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SECOND-ORDER-CONSENSUS-BASED ADAPTIVE COOPERATIVE CONTROL OF VSGS FOR AC MICROGRIDS

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Abstract. *This article introduces an adaptive cooperative control strategy for virtual synchronous generators (VSGs) based on second-order-consensus, specifically tailored for parallel inverters within microgrids. Firstly, considering the second-order oscillation characteristics of the rotor motion equation, a second-order consensus term is introduced for frequency control, which improves the consistency of frequency response. At the same time, considering the different capacities of inverters, a consensus algorithm for active power is introduced, so that each VSG can output active power according to the ratio of capacity. Furthermore, considering the different parameter settings among multiple VSGs, utilizing information exchange to adjust virtual inertia and damping in real time, which results in better transient response of the microgrid system. Ultimately, simulation and experimental results substantiate the efficacy of the proposed control strategy, affirming its capability to enhance the stability of microgrid systems.*
Keywords: Second-order-consensus, Virtual synchronous generator, Multi-agents, Adaptive cooperative control, Microgrids

1. **Introduction.** In response to the increasingly serious energy crisis, countries around the world are vigorously developing clean energy sources such as photovoltaics and wind energy. In this context, clean energy sources such as photovoltaics and wind power with dispersed distribution characteristics have been widely developed [1]. At the same time, microgrid technology has emerged. A microgrid is a small power supply network that integrates distributed power sources such as wind power generation and photovoltaics, energy storage systems, local loads, and protection and control devices [2]. At present, there has been relatively in-depth research on microgrids [3, 4]. However, distributed generation introduces a large number of power electronic devices, reducing the inertia of the large grid, which affects the stable operation of the power system. For this reason, some scholars have proposed the virtual synchronous generator (VSG) control technology [5]. The VSG technology introduces virtual inertia and damping into the microgrids,

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alleviating the oscillation problem caused by power electronic devices, which is similar to the characteristics of synchronous machines [6, 7].

At present, many scholars at home and abroad have conducted theoretical research, simulation, and experiments on the principles and control strategies of VSG in different aspects. In order to alleviate the impact of active power under high inertia condition, an improved virtual inertia strategy is proposed in [8]. This control strategy cascades the differential link to the first-order virtual inertia forward channel, which effectively maintains the steady-state characteristics of active power. In order to have more degrees of freedom to consider when designing controllers, a fractional order VSG is proposed in [9]. In order to improve the power output capability of inverters and suppress power fluctuations, a power decoupling method based on virtual inductors and virtual capacitors is proposed in [10]. [11] proposes an extended virtual synchronous generator, while using H_∞ robust control to search for optimal parameters for the virtual controller, resulting in stronger robustness of the system frequency. However, these studies only considered the case of a single VSG, and there are usually multiple inverters in microgrids.

For multiple VSGs, [12] proposes an additional damping strategy to suppress power oscillations, and designs a damping strategy through acceleration control with disturbance compensation. However, it did not consider the impact of the key parameter of virtual inertia on oscillations. [13] proposes a compensation line impedance voltage drop control strategy, which plays a key role in improving voltage consistency when multiple distributed generators operate in parallel. On this basis, it also incorporates virtual negative impedance control to achieve power decoupling, but it does not consider information exchange between virtual synchronous machines. In order to suppress oscillations caused by the coupling effect of virtual inertia and damping coefficient, [14] analyzes in detail the relationship between the two parameters and frequency/power, and proposes a collaborative control strategy. At the same time, it designs a dynamic frequency performance quantitative evaluation method based on 2-norm H_2, but it does not achieve secondary frequency control. In [15], a small signal model with multiple VSGs in parallel is established, and the dynamic characteristics are analyzed. On this basis, a collaborative control strategy that achieves consistent output frequency of each VSG through information exchange is proposed, greatly alleviating the problem of system power and frequency oscillation. [16] proposes a multi-VSG coordinated control strategy based on residual indicators and chaotic differential evolution particle swarm optimization algorithm. On the one hand, residual indicators are used to select the optimal installation position, and on the other hand, chaotic differential evolution particle swarm optimization algorithm is used to comprehensively coordinate the parameters of the multi damping controller. However, it also does not have situations where the inverter capacity is different. In order to minimize information exchange between systems as much as possible, a decentralized control for non-error frequency regulation is proposed in [17]. Although this control strategy has the advantage of not relying on communication, the consistency of frequency response has not been described. [18] proposes an adaptive secondary frequency regulation strategy based on VSG for microgrid systems containing multiple distributed energy sources, taking into account the characteristics of each distributed energy source. However, it does not consider the coupling relationship and mutual influence between VSGs with different parameters.

In practical engineering applications, micro-grid systems contain more than one inverter, and the parameters of the inverter and line impedance are different. When VSG control is applied to the coordinated control of multiple inverters, different parameters can cause inconsistent frequency response, and in severe cases, it can lead to system frequency collapse, affecting the stability of the power grid. In addition, when one or several VSGs cannot output active power according to a specific allocation strategy, it will inevitably cause chaos in the active power output of other VSGs, which will seriously affect the power stability of the system. Based on the above analysis, it can be concluded that the coordinated control direction of multiple inverters still has significant research significance. Therefore, this article proposes an adaptive cooperative control based on second-order-consensus for VSGs with different parameters. The main contributions of this article are as follows:

1) The second-order consistency strategy in multi-agent systems is introduced into the rotor motion equation, which alleviates the problem of inconsistent response speed of inverters;

2) In order to cope with the frequency drop caused by droop control, a frequency control term for local VSG has been introduced, ensuring that the frequency can be quickly adjusted to its rated value;

3) Based on the communication between VSGs, an adaptive cooperative controller considering virtual inertia and damping characteristics is designed, which ensures better transient response of VSGs operating in parallel.

The structure of this article is as follows. In Section 2, the model and structural diagram of the virtual synchronous generator are introduced. In addition, this section also introduces directed graph theory and second-order-consensus theory. In Section 3, an adaptive cooperative controller based on second-order-consensus is designed. Section 4 establishes a simulation model containing three VSGs in Simulink, and the simulation results demonstrate the superiority of the proposed control algorithm. Section 5 presents the results of hardware in the loop (HIL) experiments, further demonstrating the feasibility of applying the proposed control algorithm in practical engineering. Some conclusions are written in Section 6.

The meanings of the main notations used in this article are shown in Table 1.

Table 1. Nomenclature

Notation	Physical meaning	Notation	Physical meaning
U_{dc}	DC voltage	P_e	Electromagnetic power
R	Filter resistor	P_m	Mechanical power
L	Filter inductance	P_{ref}	Active power reference value
C	Filter capacitor	Q_{ref}	Reactive power reference value
I_{Labc}	Inductor current	Q_e	Reactive power
U_{Cabc}	Capacitive current	U_n	Rated voltage
Z_l	Line impedance	ω_n	Rated angular frequency
I_{oabc}	Output terminal current	J	Virtual inertia
U_{oabc}	Output terminal voltage	D	Virtual damping
PCC	Point of common coupling	θ	Electrical angle

2. Basic Theory.

2.1. Model and structural diagram of VSG.

The VSG has introduced virtual inertia and damping into microgrids containing a large number of power electronic devices, which greatly alleviates oscillation problems [19, 20, 21]. Figure 1 shows a simplified block diagram of a microgrid using VSG control. The rotor motion equation of VSG is as follows [22, 23]:

$$\begin{cases} J_i\omega_i\dfrac{d\omega_i}{dt} = (P_{mi} - P_{ei}) - D_i(\omega_i - \omega_n) \\ \dfrac{d\theta_i}{dt} = \omega_i \end{cases} \tag{1}$$

where J_i and D_i are the virtual inertia and damping of VSG$_i$, respectively; ω_i and ω_n represent the rated values of angular velocity and angular velocity, respectively; θ_i is the power angle of VSG$_i$. P_{mi} and P_{ei} are the mechanical power and electromagnetic power of VSG$_i$. P_{mi} can be obtained from the following equation:

$$P_{mi} = P_{i,ref} + K_f(\omega_n - \omega_i) \tag{2}$$

where $P_{i,ref}$ is a reference power that can be manually set, and K_f is the droop coefficient.

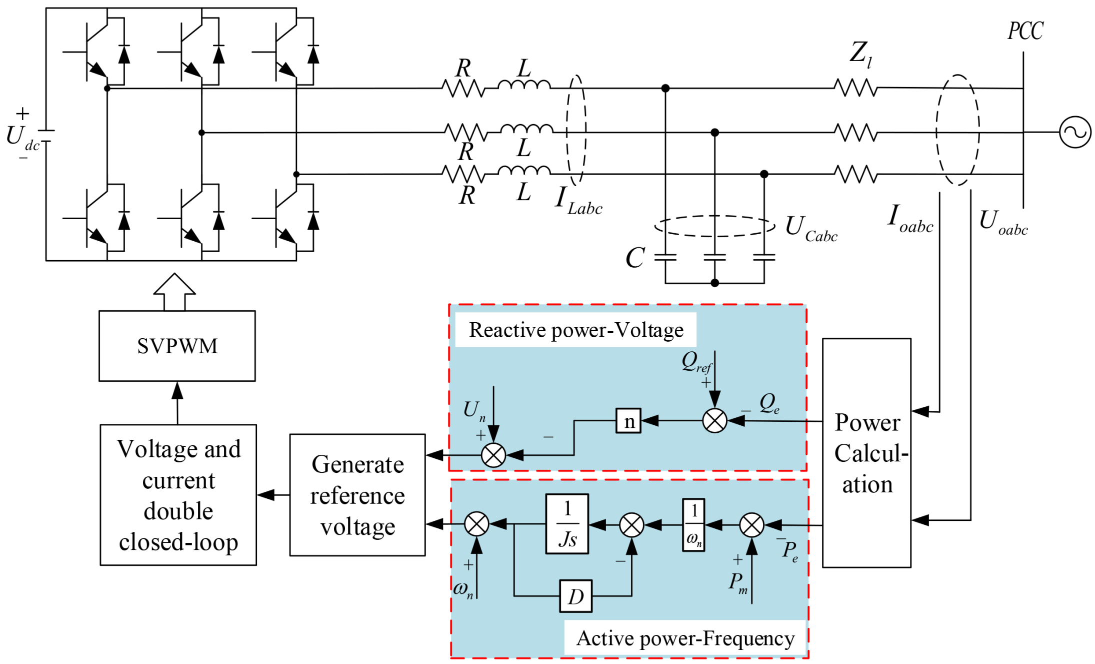

FIGURE 1. Structural diagram of VSG

2.2. **Graph theory.** In order to better describe the collaborative control between multiple VSGs, this section introduces multi-agent theory firstly [24, 25, 26]. A graph $G = (V, \hbar, A)$ is defined, where $V = (v_1, v_2, \ldots, v_n)$ represents the set of nodes (agents), $\hbar \subseteq V \times V$ is the set of edges, and $A = [a_{ij}]_{n\times n}$ represents the adjacency matrix which describes the information transmission state between adjacent agents. If the i-th agent can receive information from the j-th agent, that is $(v_j, v_i) \in \hbar$, then $a_{ij} = 1$. Otherwise, $a_{ij} = 0$. By definition, $a_{ii} = 0$ is always established. After the previous analysis, the Laplacian matrix is summarized as follows:

$$L = [l_{ij}]_{n\times n} = D - A \tag{3}$$

where $D = diag(d_1, d_2, \ldots, d_n)$, and $d_i = \sum_{j=1}^{n} a_{ij}$ is the in-degree of agent i.

In multi-agent systems, the most fundamental control problem is the consistency problem [27]. Considering that the rotor motion equation is a second-order system, the following second-order consensus algorithm is introduced:

$$\dot{\chi}_i = -k_i \sum_{j\in N_i} a_{ij}[((\chi_i - \chi_j) + \alpha_1(\dot{\chi}_i - \dot{\chi}_j)) - h_i((\chi_i - \chi_{ref}) + \alpha_2(\dot{\chi}_i - \dot{\chi}_{ref}))] \tag{4}$$

where α_1 and α_2 are the coefficients, h_i is the weight coefficient between χ_i and χ_{ref}, and $h_i > 0$. Under ideal conditions, χ_i and $\dot{\chi}_i$ will converge to χ_{ref} and $\dot{\chi}_{ref}$, respectively.

According to Equation (1), VSG is a second-order system. When we adopt VSG control for the inverter, its second-order oscillation characteristics and the difference in response speed caused by different inverter parameters have a significant impact on the frequency and active power stability of the system. On this basis, it is reasonable to introduce second-order consistency theory into VSG control to improve the consistency of frequency response speed and suppress active power fluctuations. The following will analyze the controller proposed in this article.

3. Proposed Second-Order-Consensus-Based Adaptive Cooperative Control Strategy.

3.1. Second-order-consensus-based VSG control.

When the load changes, the active power and frequency of the system will oscillate due to the second-order oscillation characteristics of the rotor motion equation.

$$J_i \frac{d\omega_i}{dt} = T_{mi} - T_{ei} - D_i(\omega_i - \omega_n) + \psi_i \tag{5}$$

$$\dot{\psi}_i = -h_i(\omega_i - \omega_n) - k_{\omega i} \sum_{j \in N_i} a_{ij}(\Delta\omega_{ij} + \alpha_{\omega i}\Delta\dot{\omega}_{ij}) - k_{Pi} \sum_{j \in N_i} a_{ij}\Delta P_{ij} \tag{6}$$

where $\Delta\omega_{ij} = \omega_i - \omega_j$, $\Delta\dot{\omega}_{ij} = \dot{\omega}_i - \dot{\omega}_j$, $\Delta P_{ij} = \frac{P_{i,ref}}{D_i} - \frac{P_{j,ref}}{D_j}$. $k_{\omega i} \sum_{j \in N_i} a_{ij}(\Delta\omega_{ij} + \alpha_{\omega i}\Delta\dot{\omega}_{ij})$ is a specially designed frequency control term for VSG, which greatly improves the consistency of frequency response in microgrids containing multiple VSGs. $k_{\omega i}$ and $\alpha_{\omega i}$ are both controller coefficients. $k_{Pi} \sum_{j \in N_i} a_{ij}\Delta P_{ij}$ is a specially designed active power control term for VSG, which guarantees the proportional active power sharing of VSGs. k_{Pi} is the coefficient of active power control.

After Laplace transform, we can obtain

$$\Delta\omega_i = \frac{s\left[(P_{i,ref} - P_{ei}) - k_{\omega i}\sum_{j \in N_i} a_{ij}\alpha_{\omega i}\Delta\omega_{ij} - k_{Pi}\sum_{j \in N_i} a_{ij}\Delta P_{ij}\right] - k_{\omega i}\sum_{j \in N_i} a_{ij}\Delta\omega_{ij}}{J_i\omega_n s^2 + (D_i\omega_n + K_f)s + h_i} \tag{7}$$

Then, through the Final value theorem, the conclusion of non-zero control can be drawn as follows:

$$\lim_{t \to \infty} \Delta\omega_i = \lim_{s \to 0} s\Delta\omega_i = 0 \tag{8}$$

It can be seen that adding $-h_i(\omega_i - \omega_n)$ to traditional VSG control can achieve frequency error free control.

3.2. Cooperative analysis of virtual inertia and damping.

According to the rotor motion equation, the virtual inertia J and damping D of VSG have a direct impact on its power and frequency stability [28]. As the value of J increases, the rate of change of frequency (RoCoF) during the transient process gradually decreases and the overshoot gradually increases, which means that the response speed becomes slower. Conversely, smaller system inertia ensures rapid response but elevates the RoCoF during substantial disturbances, compromising system stability and reliability. In terms of virtual damping, as the value of D increases, the frequency deviation and overshoot both become smaller. However, excessive damping introduces instability. On the contrary, lower damping maintains the stability of the system, but at the cost of increasing frequency deviation and response time. Therefore, considering the characteristics of virtual inertia and damping comprehensively, the technical parameters of the virtual synchronous machine are designed.

Due to the different parameters of each VSG in the microgrid, this paper utilizes the information exchange between adjacent VSGs to achieve cooperative control of parallel VSGs. Figure 2 shows the frequency oscillation process of two VSGs disturbed by system disturbances.

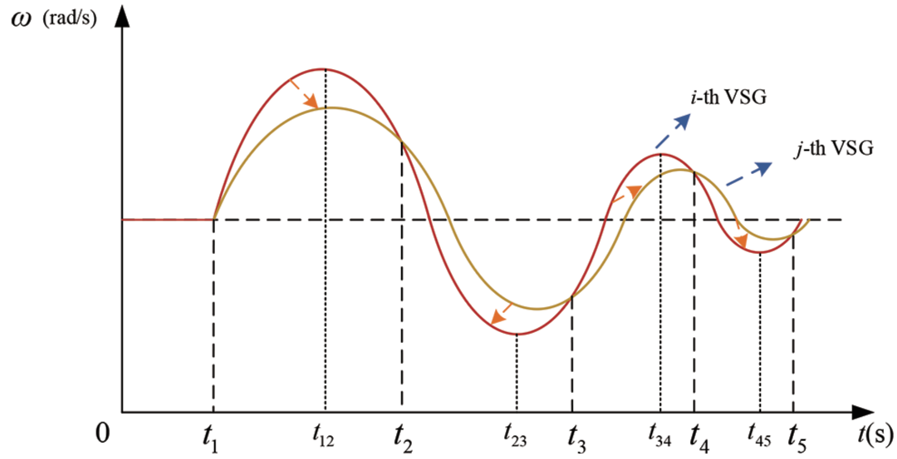

FIGURE 2. Frequency response curve of multi-VSG during disturbance

Between t_1-t_2 and t_3-t_4, the frequency response of the j-th VSG performs better than the frequency response of the i-th VSG. Therefore, we adjust the virtual inertia and virtual damping so that the frequency of the i-th VSG tracks the frequency of the j-th VSG. From t_1 to t_{12}, the frequency deviation $\Delta\omega_i$ of the i-th VSG gradually increases, and the RoCoF $\mathrm{d}\omega_i/\mathrm{d}t$ gradually decreases. In this case, the J and D should be increased to make the frequency response more consistent. From t_{12} to t_2, the $\Delta\omega_i$ begins to return and the $\mathrm{d}\omega_i/\mathrm{d}t$ increases gradually. At this stage, J should be decreased and D should be increased. From t_3 to t_4, the adjustment of J and D is the same as that at t_1-t_2. Between t_2-t_3 and t_4-t_5, the frequency response of the i-th VSG performs better than the frequency response of the j-th VSG, so the J and D of the j-th VSG are adjusted according to the previous analysis to track the i-th VSG.

3.3. **Adaptive cooperative control based on second-order-consensus.** Based on the previous analysis of the two key parameters of two VSGs under disturbance, it is natural to use virtual inertia and damping adaptive control to meet different needs in the process of controlling multiple VSGs. Due to the many couplings between parallel VSGs, it is crucial to achieve collaborative control through information exchange between them. Therefore, this section proposes an adaptive cooperative control strategy based on second-order-consensus.

For local VSG system, the most critical part of the adjustment algorithm for J and D is the local frequency deviation and RoCoF. The adjustment of virtual inertia and damping in the local VSG system can be described as follows:

$$\Delta J_{ii} = k_{1i} \frac{|\omega_i - \omega_{i,ref}|}{\omega_i - \omega_{i,ref}} \frac{d\omega_i}{dt} \tag{9}$$

$$\Delta D_{ii} = k_{2i} \left| (\omega_i - \omega_{i,ref}) \frac{d\omega_i}{dt} \right| \tag{10}$$

where ΔJ_{ii}, ΔD_{ii} are the adjustment values of J and D for the local VSG system, respectively; k_{1i}, k_{2i} are adjustment coefficients.

For multi-VSG system, it is crucial to adjust J and D in real time through frequency information exchange between different VSGs. The adjustment of virtual inertia and damping in the multi-VSG system can be described as follows:

$$\Delta J_{ij} = \frac{g_{1i}}{n} \sum_{j=1}^{n} a_{ij} (\omega_i - \omega_j) \frac{d\omega_i}{dt} \tag{11}$$

$$\Delta D_{ij} = \frac{g_{2i}}{n} \sum_{j=1}^{n} a_{ij} \left| (\omega_i - \omega_j) \frac{d\omega_i}{dt} \right| \tag{12}$$

where ΔJ_{ij}, ΔD_{ij} are the adjustment values of J and D for the multi-VSG system, respectively; g_{1i}, g_{2i} are adjustment coefficients.

Based on the above analysis, adaptive cooperative control is as follows:

$$J_i = J_{i0} + \Delta J_{ii} + \sum_{j \neq i}^{n} \Delta J_{ij} \tag{13}$$

$$D_i = D_{i0} + \Delta D_{ii} + \sum_{j \neq i}^{n} \Delta D_{ij} \tag{14}$$

In conclusion, the adaptive cooperative control strategy based on second-order-consensus is as follows:

$$\begin{aligned} &\left(J_{i0} + \Delta J_{ii} + \sum_{j \neq i}^{n} \Delta J_{ij} \right) \frac{d\omega_i}{dt} \\ &= T_{mi} - T_{ei} - \left(D_{i0} + \Delta D_{ii} + \sum_{j \neq i}^{n} \Delta D_{ij} \right) (\omega_i - \omega_n) + \psi_i \end{aligned} \tag{15}$$

Besides, to ensure the stable operation of each system, it is necessary to design the boundaries of virtual parameters. Several boundaries are designed as follows:

$$J_i = \begin{cases} J_{i,\min} & J_i \leq J_{i,\min} \\ J_i & \\ J_{i,\max} & J_i \geq J_{i,\max} \end{cases} \tag{16}$$

$$D_i = \begin{cases} D_{i,\min} & D_i \leq D_{i,\min} \\ D_i & \\ D_{i,\max} & D_i \geq D_{i,\max} \end{cases} \tag{17}$$

where $J_{i,\min}$, $J_{i,\max}$, $D_{i,\min}$, $D_{i,\max}$ are the upper and lower bounds of virtual inertia and virtual damping, respectively.

The control block diagram is shown in Figure 3.

4. **Simulations.** This section establishes a model of three VSGs operating in parallel in Matlab/Simulink. The capacities of three VSGs are set to 30 kW, 40 kW, and 50 kW, respectively. Each VSG is connected to a common connection point. At the initial moment, three VSGs jointly provide power to a 120 kW load. The filter parameters, line impedance, virtual inertia, damping coefficient of each VSG are set to different values, as shown in Table 2. Virtual inertia and damping have a significant impact on system frequency and active power. When the virtual inertia is too small, it will increase the speed of frequency recovery, but the system is prone to oscillations; Excessive virtual inertia can reduce frequency deviation but increase recovery time. When the virtual damping is too small, the system is unstable; As virtual damping increases, the system becomes

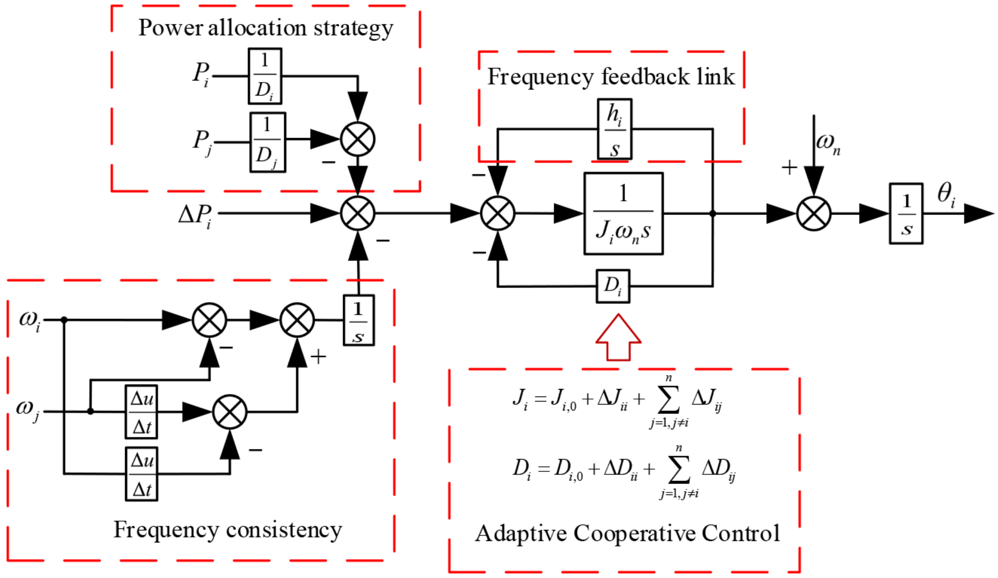

FIGURE 3. Structure diagram of the proposed control method

TABLE 2. Parameters of VSG

Symbol	VSG1	VSG2	VSG3	Unit
P_i^*	3	4	5	kW
ω_n	314	314	314	rad/s
J_0	2	3	5	kg.m^2
D_0	5	10	15	N.ms/rad
U_0	311	311	311	V
R	0.003	0.003	0.003	Ω
L	1e-4	1e-4	1e-4	H
C	8e-3	8e-3	8e-3	F
Z_i	0.03 + j0.001	0.04 + j0.0008	0.05 + j0.0006	Ω
k_{1i}, k_{2i}	5, 20	5, 20	5, 20	/
g_{1i}, g_{2i}	5, 20	5, 20	5, 20	/
h_i	3e2	4e2	5e2	/
$k_{\omega i}$, $\alpha_{\omega i}$	9, 5	12, 5	15, 5	/
k_{Pi}	30	40	50	/
$J_{i,\min}$, $J_{i,\max}$	0.2, 20	0.2, 20	0.2, 20	kg.m^2
$D_{i,\min}$, $D_{i,\max}$	5, 200	5, 200	5, 200	N.ms/rad

increasingly stable. However, excessive virtual damping can slow down the response speed of system. Therefore, it is necessary to choose the values of virtual inertia and damping reasonably. This article adopts adaptive control for virtual inertia and damping, and reasonably limits the maximum and minimum values to ensure the stable operation of the system. The consistency coefficient of frequency and active power can increase a certain steady-state margin during the increase process, but excessive coefficients can affect system damping and response speed. The parameters provided in Table 2 can ensure system stability and have good control effects.

During the simulation process, the simulation duration is set to 3 s, and the initial load is set to 120 kW. At $t = 1$ s, the load suddenly increases by 120 kW and is reduced at $t = 2$ s. Figure 4 shows the response curves of the frequency and active power of three

VSGs under three control methods. From the frequency curve in Figure 4, it can be seen that the three frequency curves under decentralized control are relatively dispersed at the beginning, indicating a significant difference in the response speed of the three VSGs, which is very detrimental to the stability of the grid frequency. At 1 s, the system load suddenly increased by 120 kW. Before reaching steady state, the three frequency curves remained relatively scattered, indicating significant differences in frequency response speed throughout the entire process. Similarly, at 2 s, the system suddenly reduced its load by 120 kW, and there is a significant difference in frequency response speed between the three VSGs. Under traditional cooperative control, the consistency of frequency response has been improved to a certain extent at the beginning, but there are still significant differences. At the moment of load switching, the consistency of the frequency curve is good, but there are significant differences during the return process. Under the control strategy proposed in this article, the consistency of frequency response at the moment of startup has been significantly improved, maintaining the same response speed. When load switching occurs, the frequency response speed remains basically the same throughout the entire transient process, which is very beneficial for the grid frequency. From the power curve graph, it can be seen that the system can output active power according to the set inverter capacity ratio. In order to better demonstrate the suppression effect of the proposed control strategy on active power fluctuations, Table 3 provides a detailed description of the overshoot of active power. Combining the active power curve with the

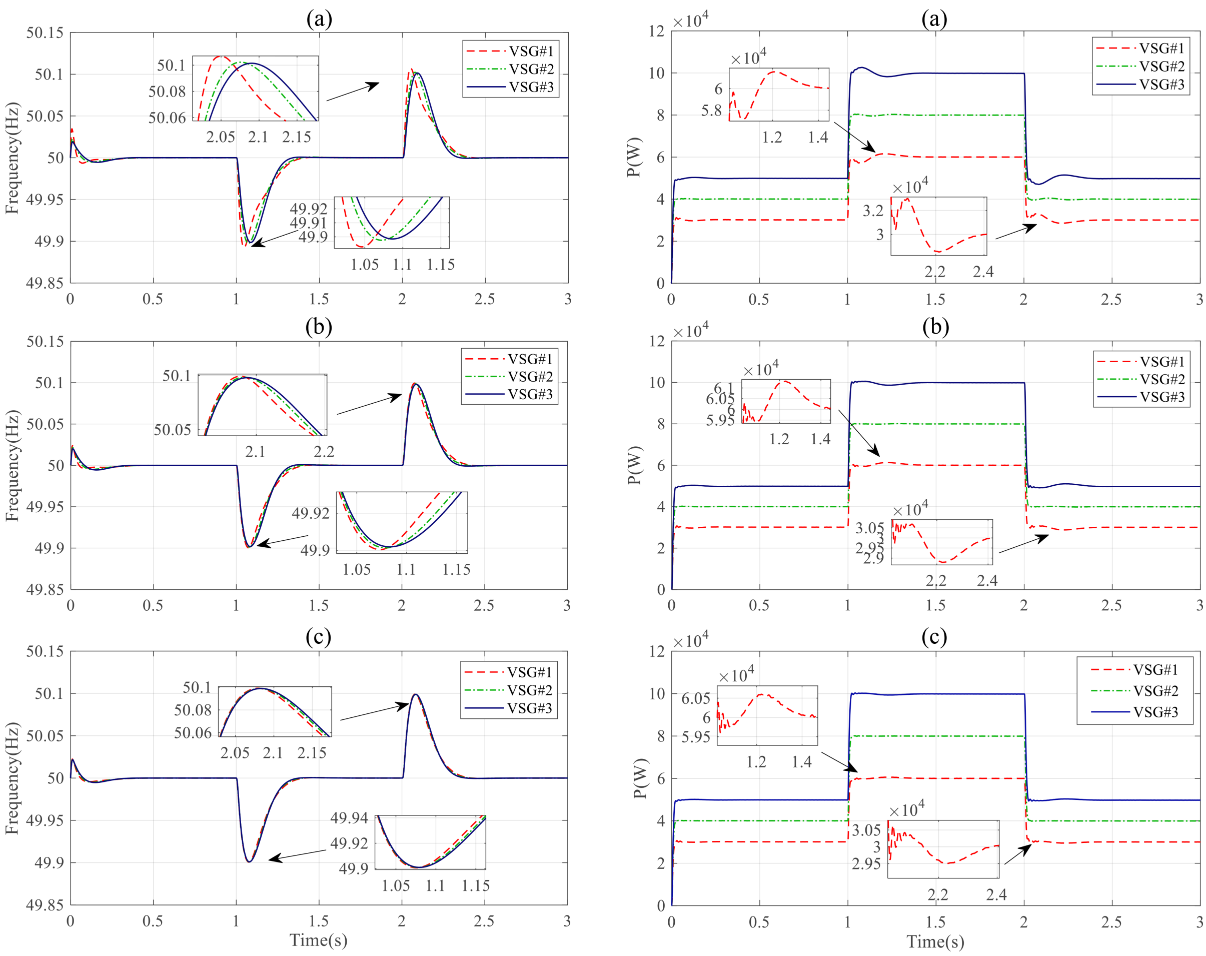

FIGURE 4. Comparison of frequency (left) and active power (right) under (a) decentralized control; (b) cooperative control; (c) proposed control

TABLE 3. Overshoot of active power

Methods	VSG#1	VSG#2	VSG#3
Proposed control	1.01%	0.145%	0.643%
Cooperative control	2.20%	0.195%	1.35%
Decentralized control	4.62%	0.591%	2.62%

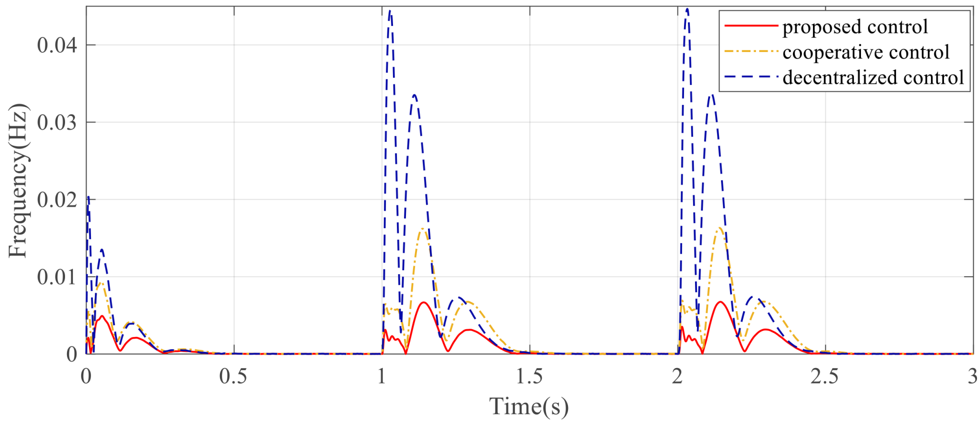

FIGURE 5. Time responses of OFD under three control methods

data in Table 3, it can be seen that under the decentralized control strategy, the instantaneous active power fluctuation during load switching is the largest, with a maximum overshoot of 4.62%. Under the proposed control strategy, the maximum overshoot is only 1.01%, which shows a very significant reduction. Although traditional cooperative control has a suppressive effect on power fluctuations, the effect is not significant enough. Under the proposed control strategy, the overshoot of the active power of each VSG is significantly reduced, indicating a significant suppression effect of power fluctuations.

In order to better demonstrate the error between frequencies under different control algorithms, this paper designs an overall frequency deviation (OFD) indicator. The OFD is designed as $\mathrm{OFD} = \sqrt{\sum_{i=2}^{n} \sum_{j=1}^{i-1} \left|(\omega_i - \omega_j)\right|^2}$. Figure 5 shows the OFD of the system under different control algorithms. It can be seen that compared to the other two control algorithms, the control algorithm proposed in this article has a significant improvement.

5. **Hardware in the Loop (HIL) Experiment.** To further verify the feasibility of the proposed algorithm in practical engineering, this paper established an HIL experimental platform as shown in Figure 6. The experimental platform consists of Starsim MT3200, dSPACE1202 toolbox, host computer, and oscilloscope. Starsim MT3200 is a simulation system specifically designed for solving algorithm validation, product testing, fault simulation, and other challenges in the field of power electronics. In the experimental platform established in this paper, it simulates a microgrid system containing three inverters. Three VSG controllers are running in the DSPACE toolbox, which simulates the control environment in practical engineering. The parameters used in the experimental section are the same as those in the simulation section. Figures 7 and 8 show the experimental results of frequency and active power under different control strategies. At $t = 2.5$ s, the system load suddenly increased by 120 kW, and decreased at $t = 5.5$ s. Obviously, each VSG outputs active power in proportion to its capacity while maintaining a stable frequency at the rated value. As shown in Figure 7, there is a significant difference between

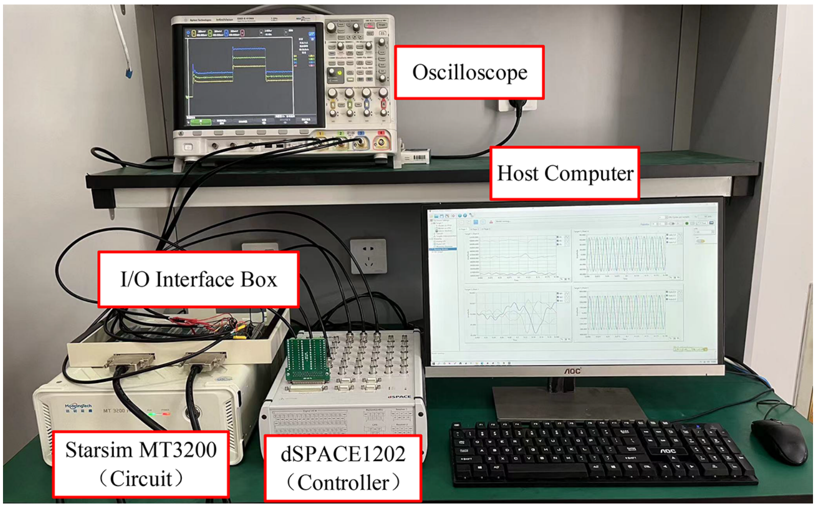

Figure 6. HIL experimental platform

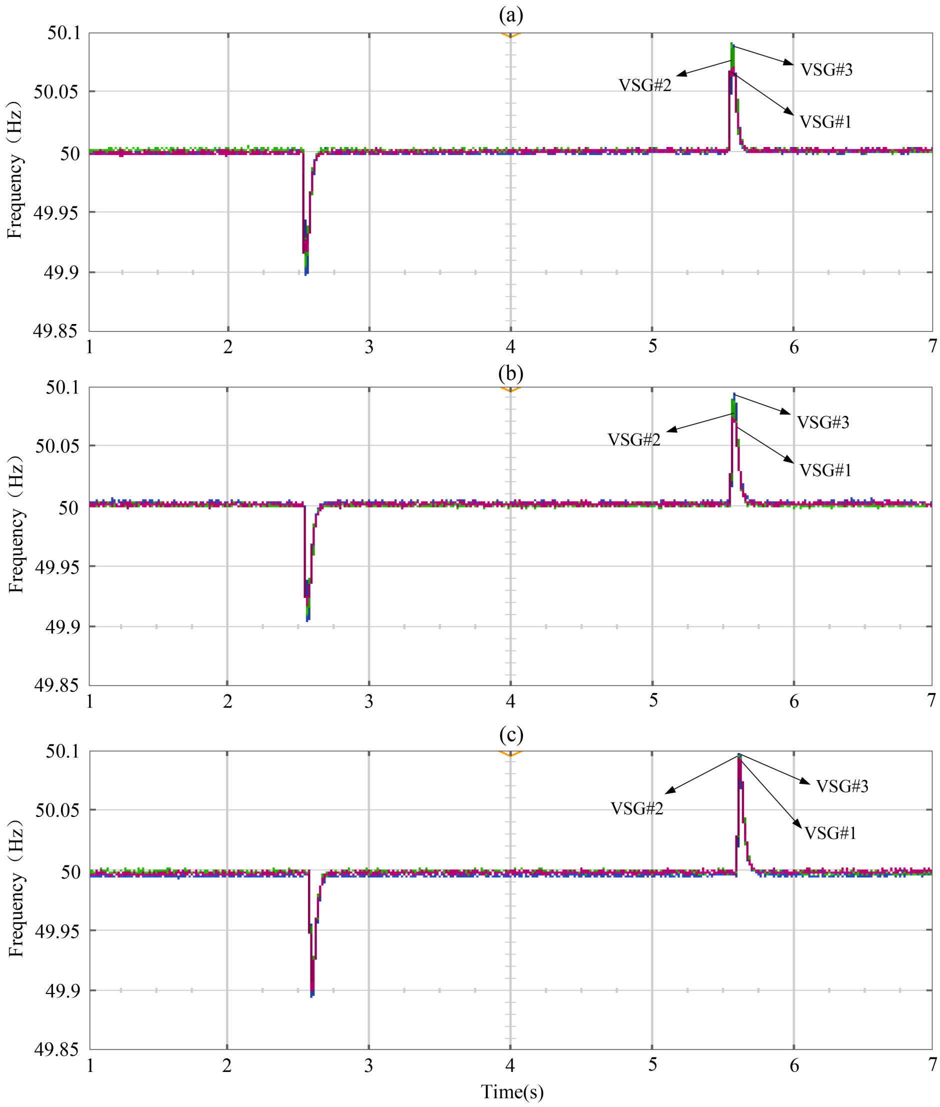

Figure 7. The frequency curve under (a) decentralized control; (b) cooperative control; (c) proposed control

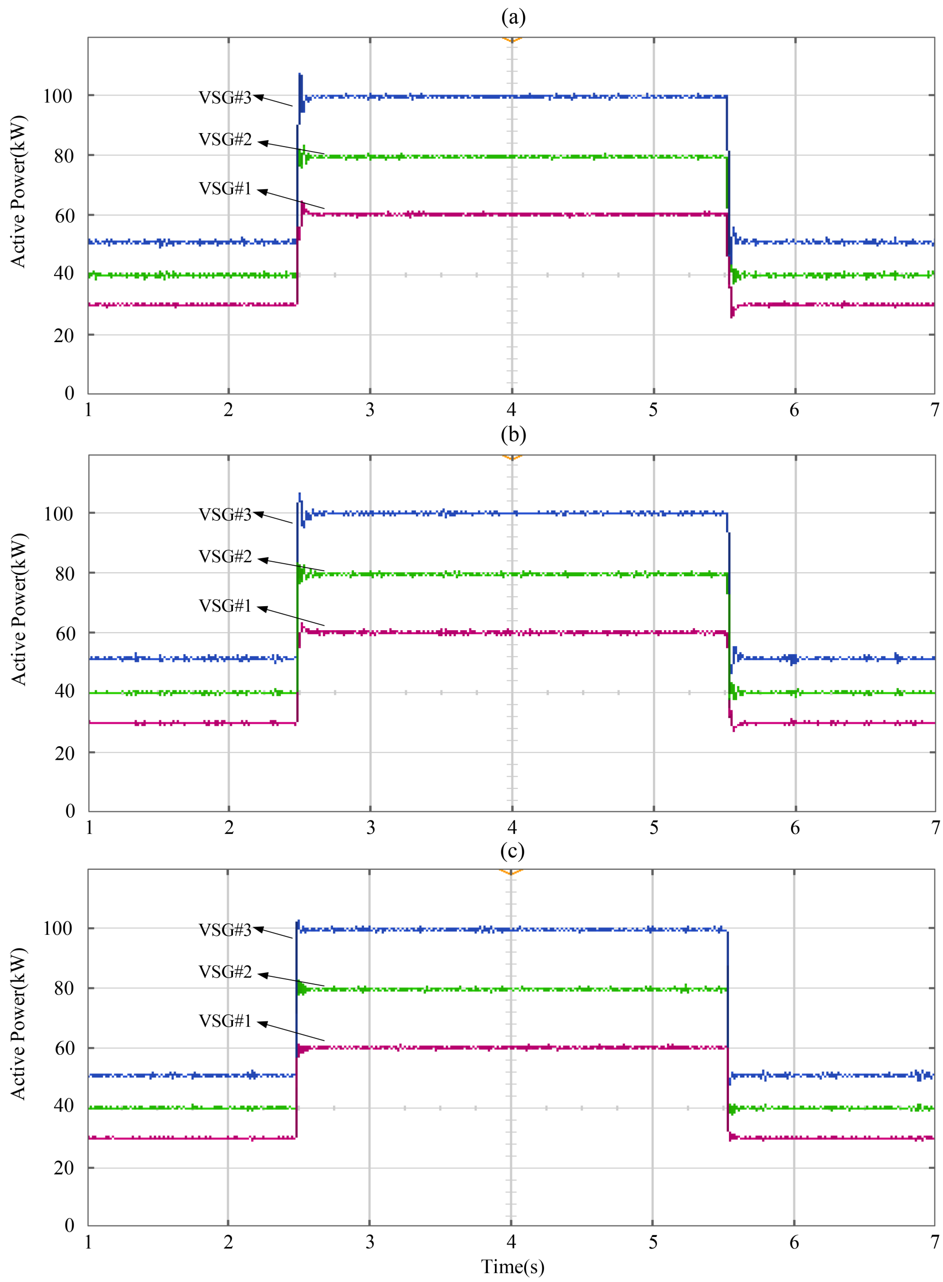

FIGURE 8. The active power curve under (a) decentralized control; (b) cooperative control; (c) proposed control

the frequency curves under the other two control algorithms, which is detrimental to the microgrid system. Figure 8 shows the active power curve, which shows that under the proposed control strategy, the adjustment time becomes shorter and the overshoot decreases.

6. **Conclusion.** This paper proposes a multi-VSG cooperative adaptive control strategy based on second-order-consensus to improve the stability of parallel inverters in microgrids. Firstly, the structural diagram and rotor motion equation of VSG are presented, and at the same time, the multi-agent theory is introduced. Then, a cooperative adaptive control strategy based on second-order-consensus is proposed to address the issues of inconsistent frequency response and active power oscillation during parallel VSGs operation. Furthermore, a simulation platform containing three VSGs was established, and

the simulation results proved the superiority of the proposed control strategy. Finally, in order to further verify the feasibility of the proposed control strategy in engineering, an HIL experimental platform was built, and the experimental results achieved the expected results.

Further work will mainly focus on the information interaction time delay of multi-agent systems and consider the instability of energy storage side.

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