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Distributed secondary control of microgrids with unknown disturbances and non-linear dynamics

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In this paper, the voltage and frequency regulation of microgrid with unknown disturbances and non-linear dynamics was studied. The disturbance observer was designed and the sliding mode control (SMC) method was used to realize the secondary regulation of voltage and frequency. First, a distributed secondary control protocol was designed to reduce the communication burden between generators and to solve voltage and frequency deviations. Second, a consensus protocol for secondary control of voltage and frequency was designed, based on the idea of multi-agent consensus, to indirectly ensure that the voltage and frequency to be adjusted reach the reference values when the consensus is realized. In addition, considering unknown disturbances in the microgrid, a sliding mode control strategy, based on a disturbance observer, was designed to overcome the influence of disturbances and to reduce chatter. This SMC scheme ensured finite time accessibility of the sliding mode surface. This design provides sufficient conditions for voltage and frequency regulation. The effectiveness of this design scheme was verified through simulation.

KEYWORDS

microgrid, secondary control, distributed control, consensus, disturbance observer

1 Introduction

In the context of the current industrial development, the scale of equipment has become more complex and information transmission between equipment is more frequent. The traditional centralized control mode lacks flexibility and cannot handle situations in which the controlled equipment or information source are too far from the host, which leads to a distributed control problem (Ding et al., 2019; Liu et al., 2022). In the context of the power grid, the control of distributed generators (DGs) has also received increasing attention, especially in microgrid systems comprising distributed energy, load, and energy storage systems, with many interesting results achieved (Espina et al., 2020;

Fan et al., 2021; Lu and Lai, 2021; Fan et al., 2022; Mohiuddin and Qi, 2022). In recent years, with the rapid development of microgrid integration technology, DGs are increasingly used in grid-connected or off-grid microgrid systems (Sarangi et al., 2020; Akbari et al., 2022; Wong et al., 2022). In this scenario, it is particularly important to control microgrid frequency and voltage by adjusting DG output to ensure microgrid stability.

Raeispour et al. (2021) described that, at the primary level of the microgrid, a primary controller is designed for current, voltage, and droop control loops and proposed a robust control structure. However, this method produced voltage and frequency deviations, which affect microgrid stability. To solve this problem, the idea of secondary control was introduced. Because of the superiority of distributed secondary control in saving communication resources between agents, this control has been studied in microgrids (Shan et al., 2021; Sun et al., 2022a; Deng et al., 2022). Bidram et al. (2013) designed a sparse communication network based on the concept of directed graphs to provide secondary control of the microgrid. Compared with centralized control, this strategy effectively improved the robustness of communication link failures. Zhang et al. (2021) described a finite time controller based on the secondary control strategy, which effectively improved the transient response of the control loop by adding an integrand to the consensus strategy. Choi et al., (2022) reported that, combined with an event-triggered strategy, communication resources are further saved by distributed secondary control and that information on neighbor generators is only obtained at the triggering instant. Fonseca et al (2022) proposed a distributed model predictive secondary control scheme to solve difficulties caused by unbalanced voltage sharing between generators.

In microgrids, due to the influence of the internal components of the grid and the internal and external environments of the system, it is often necessary to consider disturbances to the system (Lai et al., 2022). Such disturbances make secondary control of the microgrid more challenging. Sliding mode control (SMC), an effective method to address these disturbances, is widely used to improve system robustness and stability (Hu et al., 2022; Veysi et al., 2022; Alipour et al., 2023). Sun et al. (2022b) designed an SMC strategy for secondary control based on the reactive power dynamics model, which showed robust control against external disturbances such as communication failure. Alfaro et al. (2022) demonstrated that the combination of SMC and state observer ensured the elastic consensus of an AC microgrid in the presence of network attacks. Abianeh et al. (2022) designed a sliding mode cooperative controller using consensus logic, which demonstrated recovery of voltage and frequency without relying on DG parameters and correspondingly overcame the influence of system disturbances. Zehra et al. (2022) presented a novel model and non-linear barrier function-based first-order SMC of a hybrid hydrogen-electric energy storage system in a DC microgrid. By designing an obstacle Lyapunov equation, asymptotic stability of the expected tracking error is achieved.

In actual microgrids, the disturbances are usually unknown, whereas most of the disturbances considered in the aforementioned research are known. It is not ideal to address disturbances by designing to the upper bound of the disturbance, as the system often exhibits chatter under this control strategy. Researchers have designed disturbance observers to estimate the upper bound of unknown disturbances (Wang et al., 2021; Xu et al., 2021; Badar et al., 2022; Ding et al., 2022). Xu et al. (2020) designed a sliding mode surface based on the system error and applied a new estimation method to estimate unknown disturbances. Error convergence was indirectly guaranteed through the convergence of the compensation signal, resulting in voltage regulation of the DC microgrid. Ge et al. (2021) set factors such as parameter disturbance and external influence as the disturbance set and applied the Kalman filter to design disturbance observers of extended states, thus simplifying parameter selection. Jiang et al. (2021) applied an observer to estimate the state and spurious signals, considering the impact of spurious signal injection on the DC microgrid, which resulted in an elastic scheme of bus voltage output current and power sharing.

Although many results have been reported for the control of microgrid systems, few studies have simultaneously considered distributed secondary control and system chatter problems. In this context, the present article assessed the distributed secondary control of microgrid systems using the idea of multi-agent consensus. The main contributions are:

1) Based on the idea of multi-agent systems, this study designed consensus protocols for the voltage and frequency of DGs, respectively. By reaching a consensus, the voltage and frequency to be adjusted can reach the reference values. At the same time, the distributed control method does not require continuous communication between generators, instead requiring only information from their neighbors, which effectively reduces the communication burden.

2) Combined with SMC, a disturbance observer was designed to estimate unknown disturbances in the microgrid. Compared with previous results (Ge et al., 2021; Sun et al., 2022b), SMC law only depends on the bound of disturbance estimation error and not the bound of the disturbance. Therefore, this observer-based SMC scheme can effectively address the chatter phenomenon while solving the influence of disturbance on the system.

3) Unlike traditional SMC (Abianeh et al., 2022), the control strategy proposed in this study can ensure that the controlled trajectory has a finite time to reach the sliding mode surface, which improves the rapidity of the first stage of SMC. In addition, two sufficient conditions are obtained to ensure that the

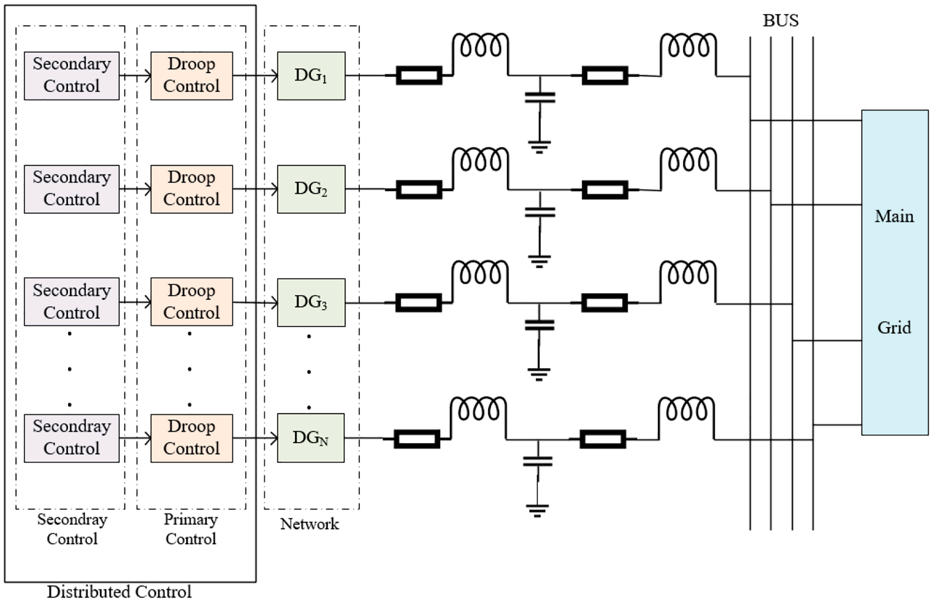

FIGURE 1
DG structure.

controlled voltage and frequency will converge to the reference values along the designed trajectory after reaching the sliding mode surface.

2 Model description and observer

2.1 Microgrid model

In microgrids, the voltage and frequency regulation of the system can usually be realized by improved droop control strategies. In the traditional primary control, the voltage and frequency of each distributed generator are transferred to the secondary control layer under the droop control strategy to achieve consensus control. The basic principle is to design a controller that solves errors and fluctuations caused by droop control. The general structure of DGs is shown in **Figure 1**.

Due to the influence of internal equipment or the external environment of microgrids, disturbances are widespread and often unknown. Hence, the microgrid model must consider unknown disturbance factors. Therefore, we provide the following frequency model of DGs:

$$\begin{cases} \dot{\omega}_i(t) = u_{\omega i}(t) + f(w_i(t)) + d_i(t), \\ y_{\omega i}(t) = \omega_i(t), \end{cases} \tag{1}$$

where $\dot{\omega}_i(t)$ represents the frequency of DGs, $u_{\omega i}(t)$ represents the frequency input signal of each generator, $f(w_i(t))$ denotes the non-linearity of power, $d_i(t)$ is an unknown disturbance and satisfies $|\dot{d}_i(t)| \le \varepsilon$, and $y_{\omega i}(t)$ indicates the output of each generator.

Similar to the frequency model **(1)**, the voltage model of the generator can be described as

$$\begin{cases} \dot{v}_i(t) = u_{vi}(t) + f(v_i(t)) + d_i(t), \\ y_{vi}(t) = v_i(t), \end{cases} \tag{2}$$

where $v_i(t)$ represents the voltage of each distributed generator, $f(v_i(t))$ indicates the non-linearity caused by the power, and $y_{\omega i}(t)$ represents the voltage input signal of each generator.

To clearly describe the control strategy used in this study, the frequency and voltage block diagrams of the secondary control are shown in **Figure 2** and **Figure 3**, respectively.

Secondary control of the microgrid is essentially a tracking problem in the control system, even if the voltage and frequency reach the desired reference values. In this study, each generator in the microgrid is considered to be an agent. Using the idea of a multi-agent system (Fan et al., 2019; Wang et al., 2020; Ferreira et al., 2022), this tracking problem can be transformed into a leader-following problem, with a fixed value for the leader agent. Then, by applying graph theory, the communication relationships between generators can be represented as a communication topology network. Assuming that the microgrid is composed of N DGs, generator j can communicate with generator i as a neighbor agent, and these can communicate in both directions; that is, the information transmission is undirected.

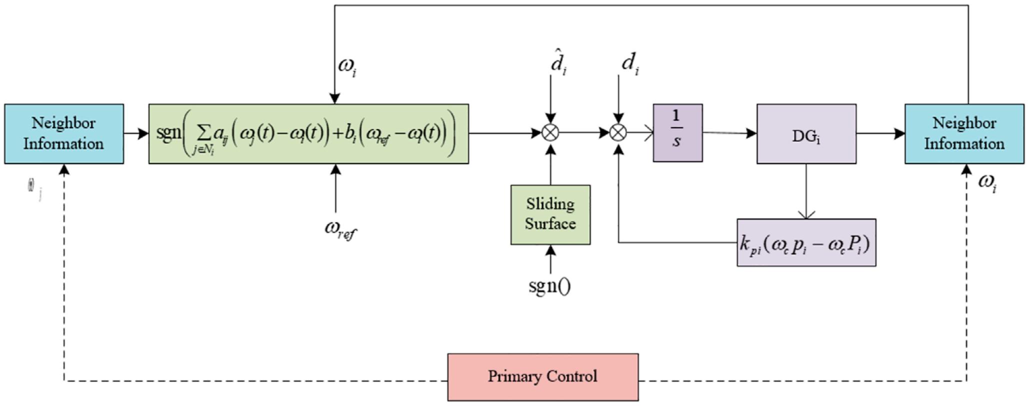

FIGURE 2
Frequency control block diagram.

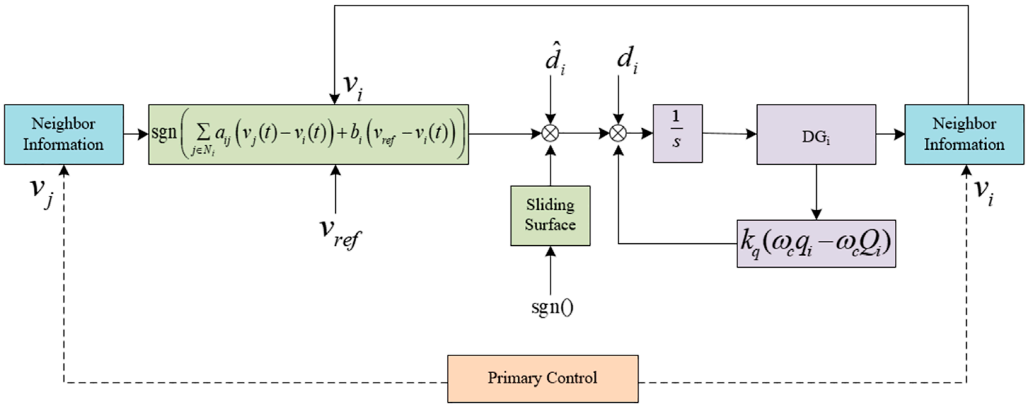

FIGURE 3
Voltage control block diagram.

Then, the undirected graph G is expressed as G=(υ,ε,A), where the vertex set υ=(υ_1, υ_2, υ_3, … , υ_N) is a non-empty finite set of DGs, N is the total number of nodes, and the edge set $\varepsilon \subseteq \upsilon^* \upsilon$ represents the communication links between DGs. $A = \left[a_{ij}\right] \in R^{N^*N}$ is the weighted adjacent matrix. If a path exists between DG i and DG j, the communication topology graph Γ is called a connection graph, which means that if $(\upsilon_i, \upsilon_j) \in \varepsilon$, then $a_{ij} = 1$; otherwise, $a_{ij} = 0$. Assuming that there is no self-loop, then $a_{ii} = 0$.

Through the aforementioned conversion, the control objectives under the consensus protocol are as follows:

$$\lim_{t\to\infty} |\omega_i(t)-\omega_{\text{ref}}| = 0, \quad \forall i = 1,2,3,\ldots,N. \tag{3}$$

$$\lim_{t\to\infty} |v_i(t)-v_{\text{ref}}| = 0, \quad \forall i = 1,2,3,\ldots,N. \tag{4}$$

Here, ω_{ref} and v_{ref} represent the reference values of frequency and voltage, respectively.

2.2 Design of the disturbance observer

To overcome the influence of unknown disturbances on the system, we design a disturbance observer to estimate the upper bound of the disturbance. The design satisfies the following form:

$$\hat{d}_i(t) = g_i(t) - mv_i(t), \tag{5}$$

$$\dot{g}_i(t) = m\left(g_i(t) - mv_i(t)\right) + m\left(f\left(v_i(t)\right) + u_{v_i}\right), \tag{6}$$

where $\hat{d}_i(t) \in R$ is the disturbance estimation, $g_i(t)$ is the observer state, and $m < 0$. $\tilde{d}_i(t) = d_i(t) - \hat{d}_i(t)$ is the estimation error.

Combining (5) and (6),

$$\begin{aligned}\dot{\hat{d}}_i(t) &= \dot{g}_i(t) - m\dot{v}_i(t)\\ &= m\left(g_i(t) - mv_i(t)\right) + m\left(u_{v_i}(t) + f\left(v_i(t)\right)\right)\\ &\quad - m\left(u_{v_i} + d_i(t) + f\left(v_i(t)\right)\right)\\ &= m\left(g_i(t) - mv_i(t)\right) - md_i(t)\\ &= -m\tilde{d}_i(t). \end{aligned} \tag{7}$$

Then, the derivative of the estimation error is

$$\begin{aligned}\dot{\tilde{d}}_i(t) &= \dot{d}_i(t) - \dot{\hat{d}}_i(t)\\ &= \dot{d}_i(t) + m\tilde{d}_i(t). \end{aligned} \tag{8}$$

To analyze the stability of the microgrid, the following assumptions must be met.

Assumption 1. *The estimation error* $\tilde{d}_i(t)$ *is bounded and satisfies* $\tilde{d}_i^* = \sup_{t>0}\left|\tilde{d}_i(t)\right|$.

Assumption 2. *There exist some known constants* $c \geq 0$, *such that*

$$\left|f\left(v_i(t)\right)\right| < c\left|v_i(t)\right|, \quad i = 1, 2, \ldots, N. \tag{9}$$

Remark 1. The non-linear term considered in this study is unknown but satisfies a linear growth condition. The linear growth condition is essentially a constraint on the state of the system in finite time to ensure that the state will not change to infinity in finite time. This is a conventional condition for addressing the non-linear uncertainty of the actual system.

3 Main results

We design a distributed secondary controller based on the idea of consensus so that the voltage and frequency of each generator can reach the reference values ω_{ref} and v_{ref}. We also design an SMC strategy based on a disturbance observer to overcome the influence of unknown disturbances. Sufficient conditions for voltage and frequency regulation are obtained.

First, the voltage error control protocol for each generator is

$$e_{v_i}(t) = \sum_{j\in N_i} a_{ij}\left(v_j(t) - v_i(t)\right) + b_i\left(v_{ref} - v_i(t)\right). \tag{10}$$

Remark 2. The design of the control protocol (10) can be divided into two parts. The first part is expressed as $v_j(t) - v_i(t)$, the relative voltage deviation between the generator and its neighbor generator. Information on all generators in the microgrid is no longer needed here; thus, it is distributed. Compared with traditional centralized control, the control strategy designed here takes up less communication bandwidth, effectively reducing the communication burden. The second part is the deviation between the ith generator and the reference signal. The reference signal here can be regarded as a special case where the leader is a constant value, which reflects the consensus idea used in this study.

We first analyze the voltage of each generator and define the voltage tracking error $\eta_{v_i}(t)$ as

$$\eta_{v_i}(t) = v_i(t) - v_{ref}. \tag{11}$$

whose derivative is

$$\dot{\eta}_{v_i}(t) = \dot{v}_i(t) = u_{v_i}(t) + f\left(v_i(t)\right) + d_i(t). \tag{12}$$

Next, we design the sliding surface and construct the sliding function as

$$s_{v_i}(t) = \eta_{v_i}(t) + \int_o^t k_1\eta_{v_i}(\tau)\,d\tau. \tag{13}$$

The secondary voltage controller is designed as

$$\begin{aligned}u_{v_i}(t) = \operatorname{sgn}&\left(\sum_{j\in N_i} a_{ij}\left(\eta_{v_j}(t) - \eta_{v_i}(t)\right) - b_i\eta_{v_i}(t)\right)\\ &- k_2\operatorname{sgn}\left(s_{vi}(t)\right) - \hat{d}_i(t) - k_1\eta_{v_i}(t)\\ &- c\left|v_i(t)\right|\operatorname{sgn}\left(s_{vi}(t)\right), \end{aligned} \tag{14}$$

where k_1 is a constant parameter, designed later.

Through the aforementioned design, the sufficiency condition of secondary voltage regulation can be obtained.

Theorem 1. *Considering the SMC strategy* (13) *and secondary voltage controller* (14), *if* $(1 + \tilde{d}^* - k_2) \leq -k$, *the state of the system* (12) *can reach the sliding mode surface in a finite time and eventually converges to 0.*

Proof: Taking the derivative of the sliding function $s_{vi}(t)$,

$$\begin{aligned}\dot{s}_{vi}(t) &= \dot{\eta}_{v_i}(t) + k_1\eta_{v_i}(t)\\ &= u_{v_i}(t) + f\left(v_i(t)\right) + d_i(t) + k_1\eta_{v_i}(t)\\ &= \operatorname{sgn}\left(\sum_{j\in N_i} a_{ij}\left(\eta_{v_j}(t) - \eta_{v_i}(t)\right) - b_i\eta_{v_i}(t)\right)\\ &\quad - k_2\operatorname{sgn}\left(s_{vi}(t)\right) - \hat{d}_i(t) - k_1\eta_{v_i}(t)\\ &\quad + d_i(t) + k_1\eta_{v_i}(t) + f\left(v_i(t)\right) - c\left|v_i(t)\right|\operatorname{sgn}\left(s_{vi}(t)\right)\\ &= \operatorname{sgn}\left(\sum_{j\in N_i} a_{ij}\left(\eta_{v_j}(t) - \eta_{v_i}(t)\right) - b_i\eta_{v_i}(t)\right) + \tilde{d}_i(t)\\ &\quad - k_2\operatorname{sgn}\left(s_{vi}(t)\right) + f\left(v_i(t)\right) - c\left|v_i(t)\right|\operatorname{sgn}\left(s_{vi}(t)\right). \end{aligned} \tag{15}$$

Considering the Lyapunov function as

$$V_1(t) = \frac{1}{2}s_{vi}{}^2(t). \tag{16}$$

the dynamic equation of $V_1(t)$ is expressed as

$$\begin{aligned}\dot{V}_1(t) &= s_{vi}(t)\dot{s}_{vi}(t)\\ &= s_{vi}(t)\Bigg[\operatorname{sgn}\left(\sum_{j\in N_i} a_{ij}\left(\eta_{v_j}(t) - \eta_{v_i}(t)\right) - b_i\eta_{v_i}(t)\right)\\ &\quad - c\left|v_i(t)\right|\operatorname{sgn}\left(s_{vi}(t)\right) - k_2\operatorname{sgn}\left(s_{vi}(t)\right)\\ &\quad + \tilde{d}_i(t) + f\left(v_i(t)\right)\Bigg]\\ &\leq s_{vi}(t)\operatorname{sgn}\left(\sum_{j\in N_i} a_{ij}\left(\eta_{v_j}(t) - \eta_{v_i}(t)\right) - b_i\eta_{v_i}(t)\right)\\ &\quad - k_2\left|s_{vi}(t)\right| + c\left|s_{vi}(t)\right|\left|v_i(t)\right|\\ &\quad - c\left|s_{vi}(t)\right|\left|v_i(t)\right| + \tilde{d}_i(t)s_{vi}(t). \end{aligned} \tag{17}$$

Recalling assumptions 1 and 2,

$$\begin{aligned}\dot{V}_1(t) &\leq |s_{vi}(t)| - k_2|s_{vi}(t)| + \tilde{d}^*|s_{\omega i}(t)| \\ &\leq \left(1+\tilde{d}^* - k_2\right)|s_{vi}(t)| \\ &\leq -k|s_{vi}(t)| \\ &\leq -kV_1^{\frac{1}{2}}(t).\end{aligned} \tag{18}$$

Then, we can obtain

$$\lim_{t\to T_1} V_1(t) = 0, \tag{19}$$

where $T_1 = \frac{V_1^{\frac{1}{2}}(0)}{k}$.

After the controlled trajectory reaches the sliding surface; i.e., $t > T_1$, $s_{vi}(t) = 0$ and $\dot{s}_{vi}(t) = 0$, the equivalent controller u_{eq_i} can be described as

$$u_{eq_i} = -\left(f\left(v_i(t)\right) + d_i(t) + k_1\eta_{v_i}(t)\right). \tag{20}$$

Substituting (20) into (12) produces

$$\dot{\eta}_{v_i}(t) = -k_1\eta_{v_i}(t). \tag{21}$$

Therefore, the Lyapunov equation $V_2(t)$ is

$$V_2(t) = \frac{1}{2}\eta_{\omega_i}(t)^2. \tag{22}$$

Taking the derivative of $V_2(t)$,

$$\begin{aligned}\dot{V}_2(t) &= \eta_{v_i}(t)\dot{\eta}_{v_i}(t) \\ &= -k_1\eta_{v_i}{}^2(t) \\ &\leq -k_1V_2(t).\end{aligned} \tag{23}$$

Then,

$$\lim_{t\to\infty}|v_i(t) - v_{\text{ref}}| = 0, \quad \forall i = 1,2,3,\ldots,N. \tag{24}$$

Therefore, the states of the system (12) converge to 0 along the sliding mode surface. This completes the proof.

The aforementioned design and analysis address secondary voltage regulation in the microgrid. Next, we briefly analyze the regulation of secondary frequency in the microgrid. Similar to voltage regulation, we first define the frequency error:

$$\eta_{\omega_i}(t) = \omega_i(t) - \omega_{ref}. \tag{25}$$

Thus, the dynamic of η_{ω_i} is

$$\dot{\eta}_{\omega_i}(t) = \dot{\omega}_i(t) = u_{\omega_i}(t) + f\left(\omega_i(t)\right) + d_i(t). \tag{26}$$

The sliding mode function is constructed as

$$s_{\omega_i}(t) = \eta_{\omega_i}(t) + \int_o^t k_1\eta_{\omega_i}(\tau)\,d\tau. \tag{27}$$

Subsequently, the controller of secondary frequency regulation is designed as

$$\begin{aligned}u_{\omega_i}(t) = \operatorname{sgn}&\left(\sum_{j\in N_i} a_{ij}\left(\eta_{\omega_j}(t) - \eta_{\omega_i}(t)\right) - b_i\eta_{\omega_i}(t)\right) \\ &- k_2\operatorname{sgn}\left(s_{\omega i}(t)\right) - \hat{d}_i(t) - k_1\eta_{\omega_i}(t) \\ &- c|\omega_i(t)|\operatorname{sgn}\left(s_{\omega_i}(t)\right).\end{aligned} \tag{28}$$

Then, we obtain the following conclusions:

Theorem 2. *Considering the secondary frequency controller (28), the state trajectories of system* (26) *can be driven by the sliding surface; i.e.,* $s_{\omega i}(t) = 0$ *in a finite time* T_1, *if there exists a positive parameter* k_2 *satisfying* $(1 + \tilde{d}^* - k_2) \leq -k$, *the trajectory will eventually converge to 0.*

The stability analysis process of secondary frequency regulation is similar to that of secondary voltage regulation, which is not given here to avoid redundancy.

4 Simulation results

We validate the effectiveness of the control method we proposed by building the simulation models of three DGs in MATLAB. We choose the reference voltage value to be $V_{ref} = 400V$ and the reference frequency value $f_{ref} = 50Hz$. As the communication topology is an undirected graph structure, and this study did not consider the influence of other factors on topology selection, we select the adjacency matrices A and B as follows:

$$A = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}. \tag{29}$$

The initial frequency values of DG1, DG2, and DG3 are selected as $f_1 = 51$ Hz, $f_2 = 49$ Hz, and $f_3 = 46.5$ Hz, respectively. The unknown disturbance is $d = \cos 2t$, and the non-linear function is $f(\omega_i(t)) = \omega_i{}^*sin(t)$. The other selected parameters are shown in Table 1.

Figures 4 and 5 can be obtained through simulations. Figure 4 shows the trajectory curves of $s_{\omega i}$, while Figure 5 depicts the trajectory curves of $\eta_{\omega i}$. As shown in Figure 4, the state trajectory of the frequency errors system is driven to the sliding surface within 0.15 s. Moreover, as shown in

TABLE 1 **Parameters for the selection of frequency.**

Control parameter			Initial value			Reference value
k_1	k_2	c	f_1	f_2	f_3	f_{ref}
5	30	0.5	51 Hz	49 Hz	46.5 Hz	50 Hz

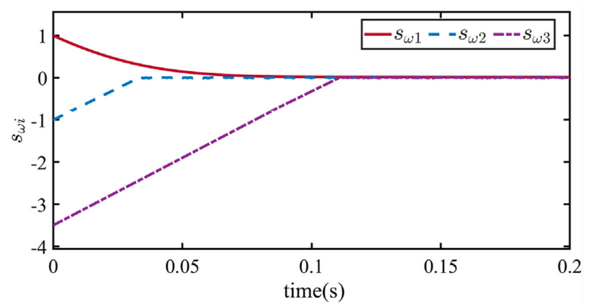

FIGURE 4
Trajectory curves of $s_{\omega i}$.

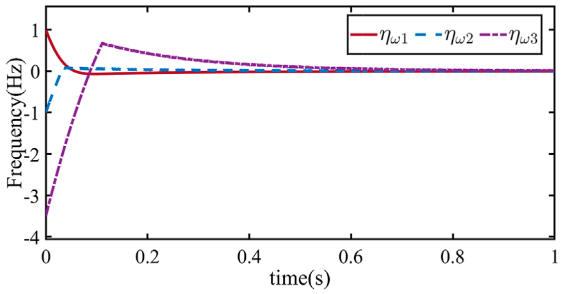

FIGURE 5
Trajectory curves of $\eta_{\omega i}$.

Figure 5, the frequencies of DG1, DG2, and DG3 converge to $f_{ref} = 50Hz$ within 0.8 s. Based on this, we conclude that under the proposed control method, the frequency of the microgrid system can be quickly adjusted to the reference frequency in a finite time, achieving secondary control of the microgrid (3).

To verify that the proposed control method can achieve the control objective (4), we choose the reference voltage as $v_{ref} = 400\ V$. The other selected parameters are shown in Table 2. The initial voltage values of DG1, DG2, and DG3 are $v_1 = 390\ V$, $v_2 = 395\ V$, and $v_3 = 405\ V$, respectively, as shown in Figures 6 and 7. Figure 6 shows the trajectory curves of s_{vi}, while Figure 7 depicts the trajectory curves of η_{vi}. As shown in Figure 6, the state trajectory of the voltage errors system is driven to the sliding surface within 0.2 s. As shown in Figure 7, the voltages of DG1, DG2, and DG3 converge to $v_{ref} = 400\ V$ within 0.8 s. Based on this, the proposed control method can quickly adjust the frequency and voltage of DGs to the reference values, thus realizing secondary control of the microgrid.

TABLE 2 **Parameters for the selection of voltage.**

Control parameter			Initial value			Reference value
k_1	k_2	c	v_1	v_2	v_3	v_{ref}
5	30	0.5	390 V	395 V	405 V	400 V

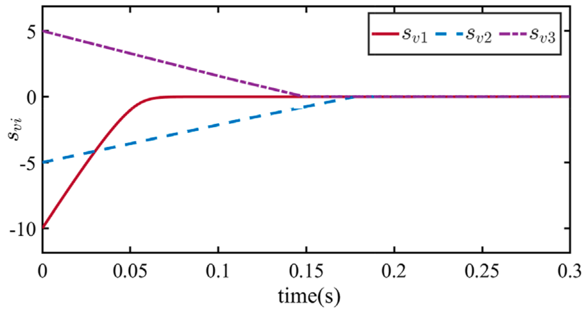

FIGURE 6
Trajectory curves of s_{vi}.

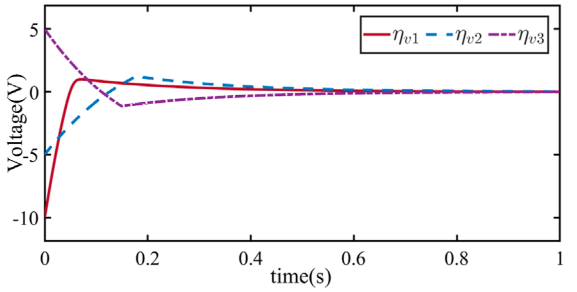

FIGURE 7
Trajectory curves of η_{vi}.

5 Conclusion

This study focused on the secondary control problem of microgrids with unknown disturbances. The distributed secondary control strategy proposed in this study only requires communication with neighboring generators, thus effectively reducing the communication burden. The designed SMC scheme, based on disturbance observers, can effectively address the influence of unknown disturbances and reduce chatter. Sufficient conditions for voltage and frequency regulation of microgrids were obtained, which create conditions for relevant work. To further reduce resource demand, subsequent work will study an event-triggered control strategy to achieve distributed secondary control relying on discontinuous communication. In addition, based on the idea of terminal SMC, another possible research direction is to realize preset time control in the two stages of SMC.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

Author contributions

SH, LH, HZ, and HL participated in article writing. XL and JQ participated in the study design.

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Conflict of interest

XL is employed by the Linyi Power Supply Company, State Grid Shandong Electric Power Company.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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