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A Control Strategy to Permanent Magnet Direct-Drive Wind Power Generation System for Grid Connection

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Abstract

As a kind of clean, renewable energy, wind energy is integrated into the integrated energy system is one of the effective measures to solve the continuous depletion of primary energy, and it also meets the increasing energy saving and environmental protection needs. This paper researches the wind power generation system in an individual energy island system. It establishes a model for the wind power generation system directly driven by a permanent magnet by combining data and mechanism, including wind turbines, permanent magnet synchronous generators, and AC-DC-AC devices such as flow converters. Dual closed-loop control strategies are adopted on both the machine side and the network side of the model. The model's applicability and effectiveness have been verified under the Simulink simulation platform, and the research indicates that the simulation system model meets the grid-connected requirements.

Keywords

Integrated energy system; Wind power system; Converter control strategy; Grid-connected.

1. INTRODUCTION

To meet the increasing energy demand this century while reducing the environmental pollution caused by fossil fuels such as coal and petroleum, the demand for sustainable and environmentally friendly green energy is becoming more urgent. As a kind of clean energy that appeared in the mid and late last century, Wind energy has the advantages of safety, sustainability, low environmental pollution and even zero pollution. Wind power technology has become a key research direction in countries around the world. Although the installed capacity has been increasing in recent years, the seasonal climate significantly impacts wind power generation. Thus the wind turbines' air intake has large fluctuations, and the power generation is unstable provided by wind power and low wind power conversion rate. According to the survey, the conversion efficiency of wind turbine blades is between 25% and 40%. The conversion efficiency of generators is between 48% and 90%, and the conversion efficiency of converters is between 28% and 87%. Taken together, the efficiency of wind turbines is between 3.25% and 38.475%, which is far lower than the conversion efficiency of other forms of power generation [1]. Hence, it is necessary to conduct in-depth research on the conversion efficiency of wind power generation. In addition to improving the shape of wind turbine blades, continuous optimization of the converter control strategy can also improve power generation efficiency.

Many scholars have done a lot of research on the wind power generation system's converter control strategies. Zhang used adaptive internal model theory to analyze the wind turbine's speed control and designed an adaptive internal model speed controller to realize real-time

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control of the speed [2]. Zhang et al. proposed a PI control method based on a genetic algorithm to find the membership function's optimal solution in the fuzzy controller. They then applied the improved fuzzy PI controller to the dual closed-loop control, using the feedforward compensation of load current to improve the system's stability [3]. Wang and Jena et al. proposed the vector control strategy. Studies have shown that the double-loop control of the generator-side converter ensures maximum power point tracking. The double-loop control of the grid-side converter ensures the DC bus voltage stability and unity power factor output [4, 5]. Aicha et al. proposed a fuzzy logic PI control strategy based on traditional PI control. Compared with the traditional PI control, the improved FLC-PI control strategy can improve the system's dynamic performance and quickly track the maximum power point [6]. Reza et al. proposed a current predictive control model based on SVPWM. By controlling the active and reactive currents on the dq axis, the unit power factor can be connected to the grid. The system's dynamic performance can be maintained even when the wind speed changes greatly [7]. To solve flux linkage error and large torque ripple in the direct torque control strategy, Shi et al. proposed a variable flux direct torque control algorithm based on SVPWM technology. This algorithm flexibly changes the stator flux linkage amplitude according to the torque, which reduces the reactive component of the stator current and increases the motor's output power [8]. Nikzad introduced the duty cycle modulation method. The method could calculate the reference vector's duty cycle, realize the fixed switching frequency control, and effectively suppress the torque ripple. But this method needed to calculate the duty cycle at each step of the prediction, and the calculation was complicated [9]. The hybrid MPPT control strategy proposed by Sitharthan can effectively estimate the generator rotor position to achieve maximum power point tracking and increase the system's reliability and reduce the converter's power loss [10]. Xie et al. proposed a direct torque control scheme with a double closed-loop control structure of flux linkage and torque. Compared with the traditional DTC (direct torque control), the improved strategy can reduce torque ripple and keep the switching frequency constant. The motor's good dynamic performance can still be maintained in the low-speed range [11]. Based on the above documents, the research on the converter control strategy mainly focuses on two aspects. One is the torque control; the permanent magnet motor and the inverter are taken to improve the system's dynamic response. The second is that the zero d-axis current control strategy controls the generator's electromagnetic torque by maintaining the d-axis current at 0 and then controls the generator speed to obtain the maximum wind energy.

As a subsystem of the integrated energy system, the wind power generation system, the correctness of its model establishment and the control strategy's pros and cons have a greater impact on the entire system. Therefore, this paper adopts the method of combining mechanism with data and uses the Simulink platform to build the permanent magnet direct-drive wind power generation system. On this basis, improve the control strategy to improve the wind power generation efficiency and make the wind power generation system meet the grid connection requirements, laying a theoretical foundation for integrating the wind power generation system into the integrated energy system.

2. WIND POWER SYSTEM MODELING

The connection between the wind turbine and the generator in the permanent magnet direct driven wind power generation system does not require a gear-box, and the structure is simple. The permanent magnet synchronous generator is connected to the power conversion circuit and then merges into the power grid. The process can improve power generation efficiency and reduce the impact on the power grid. The main components of the wind power generation system are shown in Figure 1. There are wind turbines, permanent magnet synchronous generators (PMSG), AC/DC converter, DC circuit, DC/AC converter, and load.

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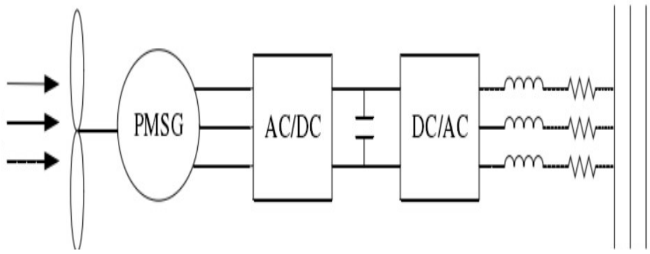

Figure 1. Wind power system

2.1. PMSG Modeling

The basic principle of the wind turbine's work is that air flows through the blades to generate thrust, which pushes the blades to rotate and converts wind energy into mechanical energy as aerodynamic torque. The fundamental relationship for the power captured by the blades is given by:

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

Where ρ is the air density, R is the radius of the blade, v is the wind speed, C_p is the wind energy utilization factor and is a nonlinear function of the tip speed ratio and the pitch angle [12]. The λ is the tip speed ratio, which is determined by:

$$\lambda = \frac{\omega R}{v} \tag{2}$$

The blade pitch angle β is always constant (β = 0), ω is the turbine's mechanical rotating speed. The output torque for the wind turbine is given by:

$$T_o = \frac{P_o}{\omega} \tag{3}$$

2.2. PMSG Modeling

The paper makes the following assumptions: the stator windings of the motor are entirely symmetrical; the air gap is evenly distributed; the magnetic circuit saturation, magnetic flux leakage, hysteresis and eddy current effects are ignored, and the damping winding on the rotor is ignored, taking the generator convention as the reference direction. According to the mathematical model of the permanent magnet synchronous generator in the dq axis coordinate system, the voltage and electromagnetic torque equations are obtained.

The dq axes voltages of PMSG can be expressed as follows:

$$\begin{aligned} u_{sd} &= R_s i_{sd} + L_d \frac{di_{sd}}{dt} - \omega_e L_q i_{sq} \\ u_{sq} &= R_s i_{sq} + L_d \frac{di_{sq}}{dt} + \omega_e L_q i_{sd} + \omega_e \psi_f \end{aligned} \tag{4}$$

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Where R_S is the stator resistance, ω_e is the electrical angular velocity of the generator rotor rotation, u_{sd} and u_{sq} are the d-q axis components of the PMSG stator voltage, i_{sd} and i_{sq} are the d-q axis components of the PMSG stator current, L_d and L_q are the inductances in the (d-q)-axis and ψ_f is the rotor magnetic flux produced by the generator.

The expression of the electromagnetic torque T_e is given by:

$$T_e = \frac{3}{2} n_p \left(\psi_f i_{sq} + \left(L_d - L_q \right) i_{sq} i_{sd} \right) \tag{5}$$

Where n_p is the number of pole pairs.

3. MPPT ALGOTITHM

Maximum power tracking technology means that the wind turbine can still capture the maximum wind energy speed under different wind speeds. As a critical part of wind power generation technology, its tracking characteristics are determined by the wind turbine, so different wind power generation systems have the same wind energy tracking thoughts.

The power signal feedback method is one of the maximum wind energy tracking strategies. Its control thought is to measure the wind turbine's rotation speed in real-time and then calculate the system's maximum output power corresponding to the rotation speed according to the wind turbine's maximum power characteristic curve. The difference between the maximum output power and the actual output power is used as the regulator's input signal. The regulator controls the wind turbine to realize the tracking of the maximum power point. The algorithm does not need to measure wind speed in real-time, eliminating the need for wind speed measurement devices, but it needs to know the wind turbine's maximum power curve at different wind speeds. But the maximum power curve is difficult to obtain. According to the analysis of the wind turbine's characteristics in the first section, the wind turbine's power curve and the torque curve are equivalent.

The expression of the mechanical power output by the wind turbine is given by:

$$P_o = 0.5 \rho \pi R^2 v^3 C_p(\lambda, \beta) = 0.5 \rho \pi R^2 \left(\frac{\omega R}{\lambda} \right)^3 C_p(\lambda, \beta) \tag{6}$$

Assuming that the best tip speed ratio of the wind turbine is λ_{opt}, then the optimal power of the wind turbine is expressed as follows:

$$P_{o-opt} = 0.5 \rho \pi R^2 \left(\frac{\omega R}{\lambda_{opt}} \right)^3 C_{p\max}(\lambda, \beta) = K_{opt} \omega^3 \tag{7}$$

According to formula (3), the best power curve can be converted into the best torque curve; the optimal torque is given by:

$$T_{o-opt} = \frac{P_{o-opt}}{\omega} = K_{opt} \omega^2 \tag{8}$$

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In motor control, the speed or power is generally not directly controlled, but the electromagnetic torque of the motor or the current that characterizes the electromagnetic torque is controlled. Therefore, it is convenient to control the generator's torque or current to achieve the wind turbine's maximum wind energy capture.

4. CONVENTER CONTROL STRATEGY

There is a crucial link in connecting wind power to the grid—the full power converter. The generator-side converter rectifies the electricity generated by the generator to the grid-side converter. The grid-side converter plays the role of inverter boosting and then integrates the electric energy into the grid.

4.1. Generator-side Converter Control

The generator-side converter's primary function is to rectify the variable frequency and amplitude alternating current from the generator into direct current and control the wind turbine speed to obtain the maximum wind energy[13]. Therefore, the control strategy of the generator-side converter usually adopts directional vector control.

After comparing the advantages and disadvantages of the zero d-axis current control, the unit power factor control method, and the maximum torque current ratio control method, the generator-side converter's control strategy in this paper selects the zero d-axis current control strategy, that is, the d-axis component of the stator current is always controlled to be zero during operation. Substitute $i_{sd} = 0$ into equation 5, the electromagnetic torque equation of generator is given by:

$$T_e = \frac{3}{2} n_p \psi_f i_{sq} \tag{9}$$

When the d-axis current is zero and n_p constant, the electromagnetic torque is related to the stator currents' q-axis component. The electromagnetic torque of the generator is a first-order linear function of the stator current. The electromagnetic torque is controlled by controlling the q-axis component of the stator current.

The steady-state voltage equation of PMSG in the dq coordinate system is given by:

$$\begin{aligned} u_{sd} &= R_s i_{sd} - \omega_e L_q i_{sq} \\ u_{sq} &= R_s i_{sq} + \omega_e L_q i_{sd} + \omega_e \psi_f \end{aligned} \tag{10}$$

From equation (10) we can know, tracking the reference current i_{sdref} and i_{sqref} by controlling the stator current i_{sd} and i_{sq} to achieve the control of the generator torque and speed, so the generator side adopts a double closed-loop to control. The outside is the speed loop, and the inside is the current loop. The control block diagram is shown in figure 2:

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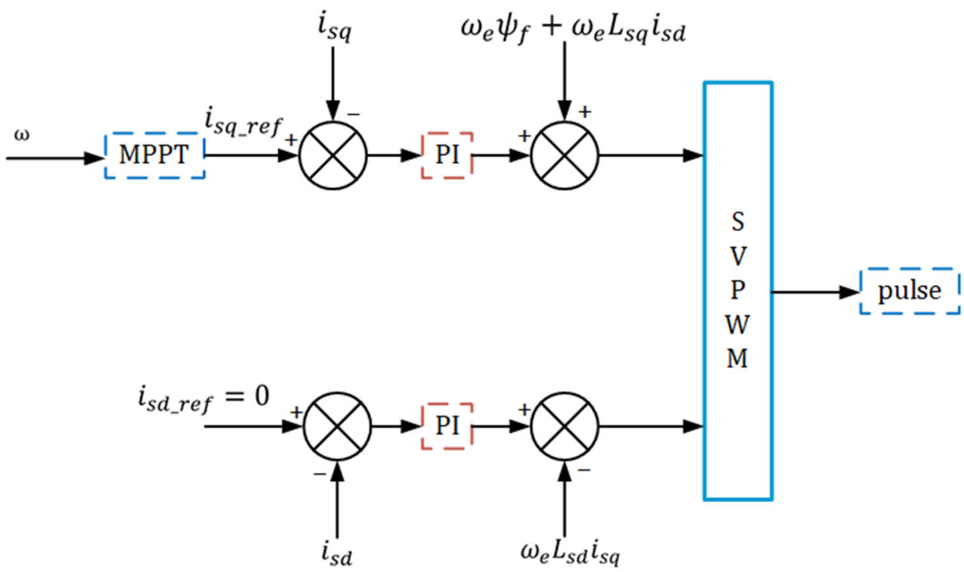

Figure 2. Control block diagram of generator-side converter

It can be seen from Figure 2 that the q-axis current reference value i_{sq_ref} is obtained according to the MPPT control strategy in the outer speed loop, and the difference between i_{sq_ref} and i_{sq} is used as the input signal of the PI regulator. At the same time, the feedforward decoupling is introduced to obtain the modulation voltage. According to the zero d-axis current control strategy, the current reference value of the d-axis is 0. Meanwhile, the modulation voltage is obtained after introducing the feedforward decoupling. Pass the obtained dq-axis modulation voltage through SVPWM to generate pulse signals to control the generator torque, and then control the generator's speed to capture the maximum wind energy.

4.2. Grid-side Converter Control

The grid-side converter's primary function is to stabilize the DC bus voltage and obtain good dynamic response performance, and to change the DC power into AC power so that the AC power meets the grid-connected requirements[14].

In this paper, the grid-side converter adopts the directional vector control based on the grid voltage, and the d-axis direction is the same as the grid voltage direction. The grid-side voltage q-axis component e_{gq} is zero. The active and reactive power equations of the grid in the dq coordinate system are given by:

$$\begin{aligned} P_g &= e_{gd} i_{gd} + e_{gq} i_{gq} = e_{gd} i_{gd} \\ Q_g &= e_{gd} i_{gq} - e_{gq} i_{gd} = -e_{gd} i_{gq} \end{aligned} \tag{11}$$

Where e_{gd} and e_{gq} are the d-q axis components of the grid voltage, i_{gd} and i_{gq} are the d-q axis components of the grid current.

It can be seen from equation (11) that the active and reactive power are related to the dq axis components of the grid current. Adjusting the active power can keep the DC bus voltage stable. Therefore, the grid-side converter control in this paper adopts dual closed-loop control. The outer loop is a voltage control loop, mainly used to stabilize the DC bus voltage; the inner loop is a current control loop that regulates the current output.

When the grid-side converter is in steady-state, the voltage control equation is given by:

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$$\begin{aligned} u_{gd} &= -R_g i_{sd} + \omega_g L_g i_{gq} + e_{gd} \\ u_{gq} &= -R_g i_{gq} - \omega_g L_g i_{gd} \end{aligned} \tag{12}$$

in equation (12), Lg is the inductance on the grid side, Rg is the resistance on the grid side, u_{gd} and u_{gq} are the d-q axis voltage components of the grid side converter, and ω_g is the grid synchronous electrical angular velocity.

In addition to being affected by u_{gd} and u_{gq}, i_{gd} and i_{gq} are coupled with each other through inductance. The i_{gd} is affected by the grid voltage e_{gd}, which is not conducive to the control of the current. Therefore, closed-loop regulation and control should be performed on i_{gd} and i_{gq} respectively, and coupling voltage $\omega_g L_q i_{gq} + e_{gd}$ and $-\omega_g L_q i_{gd}$ are compensated to obtain the dq axis control voltage. The control block diagram is shown in Figure 3:

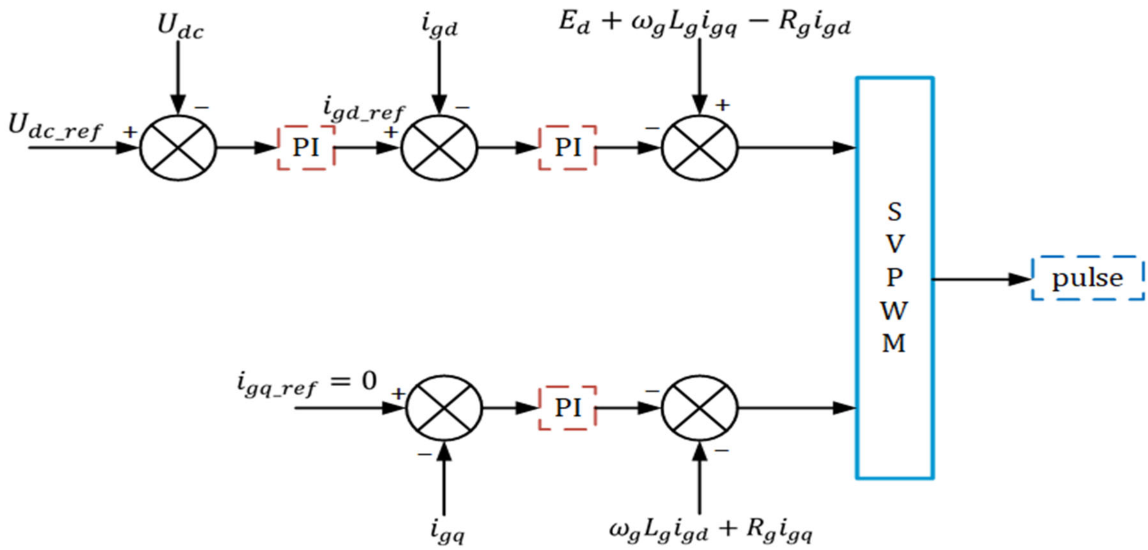

Figure 3. Control block diagram of grid-side converter

It can be seen from Figure 3 that in the voltage outer loop, the difference between U_{dc_ref} and U_{dc} is used as the input signal of the PI regulator, and the d-axis reference current i_{gd_ref} is obtained after PI adjustment. The dq axis current gets the control voltage through the PI regulator, and the compensation voltage is added to obtain the final dq axis control voltage. SVPWM modulation technology is used to generate pulse signals to control the switching devices' on and off and finally meet the grid connection requirements.

5. RESULT AND DISCUSSION

5.1. Generator-side Simulation Results and Discussion

According to the generator-side converter's control block diagram of the permanent magnet direct-drive wind power generation system, the wind power system's generator-side simulation model is built under the Simulink simulation platform. Figure 4 shows that the generator-side system includes the wind turbine model and the PMSG model, the generator-side converter model, DC-side capacitor, and the generator-side converter's control model.

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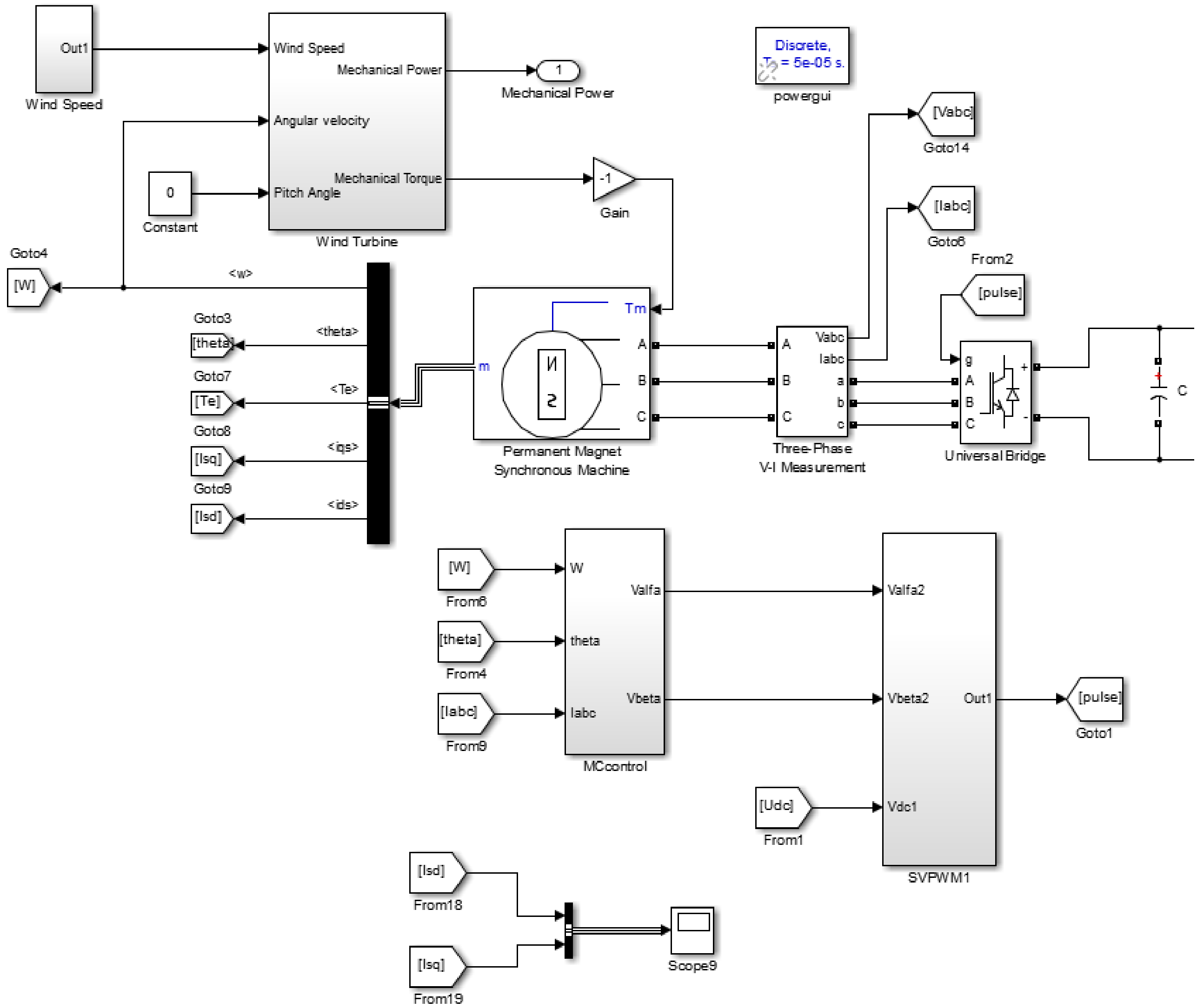

Figure 4. The simulation model of machine side

Table 1. Wind power system parameters

parameter	value	parameter	value
wind turbine radius	4 (m)	bitch angle	0°
air density	1.29 (kg/m3)	stator resistance	0.05 Ω
d-axis inductance	0.000635 H	q-axis inductance	0.000635 H
rotor flux	0.1 Wb	pole pairs	10
DC bus capacitance	0.0022 F	Bus reference voltage	650 V
grid-side resistance	0.1 Ω	Grid-side inductance	0.001 F

Referring to the company's data, the generator-side system's simulation parameters in this paper are shown in Table 1. According to the survey, the windy weather varies with the seasons in the company's area, with the most in spring and winter, followed by autumn, and least in summer. November to May of the next year is the period of high winds. April is the windiest, followed by March and November. Therefore, this paper selects a particular day in April as the wind turbine's input wind speed. The simulation time of the system is set to 1s. The wind turbine's input wind speed waveform is shown in Figure 5, including primary wind, gradual wind, and sudden wind. The primary wind has three parts: 0~0.2s, 0.4~0.6s and 0.6s~1s;

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0.2~0.4s is a gradual wind, and the wind speed changes from 8m/s to 10m/s; at 0.6s, the wind speed sudden changes from 10m/s to 12m/s.

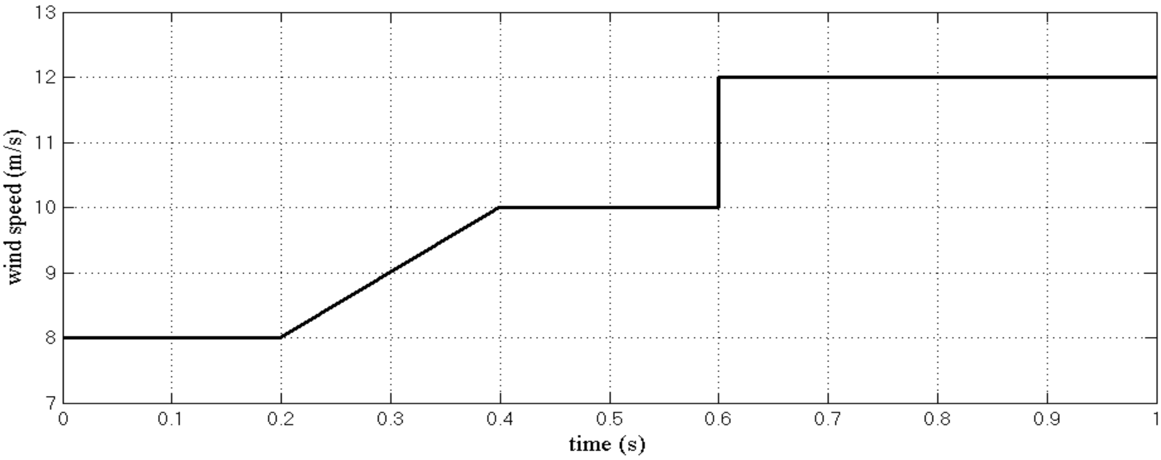

Figure 5. Wind speed waveform

Figures 6-9 are waveform diagrams of wind energy utilization coefficient, wind turbine output mechanical power, generator stator three-phase current and generator dq axis current under different wind speeds.

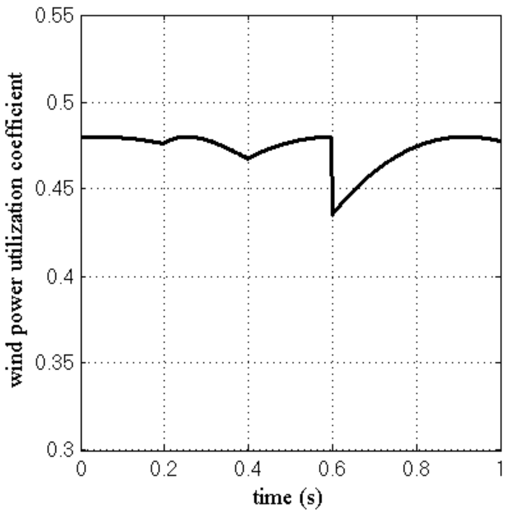

Figure 6. Wind performance coefficient

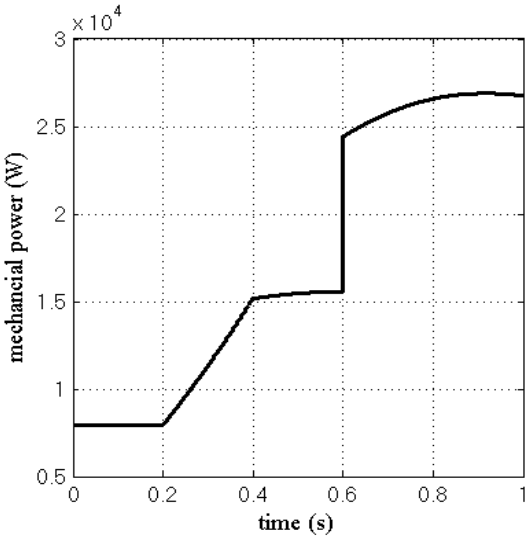

Figure 7. Mechanical power

It can be seen from Figure 5 and Figure 6 that when the wind speed changes, the MPPT control strategy can quickly adjust the wind turbine rotation speed. The wind energy utilization coefficient can quickly restore to the optimal value near 0.48, indicating that the generator-side MPPT control strategy can effectively track the maximum wind energy. It can be seen from Figure 7 that the wind turbine's mechanical power increases as the wind speed increases, and the changing trend of the two curves is the same.

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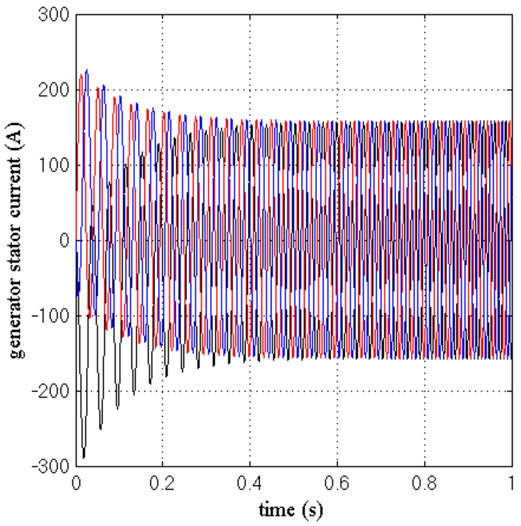

Figure 8. The generator stator current

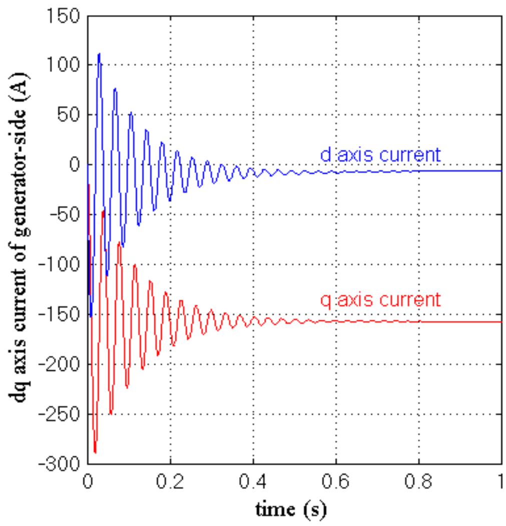

Figure 9. The dq axis current of generator-side

It can be seen from Figure 9 that when the wind speed is constantly changing, the d-axis current keeps approaching 0. After 0.5s, the d-axis component is 0, which shows the effectiveness of the generator-side control strategy selected in this paper.

5.2. Grid-side Simulation Results and Discussion

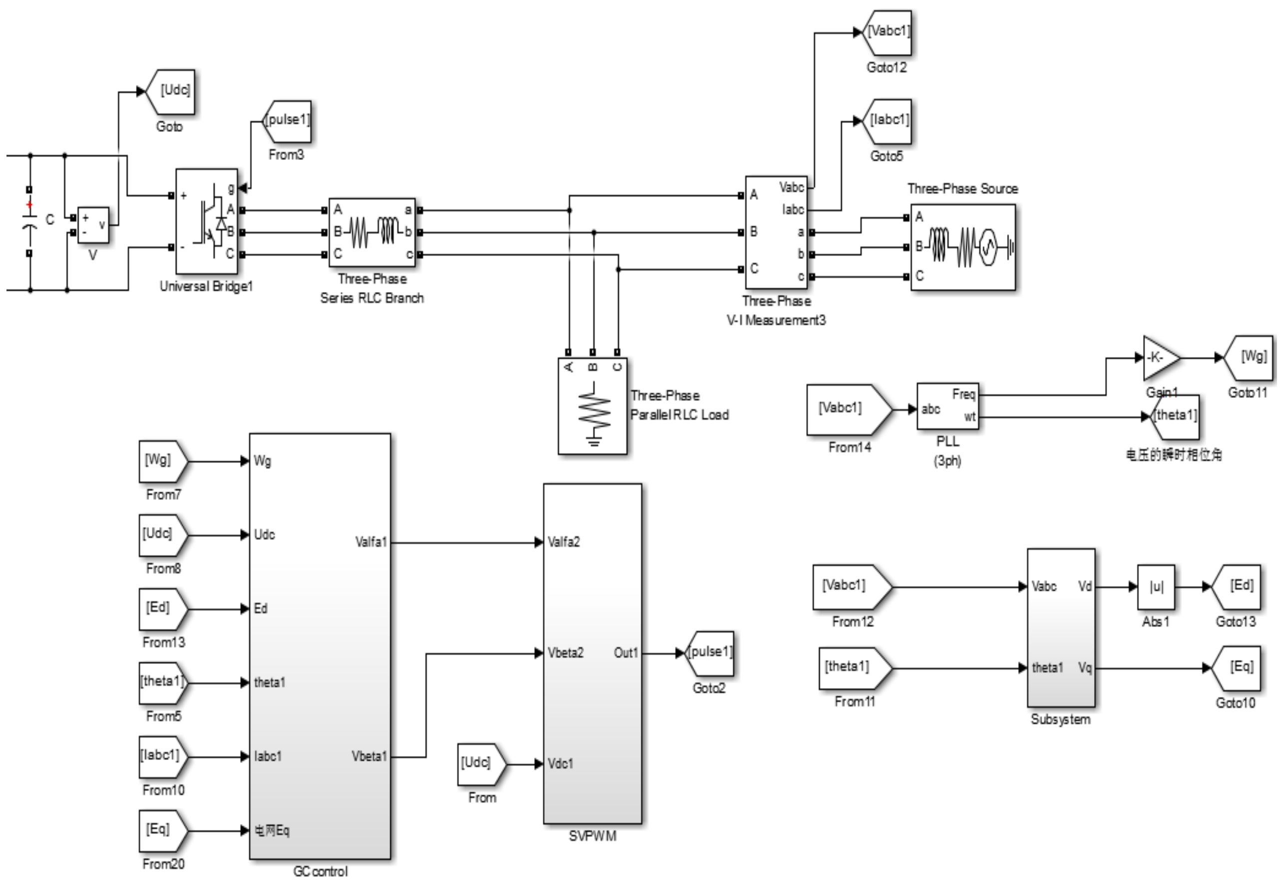

Figure.10 The simulation model of grid side

According to the control block diagram of the grid-side converter given above, the wind power system's grid-side model is built in the Simulink simulation environment. As shown in

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Figure 10, it mainly includes the grid-side rectifier, the DC-side capacitor, the control model of the grid-side converter and the PLL model.The relevant parameters of the network side system are shown in Table 1.

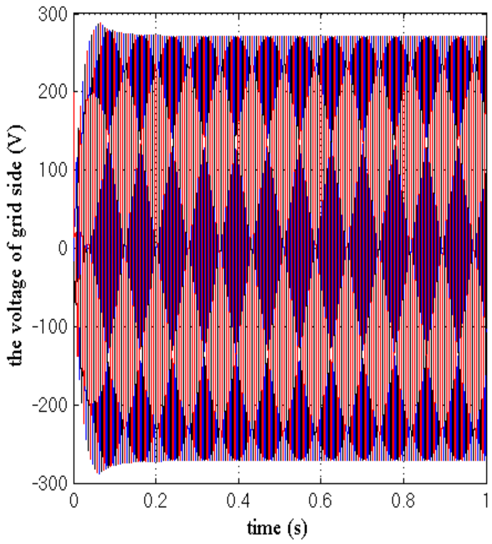

Figure 11(a). The voltage of grid side

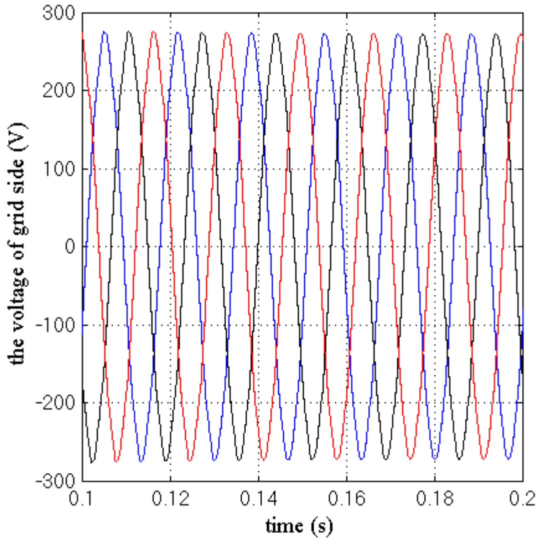

Figure 11(b). Partial enlarged view

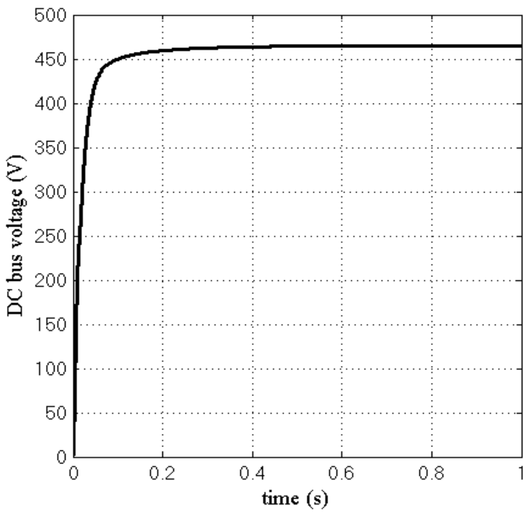

Figure 12. Dc bus voltage

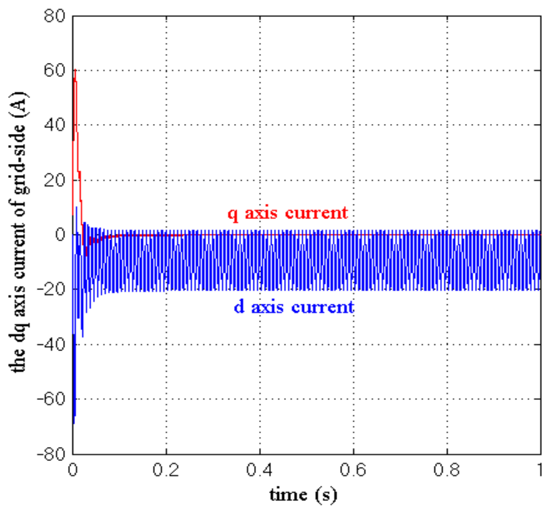

Figure 13. The dq axis current of grid side

It can be seen from Figure 12 that when the wind speed changes after 0.2s, the DC bus voltage remains unchanged. The directional vector control strategy based on grid voltage can effectively stabilize the DC bus voltage and improve the wind power system's stability.

The grid-side converter adopts the directional vector control strategy based on the grid voltage. The grid voltage vector direction is fixed on the rotating d-axis, and the grid voltage projection on the q-axis is zero; that is, the q-axis current is required to be maintained at zero. It can be seen from Figure 13 that the grid-side q-axis current is maintained near 0, which verifies the effectiveness of the grid-side control strategy selected in this paper.

The above simulation results show that the initially planned wind power system in the energy island system can meet the grid connection requirements and provide complements to the

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traditional power generation system in the energy island, thereby realizing the efficient use of multiple energy.

6. CONCLUSION

This paper adopts the method of combining mechanism with data. The author uses the Simulink simulation platform to build the permanent magnet direct driven wind power generation system based on the enterprise's data and designs the converter's control strategy. The simulation model results show that the model built in this paper and the generator-side and grid-side control strategies adopted can ensure the simulation system's stable operation and obtain simulation results that meet the grid connection requirements.

Although the effectiveness of the simulation system and control strategy established in this paper has been verified, due to the lack of field operation data, there are still two disadvantages:

(1) The simulation system in this paper is verified through a simulation platform based on theoretical analysis and has not been verified by actual field operation. Therefore, this paper's results can only provide a theoretical reference for the existing wind power system's operation.

(2) The purpose of this study is to provide theoretical guidance for the grid connection of the wind power system in the integrated energy system. Therefore, the focus is on controlling the converters on both sides of the system to ensure the power generation capacity and output power stability of the wind power system, failing to consider complicated control systems such as pitch control and yaw control.

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