An Adaptive Sliding Mode Control Based on Disturbance Observer for LFC

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In the power system, the loads and nonlinearity parameters cause the system frequency deviation, which complicates the load frequency control (LFC). To deal with the above problem, an adaptive sliding mode control (SMC) based on disturbance observer is proposed to eliminate frequency deviation for interconnected power system in this paper. Firstly, the mathematical model of the power system is established, where the power exchange between the tie line is considered as the variable of the designed sliding surface. Secondly, the nonlinear disturbance observer is constructed to estimate the parameter uncertainty and load of power system. Thirdly, combined with the estimated value of the disturbance observer and integral sliding mode surface, the SMC is designed. Moreover, considering the inherent shortcoming of SMC—the chattering problem, an adaptive strategy is applied to the SMC to ensure the stability of controller. Next, the stability of the designed SMC is proved by Lyapunov stability theory. Finally, to verify the effectiveness of the proposed controller, several simulations are presented.

Keywords: load frequency control, interconnected power system, the disturbance observer, the adaptive control, sliding mode control

INTRODUCTION

LFC is a crucial technology for stable operation of modern large-scale interconnected power systems. Due to random uncertainty such as the power demand, the power generation, the communication time lag, the device parameter, etc. The frequency and power exchange in a large range power system will fluctuate or escape from the planned tolerance. When unexpected uncertainty occurs in power system, the purpose of frequency control is to quickly stabilize the system frequency and exchange power between interconnected systems within an acceptable plan (Dou et al., 2017). Driven by the rapid development of technology, power generation units, electrical equipment, and communication systems, power systems have become more complex (Wang et al., 2021b). Therefore, an effective frequency control strategy urgently needs to be proposed to manage the challenge of complex systems.

Furthermore, micro-grid can fully exploit renewable energy to reduce carbon emission. Based on the advantages of the micro-grid, the system has been widely established. However, when micro-grid encounters the intermittency of renewable resource, the rapid fluctuations of load and the uncertainties of internal parameters, frequency regulation is more complex (Kahrobaeian and Mohamed, 2012; Khooban et al., 2017; Lu et al., 2017). To stabilize the frequency, many mature control algorithms have been implemented to solve LFC problems, such as intelligent control,
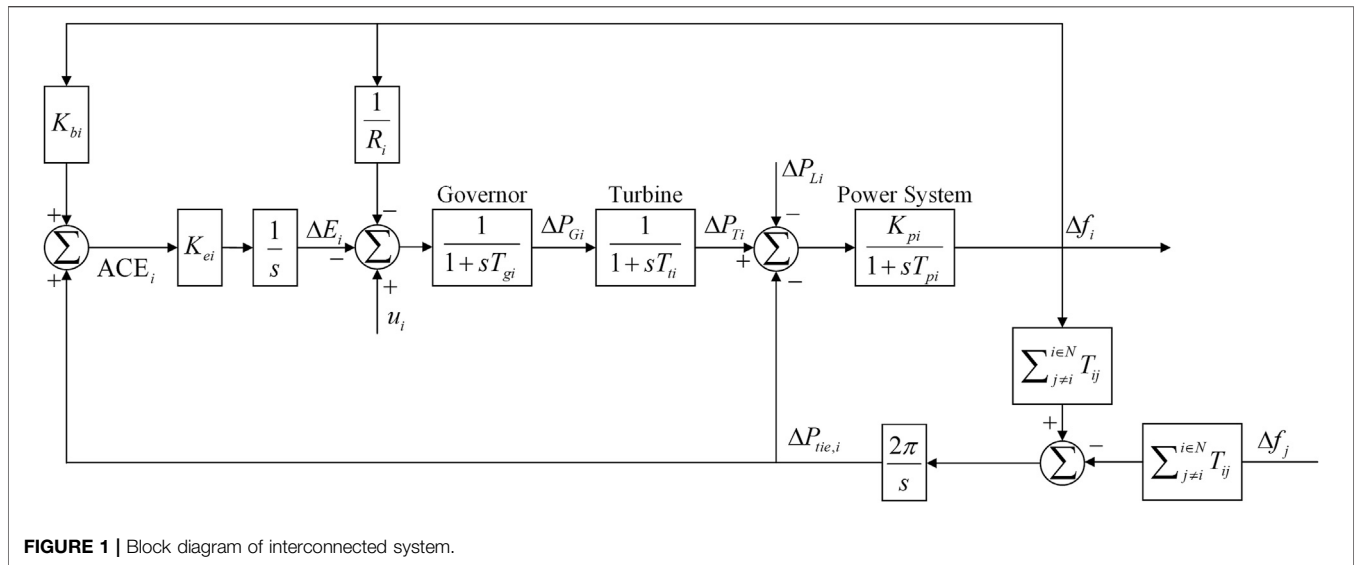
FIGURE 1 | Block diagram of interconnected system.

adaptive control (Rashidi et al., 2004), robust control (Huang et al., 2016; Jiang et al., 2012), fuzzy control (Yousef et al., 2014), proportional-integral differentiation (PID) control (Khodabakhshian and Edrisi, 2008; Tan, 2010), etc.

PID control is the common control tool to damp frequency oscillation for micro-grid which is treated as a linear model (Bevrani and Hiyama, 2008; Kamwa et al., 2001). The PID controllers are the simple and easy control tool which can powerfully tuned for several specific operation points (Wangdee and Billinton, 2006). As the integration of renewable energy power generation, the characteristics of power system are non-linear, thus the PID control has no ability to eliminate frequency deviation, especially when the actual work point of micro-grid deviates far from the expected work point (Tang et al., 2015). In (Farahani et al., 2012), the PID controller were optimized to eliminate frequency deviation. The main idea is to tune the gains of PID controller by the lozi map-based chaotic algorithm. Thus, a scheduling PID control strategy based on optimized parameters was applied to microgrid. Similarly, T. Chaiyatham proposed the fuzzy logic-PID controller which utilizes bee colony optimization to tune the fuzzy logic-PID controllers of micro-grid (Chaiyatham et al., 2019). For non-reheat thermal system, Gonggui Chen et al. utilized the fuzzy PID controller based on the Improved Ant Colony Optimization algorithm against system frequency deviation (Chen et al., 2020). Lim et al. (Lim et al., 1998) solved the LFC problem for the unmeasurable state in micro-grid using the robust control theory. Meanwhile, the adaptive control schemes were validated with system parameter uncertainties (Pan and Liaw, 1989).

Generally, as a well-known control method, SMC is a non-linear variable structure controller, whose control is discontinuity. As the advantages of strong robustness properties and quick response, it has been studied extensively (Li et al., 2017; Li et al., 2018; Ai-Hamouz and AbdeI-Magid, 1993; Wang et al., 2021a; Mi et al., 2013). Therefore, SMC is an alternative control strategy to address load frequency problems in micro-grid. Due to

external disturbances of renewable energy and parameter variations in internal system, SMC has gained significant research attentions in the field of LFC. AI Hamouz designed a variable structure controller using linear sliding surface, where a step disturbance was considered in the simulation (Ai-Hamouz and AbdeI-Magid, 1993). Therefore, there is a problem with this control strategy. In Sivaramakrishnan et al. (1984), a SMC was presented through the pole assignment technique, where the parametric uncertainties were studied with the matched condition. However, when the power grid is working normally, the system parameters cannot always meet the matched condition. Yang Mi proposed SMC based on proportion-lintegral sliding mode surface, and this method was proved that micro-grid can be immune to the external disturbances with matched and unmatched conditions. However, the aforementioned control strategy was studied based on the proportional-integral controller which has overshoot (Mi et al., 2013). In recent years, considering the parameter uncertainty and the complexity of external disturbances, the advanced SMC method based on disturbance observer was proposed (Li et al., 2016; Mu et al., 2017; Wang et al., 2019; Ma et al., 2017; Liu et al., 2016; Ginoya et al., 2014). In Mu et al. (2017), SMC with neural network observer was constructed, where the measured values were used to control law and it was proven to be superior in the simulation. However, the uncertainties of system parameters are not demonstrated. Ark Dev proposed a SMC based on Luenberger observer (Dev and Sarkar, 2019). However, the Luenberger observer is applied in the absence of rigorous theoretical proof.

In this paper, a disturbance observer, which estimates the matched and unmatched disturbances in the power system, is applied in the LFC. Furthermore, an adaptive SMC strategy based on disturbance observer is investigated to eliminate frequency deviation.

The main contributions of this paper are described as.

1) The disturbance observers are proposed and applied to estimate the disturbances of the multi-area interconnected

power system, which effectively track matching and unmatching disturbances.

2) SMC is improved to eliminate frequency deviation. Firstly, comparing the traditional proportional-integral sliding mode surface, the area control error (ACE) and estimated value are taken as state variables into the novel sliding mode surface, which ensures that the frequency deviation and the ACE converge to the equilibrium point. Secondly, to address the chattering of controller, the adaptive law is designed.

MODEL OF POWER SYSTEM

In the power system, the frequency deviation is caused by the fluctuation of the load. The function of LFC is to eliminate frequency deviation. The system proposed in many documents has been applied to LFC. In this chapter, the mathematical model of the power system is established where the types of disturbances are elaborated.

LFC block diagram of i th area power system is illustrated in **Figure 1**. Due to the complexity of the power system structure, it is regarded as a nonlinear system in practice. However, since the load fluctuation is very small, linearized power system model is approved for theoretical analysis. In this section, N multi-region interconnected systems that connect subsystems through tie lines are studied. When the system is disturbed, the system is adjusted by primary frequency control, which can restore the system frequency to the planned tolerance. Then, SMC is adopted to eliminate frequency deviation.

The mathematical dynamics of N regional systems can be expressed as

$$\Delta \dot{f}_i(t) = -\frac{1}{T_{pi}}\Delta f_i(t) + \frac{K_{pi}}{T_{pi}}\Delta P_{Ti}(t) - \frac{K_{pi}}{T_{pi}}\Delta P_{tie,i}(t) - \frac{K_{pi}}{T_{pi}}\Delta P_{Li}(t)$$

$$\Delta \dot{P}_{Ti}(t) = -\frac{1}{T_{ti}}\Delta P_{Ti}(t) + \frac{1}{T_{ti}}\Delta P_{Gi}(t)$$

$$\Delta \dot{E}_i(t) = K_{ei}K_{bi}\Delta f_i(t) + K_{ei}\Delta P_{tie,i}(t)$$

$$\Delta \dot{P}_{tie,i}(t) = 2\pi\sum_{j\neq i}^{i\in N}T_{ij}\Delta f_i(t) - 2\pi\sum_{j\neq i}^{i\in N}T_{ij}\Delta f_j(t)$$

$$\Delta \dot{P}_{Gi}(t) = -\frac{1}{R_iT_{gi}}\Delta f_i(t) - \frac{1}{T_{gi}}\Delta E_i(t) + \frac{1}{T_{gi}}u_i(t)$$

$$(1)$$

where $\Delta f_i(t)$, $\Delta P_{Ti}(t)$, $\Delta E_i(t)$, $\Delta P_{tie,i}(t)$, $\Delta P_{Gi}(t)$ are the deviation of frequency, machine mechanical output, integral control, tie-line power, valve position, respectively; T_{pi}, T_{ti}, T_{gi} are power system time constants, turbine time constants, governor time constants, respectively; K_{ei}, K_{bi} and K_{pi} are integral control gain, frequency bias factor and power system gain, respectively; R_i is speed regulation coefficient; T_{ij} is the tie-line co-efficient between area i and j; $i = 1, 2, 3, \cdots, N$ and N represents the number of subsystems.

In this paper, the i th ACE can be expressed as

$$ACE_i = \Delta P_{tie,i}(t) + K_{bi}\Delta f_i(t) \qquad (2)$$

Based on **Eq. 1**, the matrix form of power system can be expressed as

$$\dot{x}_i(t) = A_ix_i(t) + B_iu_i(t) + E_{ij}x_j(t) + L_i\Delta P_{Li}(t) \qquad (3)$$

where

$$x_i = \begin{bmatrix} \Delta f_i(t) & \Delta P_{Ti}(t) & \Delta E_i(t) & \Delta P_{tie,i}(t) & \Delta P_{Gi}(t) \end{bmatrix}$$

$$A_i = \begin{bmatrix} -\dfrac{1}{T_{pi}} & \dfrac{K_{pi}}{T_{pi}} & 0 & -\dfrac{K_{pi}}{T_{pi}} & 0 \\[2mm] 0 & -\dfrac{1}{T_{ti}} & 0 & 0 & \dfrac{1}{T_{ti}} \\[2mm] K_{ei}K_{bi} & 0 & 0 & K_{ei} & 0 \\[2mm] 2\pi\sum_{j\neq i}^{i\in N}T_{ij} & 0 & 0 & 0 & 0 \\[2mm] -\dfrac{1}{R_iT_{gi}} & 0 & -\dfrac{1}{T_{gi}} & 0 & 0 \end{bmatrix}$$

$$B_i = \begin{bmatrix} 0 & 0 & 0 & 0 & \dfrac{1}{T_{gi}} \end{bmatrix}^T,$$

$$E_{ij} = \begin{bmatrix} 0 & & 0 & 0 & 0 & 0 \\ 0 & & 0 & 0 & 0 & 0 \\ 0 & & 0 & 0 & 0 & 0 \\ -2\pi\sum_{j\neq i}^{i\in N}T_{ij} & 0 & 0 & 0 & 0 \\ 0 & & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$L_i = \begin{bmatrix} -\dfrac{K_{pi}}{T_{pi}} & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

where A_i is the system matrix; B_i is the input matrix; E_{ij} is the interconnection matrix; L_i is the load disturbance matrix.

When the system is working, there is uncertainty in the system matrix, which is an important factor leading to frequency deviation. In this section, the uncertainty of system parameters and load disturbances are regarded as concentrated disturbances which are characterized by linearity and nonlinearity. Then, according to **Eq. 3**, we get

$$\dot{x}_i(t) = A_ix_i(t) + B_iu_i(t) + E_{ij}x_j(t) + \Gamma_i(t) \qquad (4)$$

$$\Gamma_i(t) = A_i^{\vee}x_i(t) + B_i^{\vee}u_i(t) + E_{ij}^{\vee}x_j(t) + L_i\Delta P_{Li}(t) \qquad (5)$$

where $A_i^{\vee}$, $B_i^{\vee}$ and $E_{ij}^{\vee}$ are matrices with uncertain parameters. Furthermore, assume that the integrated disturbance is matched/mismatched and bounded.

$$\|\Gamma_i(t)\| \leq \alpha.$$

where α is a positive constant.

DESIGN OF SMC WITH DISTURBANCE OBSERVER

Design of Disturbance Observer

In the power system, there are matching and mismatching disturbances, which are unknown. The uncertainty and load satisfy the following assumption:

Assumption 1. $rank[B_i, \Gamma_i(t)] = rank[B_i]$ or $rank[B_i, \Gamma_i(t)] \neq rank[B_i]$.

Based on Assumption 1, the concentrated disturbance can be expressed as follows

$$\Gamma_i(t) = \begin{bmatrix} d_{i1} & d_{i2} & d_{i3} & d_{i4} & d_{i5} \end{bmatrix}^T$$

With the concentrated disturbance composed of system parameter uncertainty and load, a nonlinear disturbance observer is designed to estimate the unknown disturbance as follows

$$\begin{bmatrix} \widehat{d}_{i1} \\ \widehat{d}_{i2} \\ \widehat{d}_{i3} \\ \widehat{d}_{i4} \\ \widehat{d}_{i5} \end{bmatrix} = \begin{bmatrix} p_{i1} \\ p_{i2} \\ p_{i3} \\ p_{i4} \\ p_{i5} \end{bmatrix} + L_i x_i \tag{6}$$

$$\begin{bmatrix} \dot{p}_{i1} \\ \dot{p}_{i2} \\ \dot{p}_{i3} \\ \dot{p}_{i4} \\ \dot{p}_{i5} \end{bmatrix} = -L_i \left(L_i x_i + \begin{pmatrix} p_{i1} \\ p_{i2} \\ p_{i3} \\ p_{i4} \\ p_{i5} \end{pmatrix} \right) - L_i \left(A_i x_i(t) + B_i u_i(t) + E_{ij} x_j(t) \right) \tag{7}$$

where $\widehat{\Gamma}_i(t) = \begin{bmatrix} \widehat{d}_{i1} & \widehat{d}_{i2} & \widehat{d}_{i3} & \widehat{d}_{i4} & \widehat{d}_{i5} \end{bmatrix}^T$ is the estimated value of the disturbance, which is the matched and unmatched disturbance of the system. L_i is the designed observer matrix gain, $\begin{bmatrix} p_{i1} & p_{i2} & p_{i3} & p_{i4} & p_{i5} \end{bmatrix}^T$ is the auxiliary vector.

Design of SMC

SMC has been proven to be a powerful controller in many documents, and it is adopted to many fields, such as aircraft, robots, and inverted pendulums. Traditionally, there are two crucial steps in SMC, which are the sliding surface and the control law. The sliding surface ensures that the system state reaches the equilibrium point, and the control law drives the state of the space to the sliding surface. For matching and matching disturbances, the proportional-integral sliding surface is generally adopted in SMC.

$$s(t) = C_{i1} x_i + C_{i2} \int_0^t x_i dt \tag{8}$$

where C_{i1} and C_{i2} are the vectors of design parameters. The dimensions of vectors are $C_{i1} \in \mathbb{R}^{6 \times 1}$ and $C_{i2} \in \mathbb{R}^{6 \times 1}$. In an interconnected power system, the sliding mode surface is constructed based on $\Delta f_i(t)$, $\Delta P_{Ti}(t)$, $\Delta E_i(t)$, $\Delta P_{tie,i}(t)$ and $\Delta P_{Gi}(t)$ to ensure that the system state converges in a finite time. ACE, calculated by the integral, cannot guarantee the adjustment to zero, which drives the frequency deviation to escape the scheduled scope. Based on the above analysis, we improved the sliding surface to meet the LFC of the interconnected system.

The improved sliding surface is

$$\widehat{s}_i(t) = C_{i1} x_i + C_{i2} \int_0^t x_i dt + c_{i11} \left(\int_0^t ACE_i dt + \int_0^t \right.$$
$$\left. \times \int_0^t ACE_i dt \, dt \right) + C_i \widehat{\Gamma}_i(t) \tag{9}$$

where $C_{i1} = \begin{bmatrix} c_{i1} & c_{i2} & c_{i3} & c_{i4} & c_{i5} \end{bmatrix}$ and $C_{i2} = \begin{bmatrix} c_{i6} & c_{i7} & c_{i8} & c_{i9} & c_{i10} \end{bmatrix}$ are the designed parameters, and $C_i = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \end{bmatrix}$. c_{i11} is a positive constant.

In SMC, the chattering problem is difficult to address. In this paper, the adaptive control is used to slow down the output

chattering of the controller. Based on **Eq. 9**, the adaptive controller can be obtained

$$u_i(t) = -(C_{i1} B_i)^{-1} \left(C_{i1} A_i x_i(t) + c_{i11} \dot{ACE}(t) + C_{i2} x_i \right.$$
$$\left. + c_{i11} \int_0^t ACE dt + C_{i1} E_{ij} x_j(t) + C_{i1} \widehat{\Gamma}_i(t) + \alpha_i \widehat{s}(t) + \widehat{\beta}_i sign\left(\widehat{s}(t) \right) \right) \tag{10}$$

where c_{i11} and α_i are the positive constants, $sign(*)$ is the symbolic function, $\widehat{\beta}_i$ is the adaptive control law. The definition of $\widehat{\beta}_i$ is as follows:

$$\dot{\widehat{\beta}}_i = k \left\| \widehat{s}_i(t) \right\| \tag{11}$$

where k is a positive constant.

STABILITY ANALYSIS

In this section, the stability of disturbance observer and SMC is proved.

Stability Analysis of Disturbance Observer

To prove that the disturbance observer can track matched/unmatched disturbances, the following assumptions are necessary.

Assumption 2. The derivative of the disturbance in the system satisfies $\lim\limits_{t \to \infty} \dot{\Gamma}_i(t) = 0$.

Assumption 3. The error e_i in the system is bounded, that is, $\|e_i\| \le \|e_i^*\|$.

$$e_i = \Gamma_i(t) - \widehat{\Gamma}_i(t) \tag{12}$$

where e_i^* is a positive constant.
Proof:
    Based on Assumption 3, the derivative of the error is given

$$\dot{e}_i = \dot{\Gamma}_i(t) - \dot{\widehat{\Gamma}}_i(t) \tag{13}$$

Combining **Eqs 6**, **8**, **9**, we get

$$\begin{aligned} \dot{e}_i &= \dot{\Gamma}_i(t) - \begin{bmatrix} \dot{p}_{i1} & \dot{p}_{i2} & \dot{p}_{i3} & \dot{p}_{i4} & \dot{p}_{i5} \end{bmatrix}^T - L_i \dot{x}_i \\ &= \dot{\Gamma}_i(t) - \begin{bmatrix} \dot{p}_{i1} & \dot{p}_{i2} & \dot{p}_{i3} & \dot{p}_{i4} & \dot{p}_{i5} \end{bmatrix}^T \\ &\quad - L_i \left(A_i x_i(t) + B_i u_i(t) + E_{ij} x_j(t) + \Gamma_i(t) \right) \\ &= \dot{\Gamma}_i(t) - L_i \left(L_i x_i + \begin{bmatrix} p_{i1} & p_{i2} & p_{i3} & p_{i4} & p_{i5} \end{bmatrix}^T \right) \\ &\quad + L_i \left(A_i x_i(t) + B_i u_i(t) + E_{ij} x_j(t) \right) - L_i \left(A_i x_i(t) + B_i u_i(t) \right. \\ &\quad \left. + E_{ij} x_j(t) + \Gamma_i(t) \right) = \dot{\Gamma}_i(t) - L_i \left(\Gamma_i(t) - \widehat{\Gamma}_i(t) \right) \le -L_i \|e_i^*\| \end{aligned} \tag{14}$$

By means of **Eq. 14**, it can be concluded that the observer can estimate the disturbance in a finite time.

Stability Analysis of Improved SMC

For an adaptive controller **Eq. 10**, it is necessary to prove the stability of system **Eq. 4**. Next, the Lyapunov approach is adopted to analysis the stability of the system under the controller.
Proof:

TABLE 1 | The Parameters of interconnection system.

Area	T_{pi}	T_{ti}	T_{gi}	K_{pi}	K_{ei}	K_{bi}	E_{ij}
1	20	0.3	0.08	120	10	0.41	$E_{12} = 0.5$
2	25	0.33	0.07	113	9	0.37	$E_{21} = 0.5$

The Lyapunov function is constructed as follows:

$$S_i = \frac{1}{2}\widehat{s}_i^2(t) + \frac{1}{2k}\widetilde{\beta}_i^2 \tag{15}$$

where $\widetilde{\beta}_i = \widehat{\beta} - \overline{\beta}$, $\dot{\widetilde{\beta}}_i = \dot{\widehat{\beta}}_i - \dot{\overline{\beta}}_i = \dot{\widehat{\beta}}_i \cdot \overline{\beta}_i$ is a positive constant.

The derivative of S_i becomes

$$\dot{S}_i = \widehat{s}_i(t) \cdot \dot{\widehat{s}}_i(t) + \frac{1}{k}\widetilde{\beta}_i \cdot \dot{\widetilde{\beta}}_i \tag{16}$$

Differentiating improved sliding surface **Eq. 9**, we get

$$\dot{\widehat{s}}_i(t) = C_{i1}\dot{x} + C_{i2}x_i + c_{i11}\dot{ACE}_i(t) + c_{i11}\int_0^t ACE_i dt + C_i\dot{\widehat{\Gamma}}_i(t) \tag{17}$$

Substituting **Eq. 4**, we get

$$S_i = \widehat{s}_i(t) \cdot \left(C_{i1}\Big(A_i x_i(t) + B_i u_i(t) + E_{ij}x_j(t) + \Gamma_i(t)\Big) \right.$$
$$\left. + C_{i2}x_i + c_{i11}\dot{ACE}_i(t) + c_{i11}\int_0^t ACE_i dt + C_i\dot{\widehat{\Gamma}}_i(t) \right) + \frac{1}{k}\widetilde{\beta}_i \cdot \dot{\widetilde{\beta}}_i \tag{18}$$

Using **Eqs 6**, **10**, **11**, the $\dot{S}$ is as

$$\dot{S} = \widehat{s}_i(t)\left(C_{i1}\Big(\Gamma_i(t) - \widehat{\Gamma}_i(t)\Big) - \alpha_i\widehat{s}_i(t) - \widehat{\beta}_i sign\Big(\widehat{s}_i(t)\Big) \right)$$
$$+ \frac{1}{k}\Big(\widehat{\beta}_i - \overline{\beta}_i\Big) \cdot \dot{\widehat{\beta}}_i \leq -\alpha_i\big\|\widehat{s}_i(t)\big\|^2 - \widehat{\beta}_i \cdot \widehat{s}_i(t) \cdot sign\Big(\widehat{s}_i(t)\Big)$$
$$- \frac{1}{k}\dot{\widehat{\beta}}_i \cdot \overline{\beta}_i + \widehat{\beta}_i\big\|\widehat{s}_i(t)\big\| = -\alpha_i\big\|\widehat{s}_i(t)\big\|^2 - \overline{\beta}_i\big\|\widehat{s}_i(t)\big\| \leq 0 \tag{19}$$

where $\overline{\beta}_i \geq \big\|C_{i1}e_i^*\big\|$.

From **Eq. 19**, we can conclude that when the coefficients of the controller are selected appropriately, the frequency deviation of system **Eq. 4** is eliminated with the controller **Eq. 10**.

SIMULATION ANALYSIS

Several simulations are presented for improved SMC in this section. In the simulation, frequency deviation of single and interconnected systems is analyzed. First, in presence of load fluctuation, the control performances are presented, such as, the frequency deviation, the sliding mode surface, and the controller output. Secondly, when there are parameter uncertainties and load disturbances in the interconnected system, the designed SMC performance is analyzed. The parameters of the system are shown in **Table 1** (Mi et al., 2013).

Single-Area Power System

The step load disturbances are applied to the system. The load disturbance is applied to the system, which is a −0.1 p.u. disturbance applied on the system at 0–10 s. Moreover, the
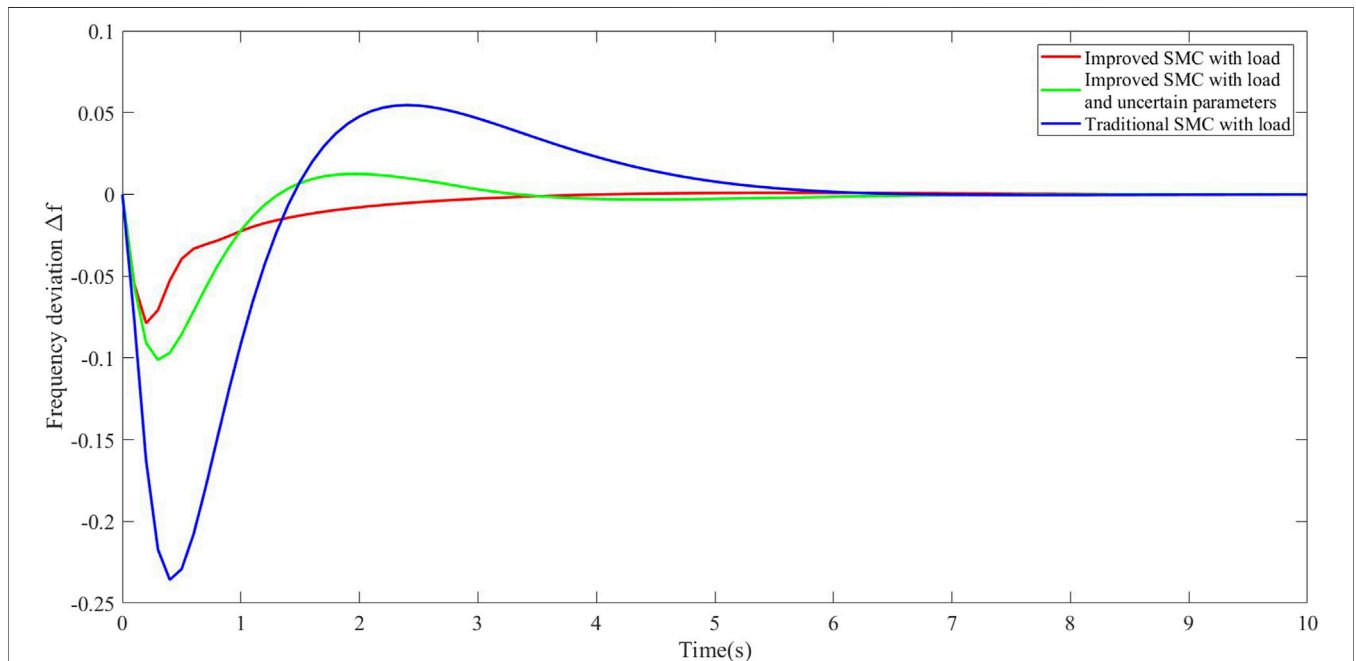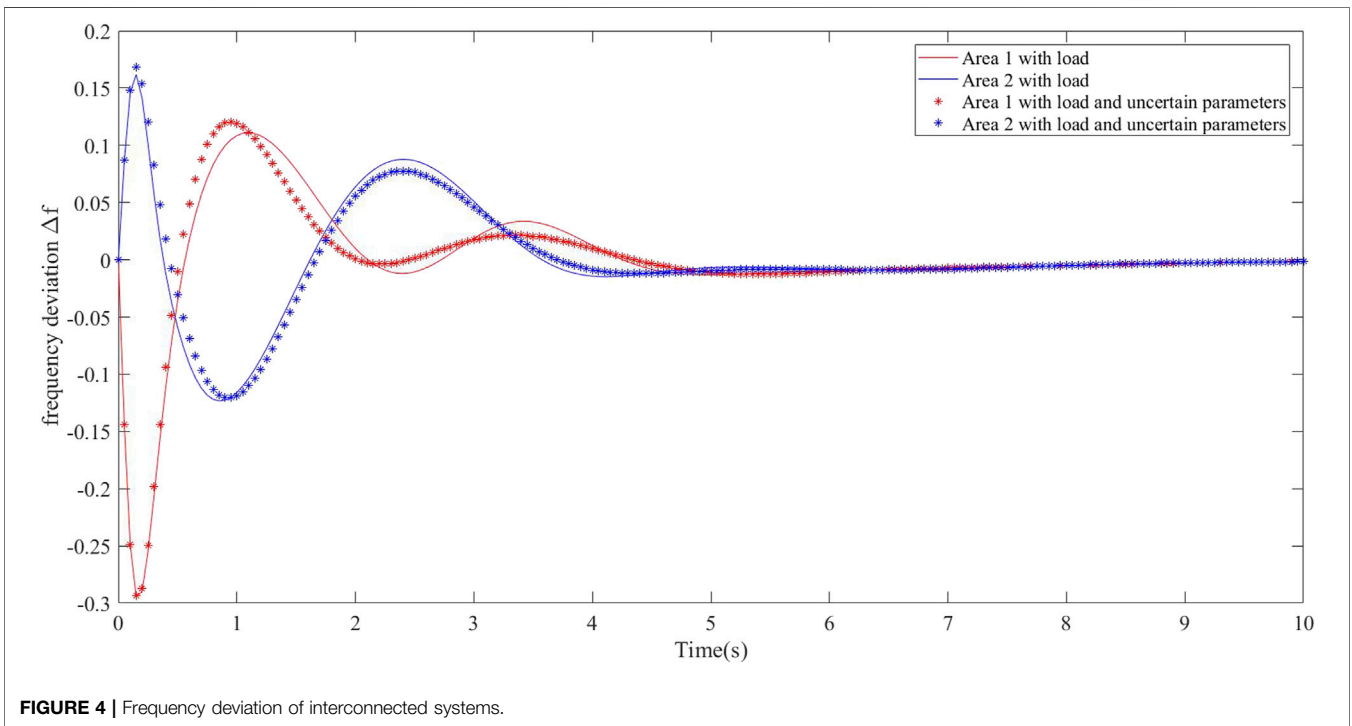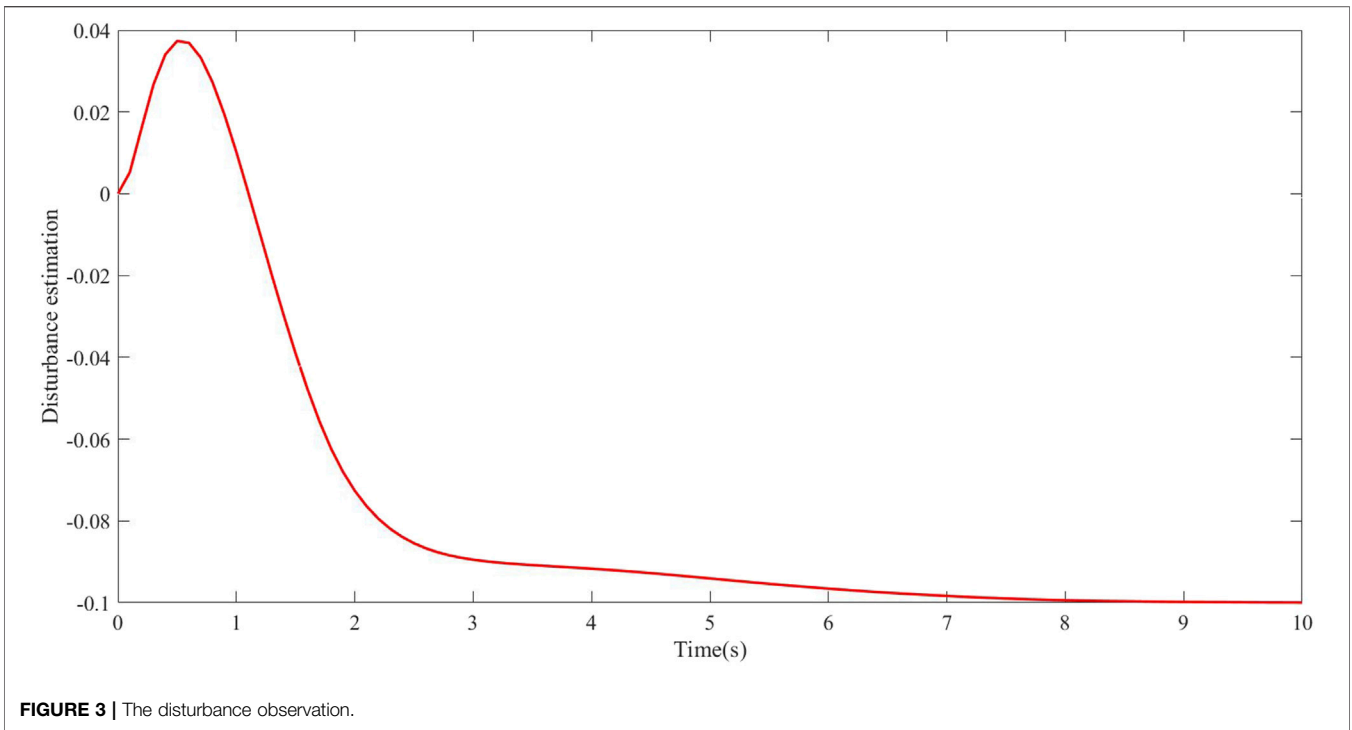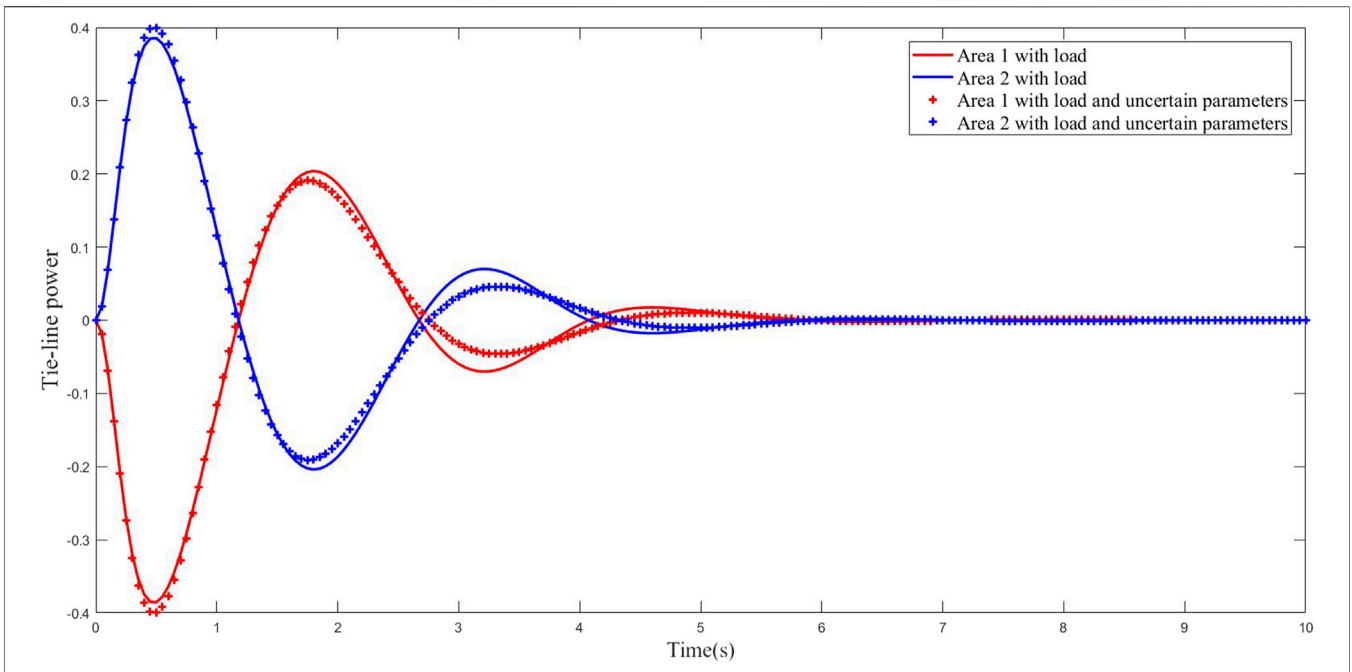

FIGURE 2 | The frequency deviation.

FIGURE 3 | The disturbance observation.

FIGURE 4 | Frequency deviation of interconnected systems.

FIGURE 5 | The power exchange of tie line.
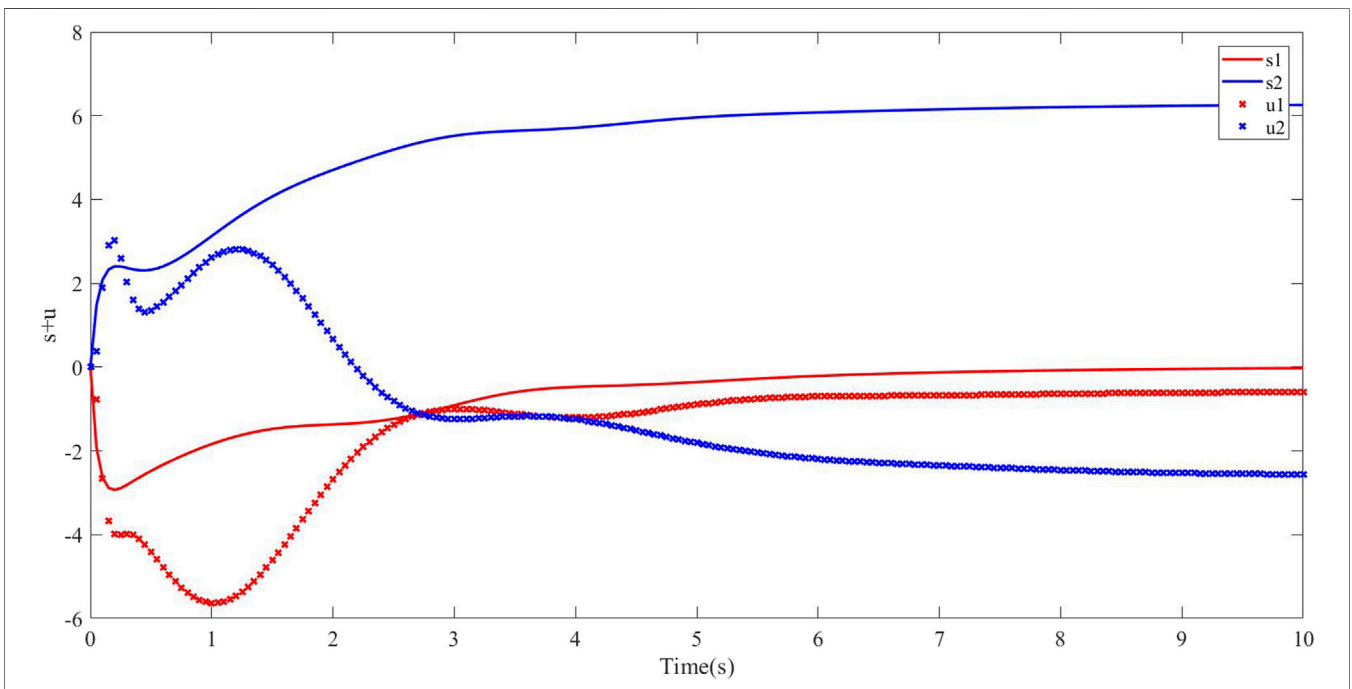
FIGURE 6 | Sliding mode surface and control law with multiple systems.

FIGURE 7 | Disturbance estimation.
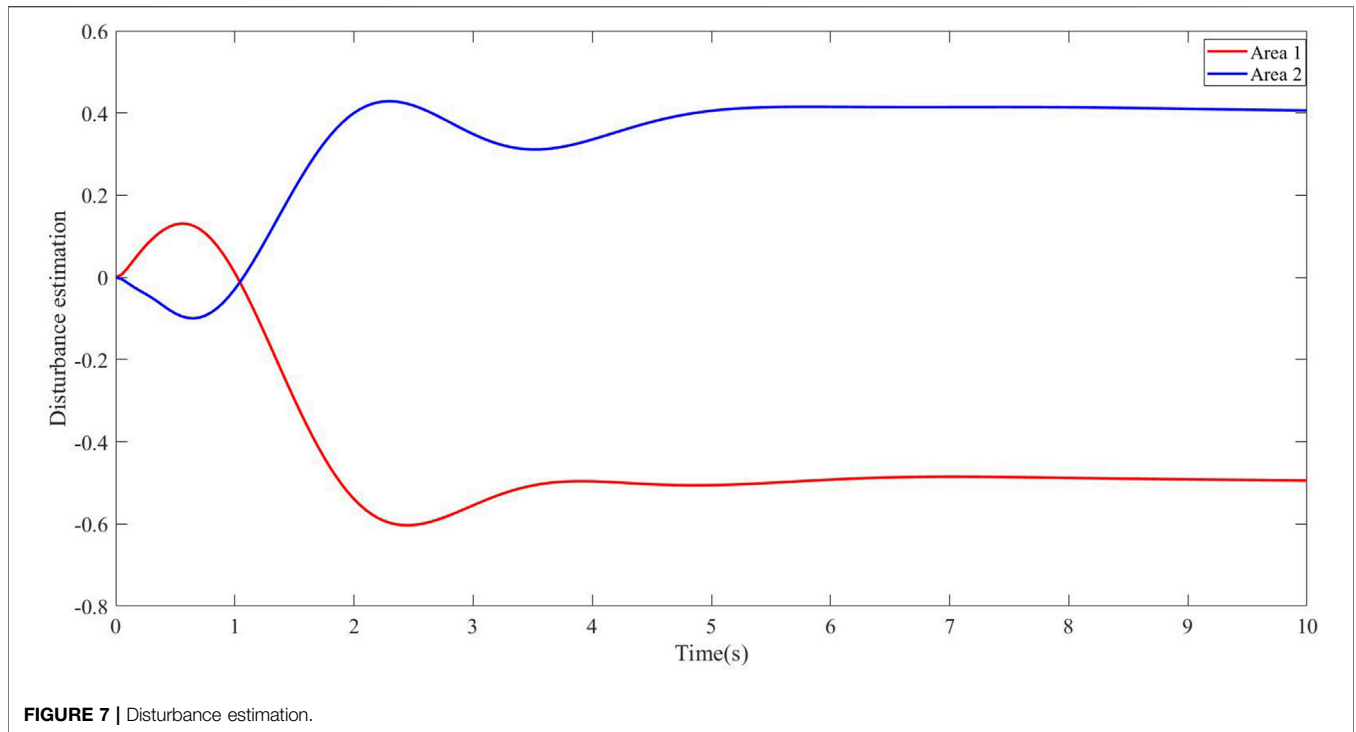
parameter uncertainty in the single system is analyzed. The parameters of disturbance observer, SMC and parameter uncertainty are as follows:

$$C_{11} = \begin{bmatrix} 20 & 9 & 1 & 1 & 1 \end{bmatrix}^T, C_{12} = \begin{bmatrix} 23 & 8 & 4 & 3 & 2 \end{bmatrix}^T,$$

$$c_{111} = 1, \alpha_1 = 6, k = 10, L_1 = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$A_1^\vee = \begin{bmatrix} 0 & e^{-t} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The frequency deviation with traditional SMC and improved SMC is shown in **Figure 2**. Compared with the traditional SMC, the designed SMC effectively suppresses the frequency deviation. In addition, the control strategy has been verified to effectively eliminate the frequency deviation caused by the uncertainty of the system parameters. From **Figure 3**, it concludes that the designed disturbance observer can track the load disturbance.

Multi-Area Power System

There are linear disturbances and parameter uncertainties in multi-area systems ($N = 2$). The load disturbance in area 1 is a −0.5 p.u., and the load disturbance in area 2 is a 0.4 p.u. The

parameters of disturbance observer, SMC and parameter uncertainties in multi-area are as follows:

$$C_{21} = \begin{bmatrix} 25 & 6 & 3 & 1 & 1 \end{bmatrix}^T, C_{22} = \begin{bmatrix} 15 & 8 & 1 & 1 & 1 \end{bmatrix}^T,$$

$$c_{211} = 1, \alpha_2 = 6, L_2 = L_1, A_1^\vee = \begin{bmatrix} 0 & 0 & 0 & \sin(t) & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$A_2^\vee = \begin{bmatrix} 0 & 0 & 0 & -\cos(t) & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

In multi-area systems, it can be concluded that when the system has disturbances and nonlinear parameter uncertainties, the system frequency can be eliminated with the designed SMC from **Figure 4**. In addition, we can know that the power exchange of tie line converges to zero at 10 s from **Figure 5**. The sliding mode surface and control law in the system are presented in **Figure 6**. In **Figure 7**, the estimated values of the disturbance observer in area 1 and area 2 can effectively estimate the load disturbance.

CONCLUSION

In this paper, the frequency in the power system, regarded as the most basic feature of the power system, is solved by the designed control strategy. An improved SMC is proposed, which guarantees the stability of the system with disturbances. Firstly, the

disturbance observer is used in LFC, which calculates the disturbance. Furthermore, it is proved by Lyapunov stability theory. Secondly, the adaptive SMC based on the disturbance observer is designed, which destroys the conservativeness of the traditional SMC. Then, it is proved to ensure the system stability. Finally, several simulation results are presented. In addition, for power systems with nonlinear characteristics, the advanced control strategy will be further studied.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

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