

Article

Adaptive Virtual Synchronous Generator Control Strategy Based on Frequency Integral Compensation

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Abstract: With the increasing proportion of power electronic equipment in the power system, improving the inertia and damping characteristics of the system through virtual synchronous generator (VSG) control technology has become a hot research topic. In terms of adjusting the output frequency, traditional primary frequency modulation control cannot ensure that the output frequency is maintained within the safe operating range when the load disturbance is large, so secondary frequency modulation with the integral link is usually adopted. However, the fixed integral coefficient cannot solve the contradiction between system regulation time and frequency oscillation. In this paper, a strategy of coordinated adaptive control based on the integral coefficient, moment of inertia, and damping coefficient is proposed. According to the offset of frequency and the change rate of the frequency offset, the value of parameters is determined, and the specific parameter setting method is determined. Finally, the correctness of the proposed control strategy is verified on a simulation platform and a semi-physical experimental platform.

Keywords: virtual synchronous generator; secondary frequency modulation; adaptive control; parameter tuning



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1. Introduction

Renewable energy has the characteristics of low emission, environmental protection, and green, and thus plays an important role in solving the energy crisis and environmental pollution [1,2]. With the steady growth of the installed capacity and proportion of renewable energy in the power system, the trend of power electronics in the power system is becoming more and more significant. This change puts forward new requirements for the stability and operation characteristics of the power system. Aiming at the characteristics of low inertia and small damping of power electronic equipment [3], VSG control technology came into being [4]. The VSG is a control strategy to improve the stability of the power grid by simulating the operation characteristics of the synchronous generator so that the inverter has the rotational inertia, damping characteristics, and droop characteristics of the synchronous generator [5,6].

The stability of VSG output active power is mainly related to the stability of the output frequency [7]. Therefore, improving the stability and dynamic response performance of the VSG output frequency is of great significance in improving the stability of the converter network [8]. In terms of frequency control, Ref. [9] proposed using the root locus method to adjust the VSG control parameters. Ref. [10] proposed combining the DC side energy storage state of charge to adjust the control parameters and improve the utilization of energy storage. In [11], an adaptive control strategy was developed according to the frequency change rate in the dynamic adjustment process. The control methods proposed in the above literature can improve the frequency response characteristics of the VSG. However, these methods can only ensure that the VSG output frequency is dynamically adjusted in a small range when the external load changes. When the system suddenly switches to a heavy

load, the VSG output frequency will drop or rise to a safe frequency range. When the load works outside the safe frequency range for a long time, it will cause serious adverse effects on the equipment and even damage the equipment. Therefore, the secondary frequency regulation control of the VSG is of great significance in improving the safety and reliability of the power system.

In terms of frequency secondary regulation, Ref. [12] proposed a VSG secondary frequency regulation control strategy based on transient derivative polarity segmentation optimization. Different integral coefficients (k) were used in the falling and rising sections of the frequency, which greatly improved the stability of the system and reduced the dynamic adjustment time of the frequency. However, because of the use of two different integral coefficients in the rising and falling sections of the frequency, the system was impacted at the moment of the integral coefficient switching, and the equipment requirements were higher in practical applications. Ref. [13] proposed an adaptive control strategy based on moment of inertia (J) and damping coefficient (D). The values of the moment of inertia and damping coefficient were dynamically adjusted according to the change in VSG output frequency. Compared with the control strategy of fixed parameters, the proposed method improved the dynamic response time of frequency and the fluctuation value of frequency. However, this method does not take into account that the dynamic adjustment of the integral coefficient can also improve the frequency response characteristics of the system.

In this paper, considering the shortcomings of [12,13], the advantages of the control strategies proposed in the two references are combined. According to the influence of the moment of inertia, damping coefficient, and integral coefficient on the dynamic response of frequency, the k - J - D adaptive control strategy is proposed. According to the offset of frequency and the change rate of the frequency offset, the values of the moment of inertia, damping coefficient, and integral coefficient are dynamically adjusted, and the variation range of each parameter is determined so that the parameter variation is always kept within a reasonable range. Compared with the traditional J - D adaptive control strategy based on the moment of inertia and damping coefficient, the proposed control strategy has a better control effect in terms of frequency adjustment time and maximum frequency offset. The VSG model is built on the MATLAB/Simulink 2022b simulation platform to verify the correctness of the control strategy. Finally, the adaptive control strategy proposed in this paper is verified by a semi-physical experimental platform.

2. The Basic Principle of VSG

Figure 1 is a simplified model of a synchronous generator, where i_a , i_b , and i_c are three-phase stator currents, θ is the rotation angle of the rotor relative to the stator A-phase winding, and r , L are the resistance and inductance of the stator winding.

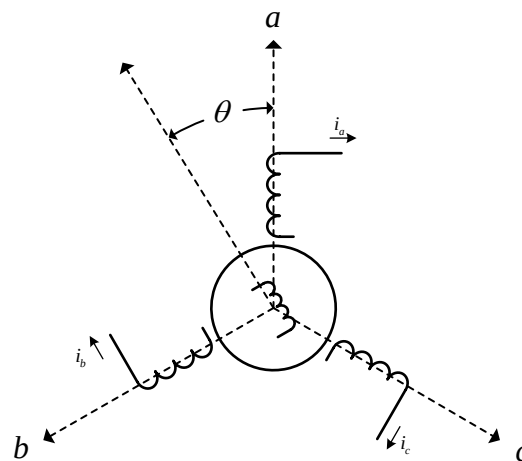


Figure 1. Synchronous generator model diagram.

Figure 2 is the equivalent circuit diagram of the synchronous generator, where e is the back electromotive force generated by the rotor on the stator and v is the port voltage of the synchronous generator.

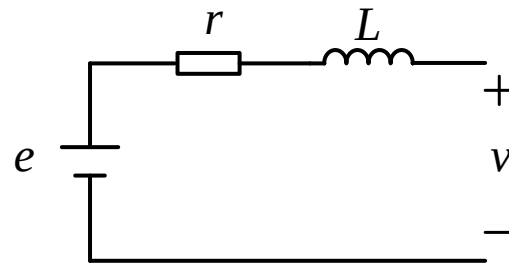


Figure 2. Equivalent circuit of a synchronous generator.

According to the equivalent circuit of the synchronous generator, the voltage equation of the synchronous generator port can be obtained by the Kirchhoff laws as follows [14]:

$$L \frac{di}{dt} + ri + v - e = 0 \quad (1)$$

According to the synchronous generator model diagram shown in Figure 1, the synchronous generator rotor motion equation is as follows:

$$J \frac{d\omega}{dt} = T_m - T_e - D(\omega - \omega_0) \quad (2)$$

where J is the moment of inertia, ω is the rotation angle frequency, T_m is the mechanical torque, T_e is the electromagnetic torque, D is the damping coefficient, and ω_0 is the reference rotation angle frequency [15].

In general, the synchronous generator generally adopts the droop control method to adjust the output power and frequency. The active power frequency droop control of the synchronous generator is as follows:

$$P_m = P_{ref} + K_p(\omega_0 - \omega) \quad (3)$$

where P_{ref} is the reference active power and K_p is the frequency droop coefficient.

The synchronous generator generally adopts the combination of droop control and excitation regulation to adjust the output voltage. The reactive power voltage droop control of the synchronous generator is as follows:

$$\Delta E_Q = K_q(Q_{ref} - Q_e) \quad (4)$$

where θ_1 , ΔE_Q is the voltage difference of droop control, K_q is the voltage droop coefficient, Q_{ref} is the reference reactive power, and Q_e is the output reactive power of the synchronous generator.

The excitation regulation of synchronous generator is as follows:

$$\Delta E_U = K_u(U_s - U_0) \quad (5)$$

where ΔE_U is the voltage difference of excitation regulation, K_u is the excitation regulation coefficient, U_s is the output voltage of synchronous generator, and U_0 is the reference output voltage of synchronous generator [16].

Then, the total excitation electromotive force of the synchronous generator can be expressed as follows:

$$E = E_0 + \Delta E_Q + \Delta E_U \quad (6)$$

where E_0 is the reference excitation electromotive force.

When the inverter is controlled, the VSG control block diagram shown in Figure 3 can be obtained by simulating the above synchronous generator rotor motion equation, stator voltage equation, and active and reactive droop control equation.

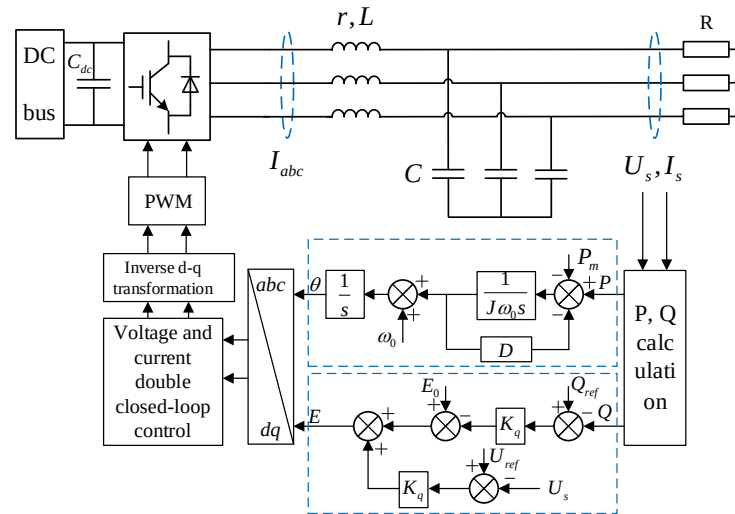


Figure 3. Virtual synchronous generator control block diagram.

3. VSG Frequency Modulation Principle

The input power of the inverter is used to replace the mechanical power of the synchronous generator, the output power P of the inverter is used to replace the electromagnetic power P_e of the synchronous generator, and the angular frequency of the output voltage of the inverter is used to replace the angular frequency of the generator rotor. At the same time, the relationship between mechanical torque, electromagnetic torque, mechanical power, and electromagnetic power is approximately expressed as follows [17]:

$$\begin{cases} P_m = \omega_0 T_m \\ P_e = \omega_0 T_e \end{cases} \quad (7)$$

According to Formula (3), the VSG active frequency control equation can be obtained as follows:

$$J \frac{d\omega}{dt} = \frac{P_m}{\omega_0} - \frac{P}{\omega_0} - D(\omega - \omega_0) \quad (8)$$

Figure 4 shows the corresponding active control block diagram.

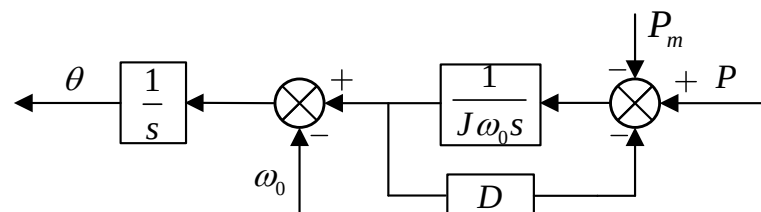


Figure 4. Active frequency control block diagram.

The deformation of Formula (8) can be obtained as follows:

$$J\omega_0 \frac{d\omega}{dt} = P_m - P - D\omega_0(\omega - \omega_0) \quad (9)$$

$$J\omega_0 \frac{d(\omega - \omega_0)}{dt} = P_m - P - D\omega_0(\omega - \omega_0) \quad (10)$$

The Laplace transform of Formula (10) can be obtained as follows:

$$J\omega_0(\omega - \omega_0)s = P_m - P - D\omega_0(\omega - \omega_0) \quad (11)$$

Bringing Formula (3) into Formula (11), we can obtain the following:

$$J\omega_0(\omega - \omega_0)s = P_{ref} + K_p(\omega_0 - \omega) - \frac{P - D\omega_0(\omega - \omega_0)}{P - P_{ref}} \quad (12)$$

The relationship between the frequency variation and the active power variation obtained by Formula (12) is as follows:

$$\frac{\omega - \omega_0}{P - P_{ref}} = \frac{-1}{J\omega_0s + K_p + D\omega_0} \quad (13)$$

Therefore, under off-grid conditions, VSG control is a droop control with inertia. When the load power is disturbed, the VSG output frequency will fluctuate. When the load power rises or falls, the VSG output frequency will change accordingly, and the output frequency will eventually reach stability.

The traditional VSG control is differential control. When the load changes, the frequency will not return to the rated value. Therefore, it is necessary to add a frequency integral compensation link to the active control link to compensate for the difference in output frequency.

The active frequency control equation after adding the integral link is as follows:

$$J\omega_0 \frac{d\omega}{dt} = P_{ref} + K_p(\omega_0 - \omega) - P - D\omega_0(\omega - \omega_0) + k \int (\omega_0 - \omega) dt \quad (14)$$

where k is the integral coefficient.

The relationship between the frequency variation and the active power variation is as follows:

$$\frac{\omega - \omega_0}{P - P_{ref}} = - \frac{s}{J\omega_0s^2 + (K_p + D\omega_0)s + k} \quad (15)$$

Figure 5 shows the active power control block diagram after adding the integral link.

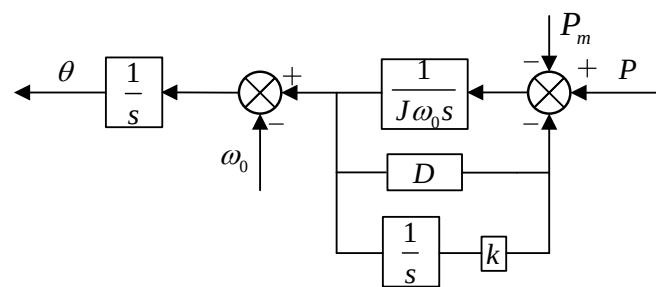


Figure 5. Active power control block diagram with frequency integral.

According to Formula (15), the characteristic equation corresponding to the frequency response transfer function can be obtained as follows:

$$J\omega_0s^2 + (K_p + D\omega_0)s + k = 0 \quad (16)$$

The corresponding natural oscillation angular frequency and damping ratio are as follows:

$$\begin{cases} \omega_n = \sqrt{\frac{k}{J\omega_0}} \\ \zeta = \frac{K_p + D\omega_0}{2\sqrt{J\omega_0k}} \end{cases} \quad (17)$$

$$\begin{cases} \sigma\% = e^{-\pi\zeta/\sqrt{1-\zeta^2}} \times 100\% \\ t_s = \frac{4}{\zeta\omega_n} \end{cases} \quad (18)$$

where ω_n is the natural oscillation angular frequency, ζ is the damping ratio, σ is the overshoot, and t_s is the adjustment time.

Formula (18) indicates that the dynamic response process of the output frequency of the synchronous generator is affected by the following three parameters: J , D , and k . Figure 6 shows the influence of different J , D , and k values on the characteristic root distribution of the characteristic equation.

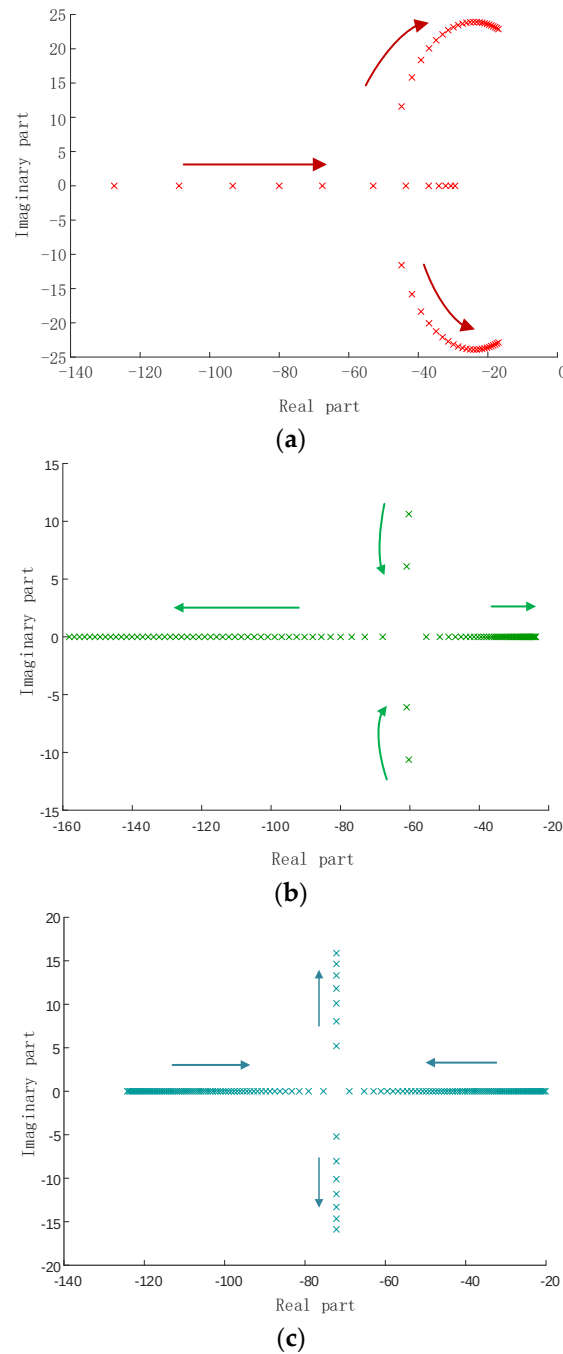


Figure 6. Effects of parameters on the distribution of eigenvalues. (a) The influence of J on the distribution of characteristic roots. (b) The influence of D on the distribution of characteristic roots. (c) The influence of k on the distribution of characteristic roots.

It can be seen in Figure 6a that as the moment of inertia J increases, the frequency response of the system decelerates, and the stability of the system increases. It can be seen in Figure 6b that when the damping coefficient D increases, the frequency response of the system slows down, and the stability of the system increases. It can be seen in Figure 6c that when the integral coefficient k increases, the frequency response of the system accelerates, and the stability of the system increases.

4. VSG Secondary Frequency Modulation Control Strategy

The specific influence of the J , D , and k parameters on the frequency response is analyzed as follows:

It can be seen in Figure 7a that as the moment of inertia J increases, the frequency response of the system decelerates, and the stability of the system increases. It can be seen in Figure 7b that when the damping coefficient D increases, the frequency response of the system slows down, and the stability of the system increases. It can be seen in Figure 7c that when the integral coefficient k increases, the frequency response of the system accelerates, and the stability of the system increases. However, when the integral coefficient is too large, the system will overshoot, which is not conducive to the stability of the system.

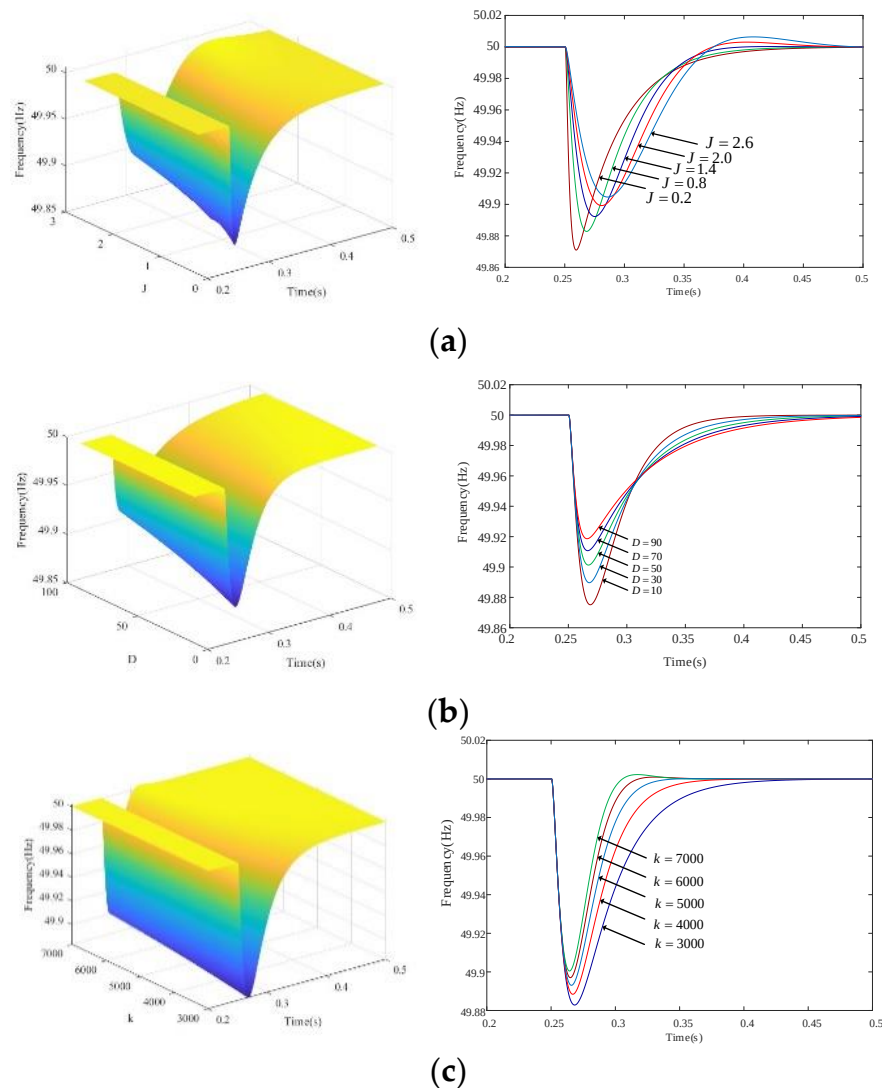


Figure 7. Effect of parameters on the frequency response. (a) The influence of J on frequency response. (b) The influence of D on frequency response. (c) The influence of k on frequency response.

The influences of the parameters on system performances are analyzed in Figures 6 and 7, which provide a reference for the adaptive adjustment of parameters. Therefore, this paper proposes a parameter adaptive control method to improve the performance of the system frequency response by dynamically adjusting the J , D , and k parameters.

Considering the size of the frequency deviation and the rate of change in the frequency deviation, this paper proposes the following adaptive control strategy:

$$\begin{aligned} k &= k_0 + a(b - |\Delta\omega|) \\ J &= \begin{cases} J_0, & 0 < \frac{d|\Delta\omega|}{dt} \leq \varepsilon_1 \cup \frac{d|\Delta\omega|}{dt} \leq \varepsilon_2 \\ J_0 + c \frac{d|\Delta\omega|}{dt} + m|\Delta\omega|, & \frac{d|\Delta\omega|}{dt} > \varepsilon_1 \\ J_0 + n \frac{d|\Delta\omega|}{dt}, & \varepsilon_2 < \frac{d|\Delta\omega|}{dt} < 0 \end{cases} \\ D &= \begin{cases} D_0, & |\Delta\omega| \leq \varepsilon_3 \\ D_0 + f|\Delta\omega| + g \frac{d|\Delta\omega|}{dt}, & \frac{d|\Delta\omega|}{dt} < 0 \\ D_0 + h|\Delta\omega|, & |\Delta\omega| > \varepsilon_3 \cup \frac{d|\Delta\omega|}{dt} \geq 0 \end{cases} \end{aligned} \quad (19)$$

The control strategy is explained as follows. In Figure 7, in the frequency recovery stage, the smaller the frequency deviation, the slower the frequency change rate, and the longer the adjustment time. Therefore, when the frequency deviation is large, we take a smaller k value, and when the frequency deviation is small, we take a larger k value. When the change rate of the frequency deviation is large, the value of J is increased, and the change in the frequency is reduced. Similarly, when the frequency deviation increases and the deviation exceeds a certain threshold, the value of D increases. When the deviation decreases, the value of D is appropriately reduced according to the frequency deviation and the deviation change rate.

5. Parameter Tuning

(1) Determination of J_0 , D_0 , and k_0 :

The moment of inertia J_0 is determined by the inertia time constant and rated capacity of the synchronous generator [18].

$$J_0 = \frac{S_n H}{\omega_0^2} \quad (20)$$

where H is the inertial time constant and S_n is the rated capacity.

The damping coefficient D_0 is determined by the unit frequency drop during primary frequency modulation. When the frequency is stable during primary frequency modulation, it can be obtained from Formula (12) as follows:

$$0 = P_{ref} + K_p(\omega_0 - \omega) - P - D\omega_0(\omega - \omega_0) \quad (21)$$

$$D = \frac{P_{ref} - P + K_p(\omega_0 - \omega)}{\omega_0(\omega - \omega_0)} \quad (22)$$

When the primary frequency is set, when the load changes by 20 kW, the frequency changes by 0.87 Hz, so the value of D_0 is determined.

According to reference [11], the frequency integral coefficient corresponds to the damping ratio of the second-order system in the range of 0.1~0.3. According to Formula (17), k satisfies the following conditions:

$$\begin{cases} \zeta = \frac{K_p + D\omega_0}{2\sqrt{J\omega_0 k}} \\ 0.1 \leq \zeta \leq 0.3 \end{cases} \quad (23)$$

The value of k_0 is determined by considering the parameters such as the VSG capacity.

(2) The determination of the adaptive adjustment coefficient (a, b, c, m, n, f, g, h):

According to Formula (23), the value range of the integral coefficient k can be obtained as follows:

$$\frac{\left(\frac{K_p + D\omega_0}{0.6}\right)^2}{J\omega_0} \leq k \leq \frac{\left(\frac{K_p + D\omega_0}{0.2}\right)^2}{J\omega_0} \quad (24)$$

Then, the value ranges of a and b are as follows:

$$\frac{\left(\frac{K_p + D\omega_0}{0.6}\right)^2}{J\omega_0} - k_0 + a|\Delta\omega|_{\max} \leq ab \leq \frac{\left(\frac{K_p + D\omega_0}{0.2}\right)^2}{J\omega_0} - k_0 \quad (25)$$

where $|\Delta\omega|_{\max}$ is the maximum value of the angular frequency difference, and the specific values of a and b are determined by considering the dynamic response process of the system.

Referring to the Luwen University VSG control scheme, the $J_{\max}$ value is as follows [19]:

$$J_{\max} = \frac{P_{\max}}{\max\left\{\omega \frac{d\omega}{dt}\right\}} \quad (26)$$

In the process of dynamic adjustment, the value ranges of J are as follows:

$$\frac{S_n H}{\omega_0^2} \leq J \leq \frac{P_{\max}}{\max\left\{\omega \frac{d\omega}{dt}\right\}} \quad (27)$$

In order to avoid frequency overshoot in the dynamic response process, the second-order system is generally set to work in the underdamped state of $0.8 \leq \zeta \leq 1$ [20]. According to Formula (17), the range of the damping coefficient D can be determined as follows:

$$\frac{1.6\sqrt{J\omega_0 k} - K_p}{\omega_0} \leq D \leq \frac{2\sqrt{J\omega_0 k} - K_p}{\omega_0} \quad (28)$$

According to Formula (14), the second-order differential equation of $\Delta\omega$ can be obtained as follows:

$$J\omega_0 \frac{d^2\Delta\omega}{dt^2} + k\Delta\omega + K_p + D\omega_0 = 0 \quad (29)$$

Combined with the value range and Formula (29) of the moment of inertia and the damping coefficient, the specific values of parameters c , m , n , f , g , and h can be selected.

(3) The determination of threshold ε_1 , ε_2 , and ε_3 :

The microgrid operation standard of the VSG is set as follows:

$$\begin{cases} \frac{d|\Delta\omega|}{dt} \leq K_1 \\ \Delta\omega \leq K_2 \end{cases} \quad (30)$$

The values of K_1 and K_2 are determined according to the specific microgrid standards.

The values of ε_1 , ε_2 , and ε_3 are determined according to the operation standard of the power grid and the numerical changes in $d|\Delta\omega|/dt$ and $\Delta\omega$.

$$\begin{cases} \varepsilon_1 = 15 \\ \varepsilon_2 = -15 \\ \varepsilon_3 = 0.1 \end{cases} \quad (31)$$

6. Simulation Construction

In order to verify the correctness of the control strategy proposed in this paper, a 70 KVA capacity VSG off-grid model is established in MATLAB/Simulink 2022b. In this model, only the active frequency change under the condition of pure resistive load is considered. When the load is set to 0.15 s, the active load increases from 35 kW to 70 kW, and the VSG output frequency change curves under the traditional primary frequency modulation and J - D adaptive control and the k - J - D adaptive control strategy proposed in this paper are collected. The simulation parameter setting is shown in Table 1. The specific frequency output waveform is shown in Figure 8.

Table 1. Simulation parameter setting.

Parameter	Mark	Value
DC bus voltage	U_{dc}	700 V
Inductance	L	0.001 H
Inductor resistance r	r	0.001 Ω
Capacitance	C	4.7 μ F
Resistive load	P_{load}	35 kW
Active-frequency droop coefficient	K_p	30,000
Steady-state integral coefficient	k_0	3000
Steady-state moment of inertia	J_0	0.8 $\text{Kg}\cdot\text{m}^2$
Steady-state damping coefficient	D_0	20 $\text{N}\cdot\text{m}\cdot\text{s}\cdot\text{rad}^{-1}$
Reference output voltage	U_0	311 V
Reference rotation angle frequency	ω_0	314 rad/s

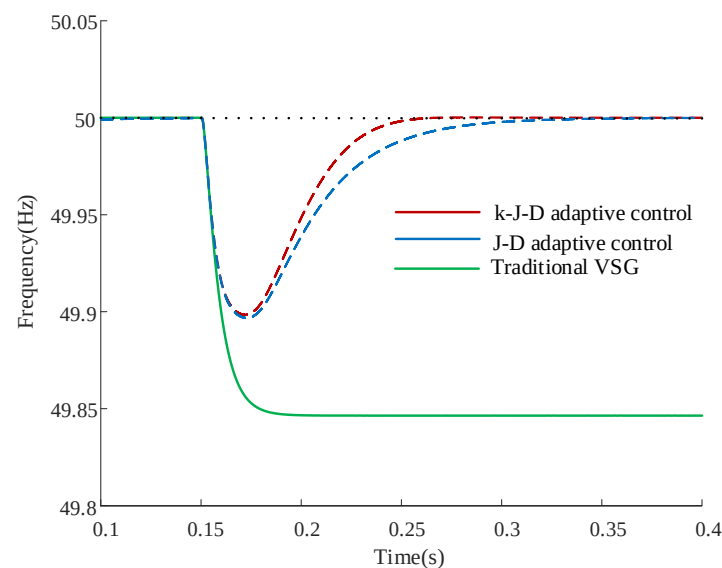


Figure 8. Frequency variation with load variation.

Based on Figure 8, it can be concluded that when the active load is doubled, the VSG output frequency decreases from 50 Hz to 49.84 Hz under the traditional primary frequency modulation, and the decline time is close to 0.03 s. The traditional primary frequency modulation control increases the inertia of the system. Under the action of J - D adaptive control, after the output frequency drops to the lowest frequency of 49.89 Hz, the frequency rises to 50 Hz under the action of the integral link, and the adjustment time is 0.2 s. Under the action of k - J - D adaptive control, the lowest point of the output frequency drop is 49.9 Hz, and the adjustment time is 0.1 s. In terms of increasing inertia and reducing frequency drop, k - J - D adaptive control is better than J - D adaptive control.

In order to verify that the output frequency of the VSG under the control strategy proposed in this paper still has better dynamic response characteristics when the load is

reduced, a periodic load is applied to the VSG, and the load is increased by 35 kW at 0.15 s. At 0.6 s, the increased load is removed, and the frequency change is observed at this time.

In the simulation process, the change in the integral coefficient k is shown in Figure 9a, and the integral coefficient is within a reasonable range. The change in the moment of inertia J is shown in Figure 9b. J only changes when the frequency deviation exceeds the threshold, which reduces the number of dynamic adjustments of parameters, and all parameters are in the correct range of change. As shown in Figure 9c, when the load increases, the damping coefficient D increases according to the adaptive strategy, and when the load decreases, D decreases accordingly. Each parameter changes within the set range, which verifies the correctness of the threshold setting of the control strategy proposed in this paper.

The output frequency variation waveform is shown in Figure 10. When the disturbance is removed, the frequency gradually increases from 49.84 Hz to 50 Hz under the traditional primary frequency modulation control. In terms of maximum frequency offset and adjustment time, the effect of the k - J - D adaptive control proposed in this paper is better than that of traditional J - D adaptive control, which verifies the correctness of the adaptive control strategy proposed in this paper and the improvement effect in the process of frequency secondary regulation.

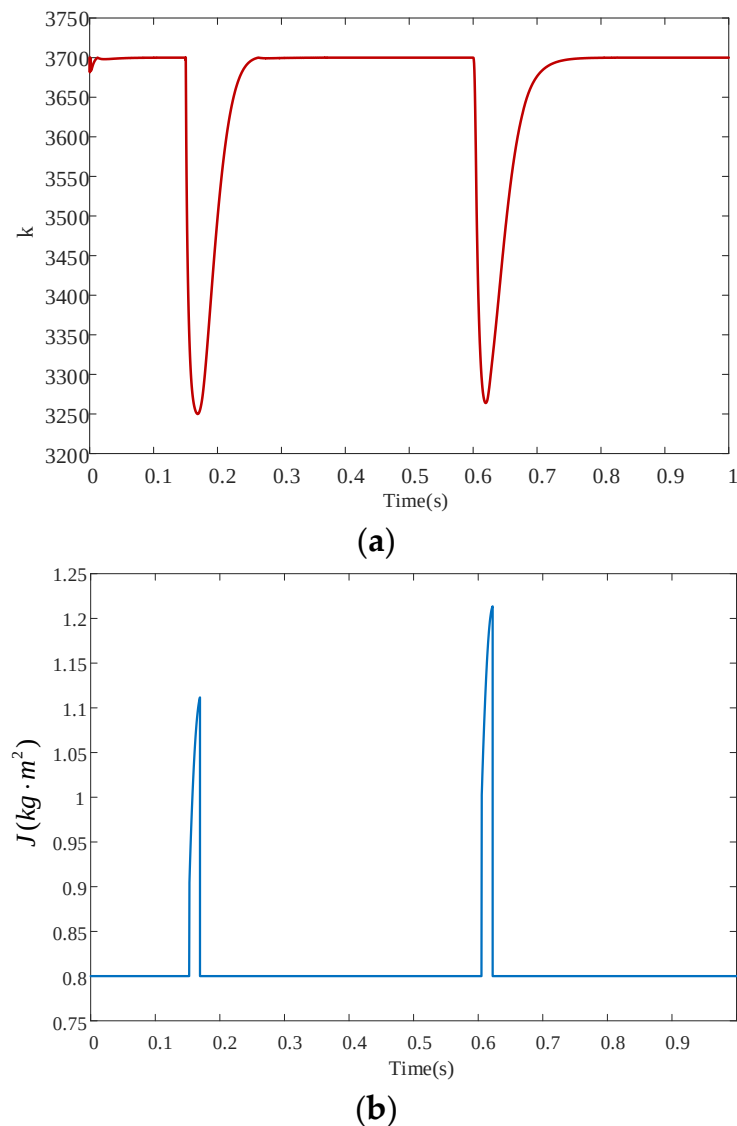


Figure 9. Cont.

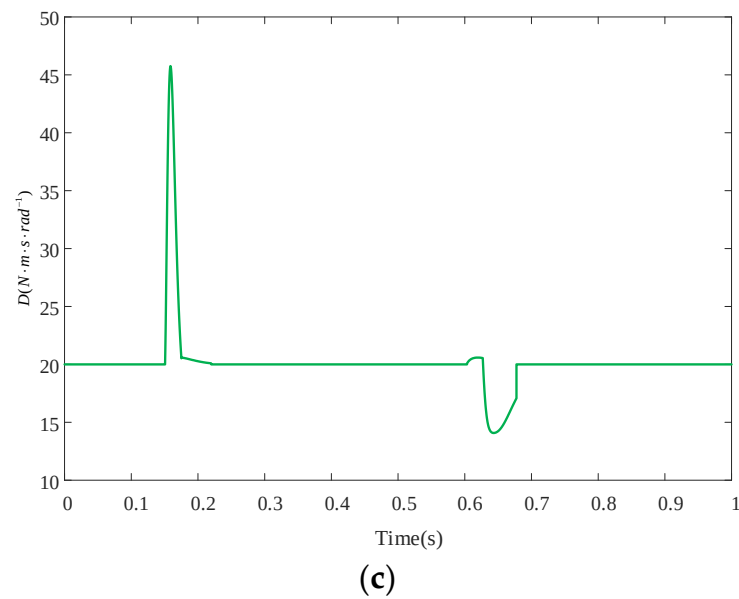


Figure 9. Coefficient variation diagram. (a) Integral coefficient k change diagram. (b) Variation diagram of the moment of inertia J . (c) Damping coefficient D variation diagram.

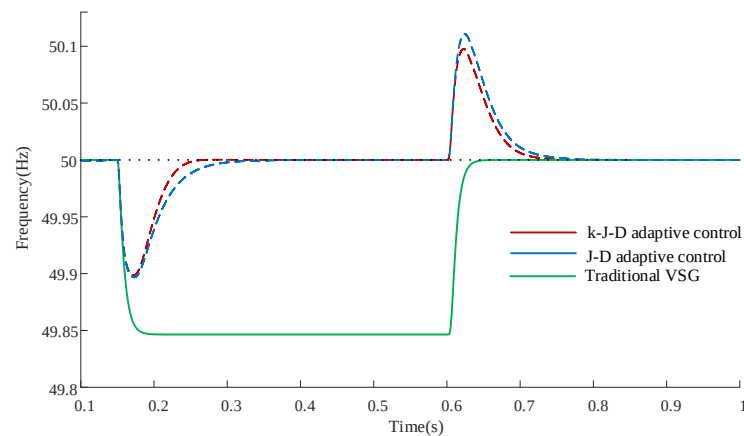


Figure 10. Frequency change during periodic load disturbance.

7. Experimental Verification

In this paper, the hardware-in-the-loop simulation platform shown in Figure 11 is used to verify the hardware-in-the-loop experiment. MicroBox is a power electronic real-time simulator based on FPGA architecture, and CBox is a rapid prototyping controller. In the simulation system, the MicroBox real-time simulator acts as the controlled object, and the CBox rapid prototyping controller acts as the control object. The built experimental model is deployed into MicroBox and CBox through the upper computer DeskSim software 2023. At the same time, MicroBox and CBox interact with each other through the physical hardware box. All communications are connected through Ethernet ports and network cables. CBox collects the analog signal from MicroBox in real time, and MicroBox collects the digital signal from CBox in real time. The whole simulation system forms a closed loop. In this paper, the power supply and load in the experimental process are realized by model building, and the real-time data waveform parameter monitoring and management are carried out by the host computer Desksim software.

The experimental parameters are consistent with the simulation parameters. The fixed load is set to 35 kW, and the load disturbance of 35 kW is added to observe the changing waveform of output active power and frequency.

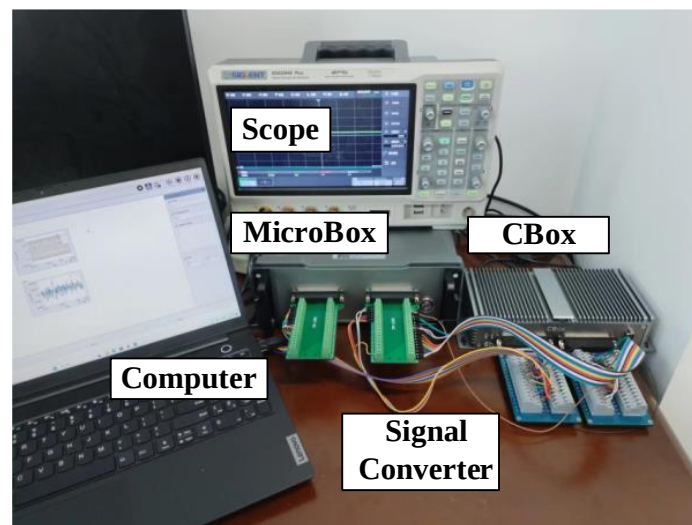


Figure 11. Semi-physical simulation platform diagram.

Figure 12 shows the output waveform diagram of the k - J - D adaptive control strategy proposed in this paper. Figure 12a shows the change diagram of the output active power when the load disturbance is applied. After the disturbance is applied, the output power increases from 35 kW to 70 kW. Figure 12b shows the overall frequency change diagram under load disturbance. Under the action of the integral link, the frequency can be restored to 50 Hz. Figure 12c shows a local amplification diagram of frequency change, 9.6 s of load disturbance, 10.3 frequency recovery of 50 Hz, and dynamic adjustment time of 0.7 s. Figure 12d shows an enlarged figure when the frequency decreases, and it can be seen that the frequency change has a certain inertia. Figure 13 shows the frequency change diagram of traditional J - D adaptive control. In the frequency change amplification diagram in Figure 13b, it can be seen that the dynamic adjustment time of the traditional J - D adaptive control frequency is 0.9 s. Figure 14 shows the frequency change diagram of primary frequency modulation. Because of various losses in the experimental process and the limitation of the experimental sampling step size, the experimental results have certain errors, and the experimental output waveform fluctuates. At the same time, the output frequency is lower than the simulation output result, and the decrease value is within the error range.

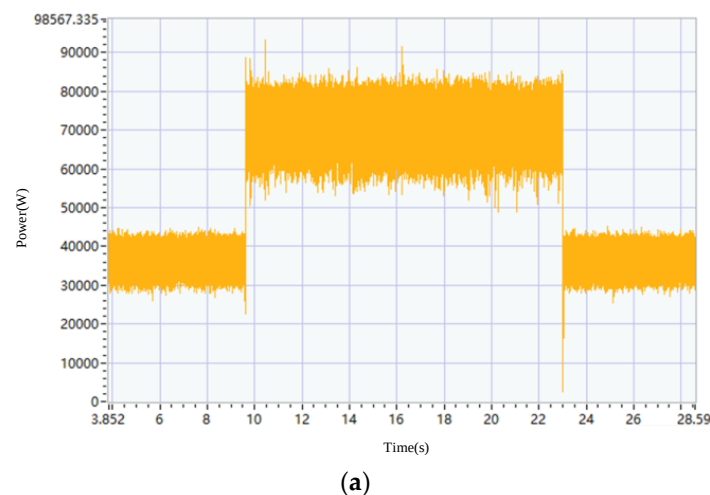


Figure 12. Cont.

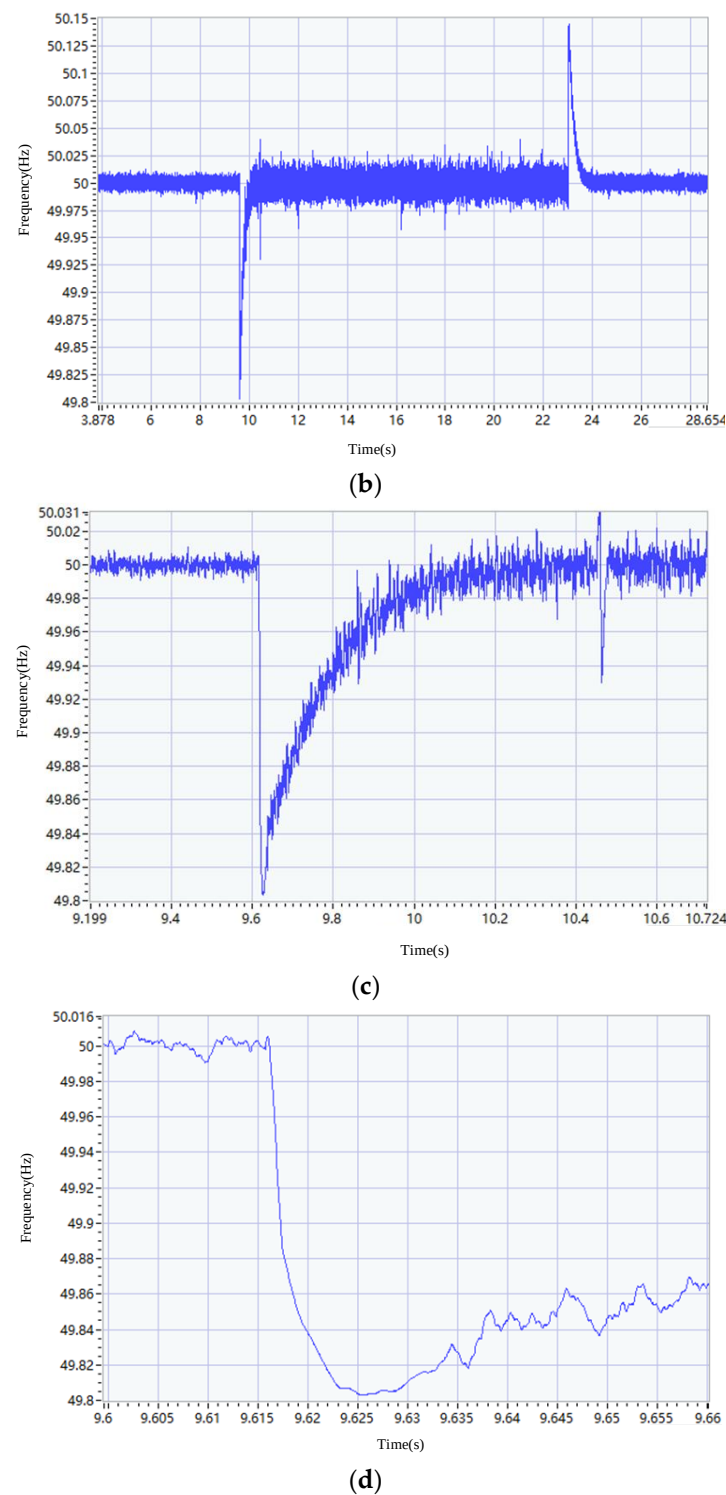


Figure 12. Power and frequency diagram. (a) Power change diagram. (b) Frequency overall figure. (c) Frequency local graph. (d) Frequency drop process diagram.

Through comparative analysis, it can be concluded that under the same load disturbance, the frequency dynamic adjustment effect of the k - J - D adaptive control strategy proposed in this paper is better than that of the traditional J - D adaptive control strategy, which verifies the correctness of the control strategy proposed in this paper.

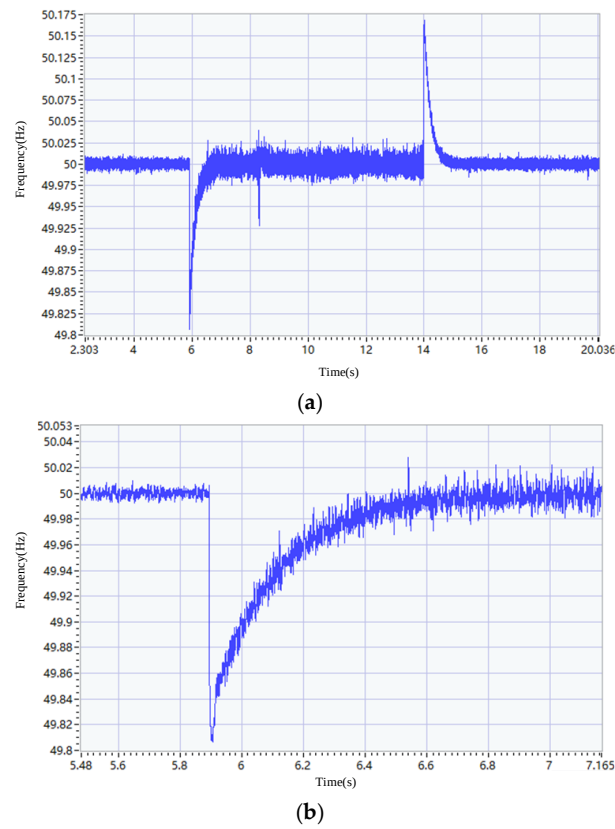


Figure 13. Frequency diagram. (a) Frequency overall figure. (b) Frequency local graph.

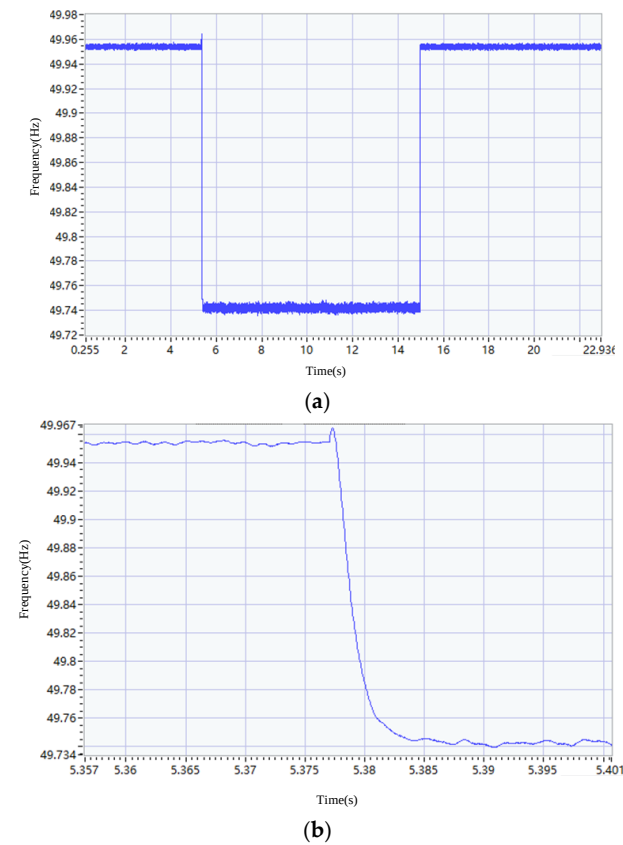


Figure 14. Frequency diagram. (a) Frequency overall figure. (b) Frequency local graph.

8. Conclusions

In this paper, an adaptive control method based on the integral coefficient, the moment of inertia, and damping coefficient parameters is proposed. The values of each parameter are determined according to the change in the frequency offset, and the dynamic response of the VSG secondary frequency modulation process is improved. Through simulation and experimental verification, the k - J - D adaptive control strategy proposed in this paper is shown to accelerate the frequency adjustment time by 22.22%. Under the same disturbance adjustment, the frequency variation is slightly shortened. The adjustment effect is better than the control effect of the traditional J - D adaptive control strategy, which provides a new idea for improving the performance of VSG secondary frequency modulation.

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