the speed command and the feedback value, and then outputs a q-axis current command ( $I_{qref}$ ) to eliminate this steady-state error<sup>[4]</sup>. In the vector control framework of the permanent magnet synchronous motor, the q-axis current directly determines the magnitude of the motor's electromagnetic torque.

The inner loop of the control strategy is the current regulation loop, whose given input is the q-axis current command ( $I_{qref}$ ) output by the outer loop speed controller. The current feedback signal is obtained by real-time measurement of the three-phase current of the generator, followed by Clark transformation and Park transformation. The inner loop PI controller is designed to have an extremely high response speed. Its core function is to quickly calculate the deviation between the current command and the feedback value, and accordingly output the q-axis voltage command ( $V_{qref}$ ) required to drive the converter, thereby forcing the actual current to quickly and accurately track the given current command<sup>[5]</sup>.

## 4. Overall structure and modeling of the wind power generation system

### 4.1. System structure

Based on the above analysis, a simulation of the entire direct-drive permanent magnet synchronous wind power generation system is established, and the simulation results are analyzed. The simulation diagram is shown in **Figure 1**. The upper left part of the figure is the permanent magnet synchronous generator controller, whose main purpose is to output the most suitable generator torque  $T_e$  at the current stage according to the actual wind speed and the actual speed of the generator at the current stage. The lower left part is the permanent magnet synchronous wind turbine generator, which realizes the conversion of wind energy into electrical energy. On the right side of the permanent magnet synchronous motor is a three-phase uncontrolled rectifier, which rectifies the three-phase AC into DC. The circuit on the right side of the rectifier is a Boost step-up chopper circuit, which realizes the conversion from low DC voltage to high DC voltage<sup>[6]</sup>.

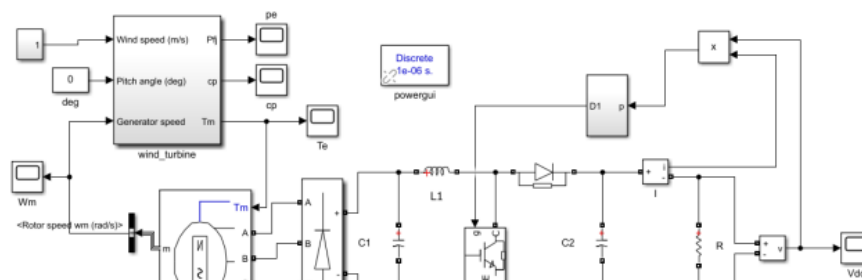
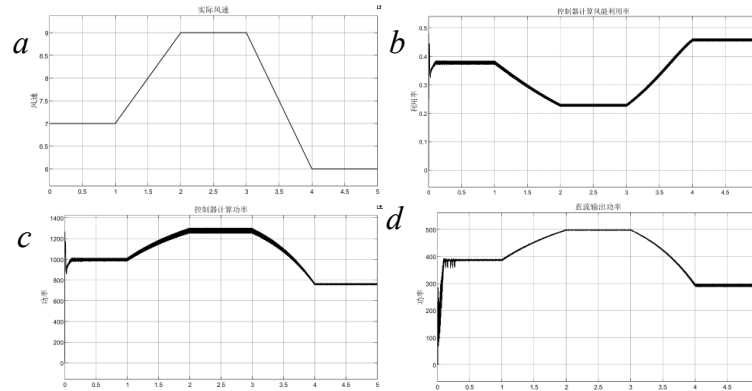


Figure 1. System simulation experiment diagram.

## 4.2. System simulation and result analysis

To verify the effectiveness of the control strategy, the waveforms at various points during the simulation process are sorted out, and the results are shown in **Figure 2**.



**Figure 2.** System simulation experiment result diagram.

As shown in **Figure 2**, Subgraph (a) is the real-time wind speed in the natural environment. The real-time wind speed and actual speed are input into the controller of the permanent magnet synchronous motor as input quantities<sup>[7]</sup>. Subgraphs (b) and (c) represent the two main output quantities of the controller, namely the wind energy utilization coefficient  $C_p$  calculated by the controller and the controller's calculated power. Subgraph (d) represents the power output on the DC side. During the time periods of 0–1s, 2–3s, and 4–5s, the wind speed in the natural environment is constant, and both the power calculated by the controller and the power output on the DC side remain constant. During the time periods of 1–2s and 3–4s, the wind speed in the natural environment increases and decreases, and both the power calculated by the controller and the power output on the DC side follow the increase and decrease of the environmental wind speed. It can be seen that the wind power generation system can real-time adjust the working condition of the permanent magnet synchronous motor according to the wind speed in the natural environment, achieving the purpose of tracking the maximum power<sup>[8]</sup>.

## 5. Conclusion

This study takes the direct-drive permanent magnet synchronous wind power generation system as the research object, focusing on its maximum power point tracking control strategy to improve wind energy conversion efficiency. Comprehensive methods such as theoretical derivation, control method construction, and digital simulation verification are used to comprehensively evaluate the feasibility and performance of the proposed control strategy.

To test the control effect, an overall system simulation model is established in the Simulink platform, and operating scenarios with constant wind speed and step change wind speed are simulated<sup>[9]</sup>. The simulation results (**Figure 2**) show that the control method designed in this paper can accurately realize the maximum power tracking function. Under constant wind speed conditions, the system can quickly converge to the optimal operating point and maintain the stable operation of the wind energy utilization coefficient, output electrical power, and DC bus voltage; when the wind speed changes suddenly, the system shows good dynamic adjustment ability. By timely adjusting the generator speed and electromagnetic torque, the output power smoothly approaches the new maximum power point, reflecting excellent dynamic tracking characteristics<sup>[10]</sup>.

## Disclosure statement

The authors declare no conflict of interest.

## References

- [1] Gong S, 2021, Teaching Reform of Statistics Mass Innovation talent Training under the background of Big Data. *Science and Education Forum*, 2021(9): 67–69.
- [1] Hong GQ, Wu GY, Jin YQ, et al., 2024, Review on Modeling and Simulation of Wind Power Generation in Power Systems. *Automation of Electric Power Systems*, 48(17): 22–36.
- [2] Li SL, Wang WS, Zhang X, et al., 2019, Impact of Wind Power Generation on System Frequency and Comprehensive Control of Virtual Inertia. *Automation of Electric Power Systems*, 43(15): 64–70.
- [3] Huang SD, Zhang YF, Feng YJ, et al., 2025, Review on the Technical Development of Permanent Magnet Wind Turbine Generators. *Journal of Electrical Engineering*, 20(4): 22–42.
- [4] Chen DH, Chen ZW, Wang HF, et al., 2024, Constant Power Control of PMSG Based on RBF-PID and Sensitive Variable Sliding Mode Approaching Law. *Acta Energiæ Solaris Sinica*, 45(12): 307–315.
- [5] Ye JH, 2024, Simulation of Control System for Direct-Drive Wind Turbine Generator Based on Simulink. *New Technology & New Products of China*, (23): 4–7.
- [6] Ma H, 2024, Simulation Research on Control Strategy of Grid-Side Converter in Permanent Magnet Direct-Drive Wind Power System. *Ningxia Electric Power*, (5): 13–19.
- [7] Chi XH, Yi H, Wang F, et al., 2024, Teaching Application of Speed Regulation Simulation System for Direct-Drive Permanent Magnet Synchronous Wind Turbine Generators — Taking the Course “Electric Drive and Automatic Control Systems” as an Example. *Industry and Information Technology Education*, (8): 46–50.
- [8] Pei J, Liu SL, Fan GD, 2019, Maximum Power Point Tracking Control of Permanent Magnet Direct-Drive Wind Turbine Generators Based on Fuzzy Control. *Journal of Sichuan University of Science & Engineering (Natural Science Edition)*, 32(6): 1–6.
- [9] Wang MD, He SX, Li XL, et al., 2021, Grey Prediction PI Control for Direct-Drive Permanent Magnet Synchronous Wind Turbine Generators. *Water Resources and Power*, 39(10): 165–168.
- [10] Kong SJ, 2021, Research on Control Methods of Wind Power Generation Systems, thesis, Liaoning University of Technology.

### Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.