Research Article

Distributed Sliding Mode Fault-Tolerant LFC for Multiarea Interconnected Power Systems under Sensor Fault

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This paper focuses on the problem of load frequency control and sensor fault-tolerant control in the multiarea power grid. To solve these problems, a sliding mode control strategy based on an interval observer is designed. First, an interval observer is designed to obtain the boundary estimation information of the system state online, which is used to reconstruct the load disturbance online. Based on the reconstructed values, an integral sliding mode controller is designed to keep the system frequency stable when the load is disturbed. Then, sensor fault is diagnosed by interval residual. An augmented observer is designed to estimate sensor fault online by equivalent transformation, and the sensor fault is compensated by the fault estimation to reduce the influence of fault on system performance and ensure the reliable and stable operation of the power system. The simulation results show the superiority of the proposed control strategy.

1. Introduction

1.1. Literature Review. Because of the increasing size, interconnection, and complexity of power systems, today's power grids are composed of multiple highly interconnected areas, and various communication devices are used to protect, monitor, and control the power grid [1, 2]. The areas are connected via tie lines to eliminate any mismatching between generating and demand. Frequency, as an important index of power quality, should be stable within a certain range, so the active power balance should be guaranteed in the operation of power system [3]. However, because of the continuous growth of the installed capacity of power systems, the continuous access of new energy and distributed energy storage system have brought new challenges to maintaining system frequency stable [4, 5]. For example, the high permeability of renewable energy, such as wind power, can lead to power quality and stability problems in

the power grid, which adversely affect the operation frequency of the grid [6, 7]. Thus, frequency regulation is becoming more prominent in the reconstituted power systems [8]. Besides, the change of the load will cause the corresponding deviation of the system frequency and the power of the link line, resulting in the corresponding change of the power generated [9]. At the same time, network security [10, 11] and sensor fault [12–14] cannot be ignored. When the sensor is faulty due to malicious attack signals, the fault will lead to a large frequency deviation. Even in the normal operation of communication network, sensors will inevitably be damaged or affected by interference signals, resulting in fault. The sensor faults can make a harmful effect on the power grid or even cause damage to the power grid during operating [15, 16]. Therefore, it is particularly important to design an effective LFC strategy with fault diagnosis and FTC scheme to reliably control the frequency of power system within an acceptable range.

1.2. Research Gap and Motivation. At present, the main method for improving the frequency stability of each area in power system is the load frequency control, which continuously adjusts the active output of the frequency-modulated generator set in the system to maintain the real-time active power balance between the generating side and the demand side [17]. However, with the increasing power demand and the increasing complexity of the system structure, the uncertainty of the system model is bound to increase, which reduces the accuracy and speed of load frequency control. In order to design a load frequency controller with good control performance, scholars at home and abroad have made great achievements in the physics-based dynamic model and data-driven methods, such as fuzzy logic control [18, 19], optimal control [20], model-free adaptive control [21], model predictive control [22, 23], robust control [24, 25], and other advanced control theories [26, 27]. Among them, a distributed optimal load frequency control scheme that can realize frequency regulation and economic scheduling was proposed in [20]. Because of the characteristics of random fluctuations in load disturbances, an LFC strategy based on a disturbance observer is proposed in [27]. However, the complex structure of the disturbance observer limits the practical application of these methods. The interval observer can determine the bound values of the state by assuming that the uncertainty in the system is unknown but bounded [28–30]. This advantage has been applied to state estimation [29] and fault detection [31]. However, unknown input reconstruction based on the interval estimation is still a problem to be solved.

In addition, in recent decades, research on system faults has been focused on fault detection and FTC and lots of significant fruits have been achieved [32–36]. For a class of nonlinear Markovian jump systems, an observer-based fault-tolerant control scheme is proposed to make the closed-loop system randomly stable [32]. The distributed fault-tolerant control for interconnected systems is proposed to ensure the overall stability and constraints of the system when faults occur [33]. In order to solve the problem of sensor fault in nonlinear systems with uncertain parameters, a fault estimation technique based on an adaptive sliding mode observer was investigated in [37]. In addition to the large and complicated power network of a power system, the power system is operated, protected, and controlled through an intricate communication system [38]. Therefore, reducing the impact of sensor failures on the system is a serious challenge.

Based on the above research, we propose an interval disturbance reconstruction technique to rapidly and accurately decouple and reconstruct the load disturbances in each region, so that the sliding mode load frequency control strategy based on interval disturbance reconstruction can effectively and quickly respond to the load changes and keep the system frequency deviation within a small range. Aiming at the sensor fault problem, we design a controller based on fault compensation to reduce the influence of the fault on the system and improve the system performance.

1.3. Contribution and Paper Organization. In this paper, load disturbance and sensor fault are considered to stabilize the system frequency. Considering load fluctuation reconstruction, parameter uncertainty, sensor fault diagnosis, fault estimation, and fault transition, this paper proposes a fault-tolerant load frequency control strategy based on interval disturbance reconstruction. The main contributions are summarized as follows:

- (1) Interval observers are designed in each area of the LFC model of the multiarea interconnected power system, and the boundary value of system state quantity in each area is estimated rapidly and stably by using the designed observer.
- (2) Using the estimation values of the bound values of the system state combined with the disturbance reconstruction technology, the system uncertainty items including load disturbance and uncertain parameters are reconstructed online.
- (3) The interval residual errors based on the interval observer can be used for online monitoring and diagnosis of system sensor faults.
- (4) The system sensor fault is regarded as a system state. An augmented observer is designed to estimate the sensor fault online, and the fault estimate is used for fault compensation. The sliding mode fault-tolerant load frequency control strategy is proposed to maintain the reliability and stability of the system under the problems of load disturbance and sensor fault.

The remainder of this research is organized as follows. The LFC model in the multiarea interconnected power grid and some preliminaries are introduced in Section 2. The interval observer-based disturbance reconstruction and the new-type load frequency controller are presented in Section 3. Sensor fault diagnosis, fault estimation, and the corresponding FTC strategy are given in Section 4. The simulation results are demonstrated in Section 5, and the conclusions are shown in Section 6.

2. Problem Formulation and Preliminaries

2.1. LFC System. The LFC problem for the multiarea power grid is considered in this paper. A three-area interconnected power grid is shown in Figure 1. Although the power grid has nonlinear and time varying characteristics, under stable operating conditions, the load variation range is small. It is possible to consider a linearized model near the steady-state operating point of system. A multiarea power grid usually consists of N LFC areas. For the sake of simplicity, use one equivalent generator to replace other generators in an area.

In each LFC subsystem, the frequency dynamic equation can be written as

$$\Delta \dot{f}_i = -\frac{D_i}{H_i} \Delta f_i + \frac{1}{H_i} \Delta P_{mi} - \frac{1}{H_i} \Delta P_{tie,i} - \frac{1}{H_i} \Delta P_{di}, \quad (1)$$

where Δf_i , ΔP_{di} , D_i , and H_i are the deviation of frequency, load disturbances, equivalent inertia constant, and equivalent damping coefficient; ΔP_{mi} and $\Delta P_{tie,i}$ are generator

output power and tie-line power, respectively, which can be described as

$$\Delta \dot{P}_{mi} = -\frac{1}{T_{ti}} \Delta P_{mi} + \frac{1}{T_{ti}} \Delta P_{gi}, \quad (2)$$

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

where T_{ti} is the time constants of turbine, T_{ij} is the synchronizing power coefficient in connection areas, N means there are N control areas, and ΔP_{gi} is governor valve position, which is determined by Δf_i and power generation set points ΔP_{ci} and defined as

$$\Delta \dot{P}_{gi} = -\frac{1}{R_i T_{gi}} \Delta f - \frac{1}{T_{gi}} \Delta P_{gi} - \frac{1}{T_{gi}} u_i, \quad (3)$$

where R_i and T_{gi} are the droop coefficient and time constants of governor and u_i is a power command signal generated by the automatic generation control (AGC) system to achieve the balance between the generating side and the demand side.

Combining (1)–(4), the state-space equation of i -th area can be described as

$$\dot{x}_i(t) = A_{ii}x_i(t) + B_i u_i(t) + \sum_{j \neq i}^N A_{ij}x_j(t) + F_i \Delta P_{di}(t), \quad (4)$$

$$y_i(t) = C_i x_i(t) + f_{si}(t),$$

where $x_i(t) \triangleq [\Delta f_i \ \Delta P_{mi} \ \Delta P_{gi} \ \Delta P_{tie,i}]^T$,

$$A_{ii} \triangleq \begin{bmatrix} -\frac{D_i}{H_i} & \frac{1}{H_i} & 0 & -\frac{1}{H_i} \\ 0 & -\frac{1}{T_{ti}} & \frac{1}{T_{ti}} & 0 \\ -\frac{1}{R_i T_{gi}} & 0 & -\frac{1}{T_{gi}} & 0 \\ 2\pi \sum_{j \neq i}^N T_{ij} & 0 & 0 & 0 \end{bmatrix},$$

$$A_{ij} \triangleq \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -2\pi T_{ij} & 0 & 0 & 0 \end{bmatrix},$$

$$C_i \triangleq \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$B_i \triangleq \begin{bmatrix} 0 & 0 & -\frac{1}{T_{gi}} & 0 \end{bmatrix}^T, \quad F_i \triangleq \begin{bmatrix} -\frac{1}{H_i} & 0 & 0 & 0 \end{bmatrix}^T. \quad (5)$$

Also, $x_i(t) \in \mathbb{R}^n$, $u_i(t) \in \mathbb{R}^m$, $y_i(t) \in \mathbb{R}^p$, and $f_{si}(t) \in \mathbb{R}^p$.

The actual power system is large and complex. Considering the system parameter uncertainties, the system model can be expressed as

$$\begin{aligned} \dot{x}_i(t) &= (A_{ii} + \Delta A_{ii})x_i(t) + (B_i + \Delta B_i)u_i(t) \\ &+ \sum_{j \neq i}^N ((A_{ij} + \Delta A_{ij})x_j(t) + (F_i + \Delta F_i)\Delta P_{di}(t)), \end{aligned} \quad (6)$$

where ΔA_{ii} , ΔB_i , ΔA_{ij} , ΔF_{1i} , and ΔF_{2i} denote the parameters of uncertainties.

Define

$$\begin{aligned} d_i(t) &= \Delta A_{ii}x_i(t) + \Delta B_i u_i(t) + \sum_{j \neq i}^N \Delta A_{ij}x_j(t) \\ &+ (F_i + \Delta F_i)\Delta P_{di}(t). \end{aligned} \quad (7)$$

Then, the model in (6) can be rewritten as

$$\begin{aligned} \dot{x}_i(t) &= A_{ii}x_i(t) + B_i u_i(t) + \sum_{j \neq i}^N A_{ij}x_j(t) + d_i(t), \\ y_i(t) &= C_i x_i(t) + f_{si}(t). \end{aligned} \quad (8)$$

Definition 1 (see [29]). A matrix is called Metzler matrix with nonnegative off-diagonal elements. A matrix is defined as a Hurwitz matrix if all eigenvalues have strictly negative real parts.

Lemma 1 (see [39]). For a system of the form $\dot{x}(t) = Ax(t) + \omega(t)$, where matrix A is Metzler, it has $x(t) \geq 0$ for all $t > 0$ with $x(0) > 0$, $\omega(t) > 0$.

Lemma 2 (see [40]). For the transfer function of the form $\mathcal{G}(s) = \mathcal{C}(sI - \mathcal{A})^{-1}\mathcal{B} + \mathcal{D}$, we can get the following two equivalent conditions:

- (1) $\|\mathcal{C}(sI - \mathcal{A})^{-1}\mathcal{B} + \mathcal{D}\|_\infty < \rho$ with $\mathcal{A}$ stable.
- (2) There exists a positive matrix P satisfying

$$\begin{bmatrix} P\mathcal{A} + \mathcal{A}^T P & P\mathcal{B} & \mathcal{C}^T \\ * & -\rho I & \mathcal{D}^T \\ * & * & -\rho I \end{bmatrix} < 0. \quad (9)$$

Assumption 1. The system state vector $x_i(t)$ is available for measurement.

FIGURE 1: Three-area power system.

Assumption 2. There exist two known vectors $d_i^+ > 0$ and $d_i^- < 0$ such that $d_i^- \leq d_i(t) \leq d_i^+$.

3. Interval Observer-Based Disturbance Reconstruction and Sliding Mode LFC (DR-SMC-LFC)

In this section, the load disturbance in the power system will be reconstructed with the designed interval observer. To make the perfect transient and steady-state performance under the load disturbance, an integral-type sliding mode controller will be developed in this section by using the reconstructed value.

3.1. Interval Observer Design. Design an interval observer of the following form:

$$\begin{aligned}\dot{\hat{x}}_i^+(t) &= A_{ii}y_i(t) + B_iu_i(t) + \sum_{j \neq i}^N A_{ij}y_j(t) \\ &\quad + d_i^+ - d_i^- + L_i(y_i(t) - C_i\hat{x}_i^+(t)), \\ \dot{\hat{x}}_i^-(t) &= A_{ii}y_i(t) + B_iu_i(t) + \sum_{j \neq i}^N A_{ij}y_j(t) \\ &\quad + d_i^- - d_i^+ + L_i(y_i(t) - C_i\hat{x}_i^-(t)),\end{aligned}\quad (10)$$

where $\hat{x}_i^+(t)$ and $\hat{x}_i^-(t)$ are the boundary estimations of $x_i(t)$, respectively, and L_i is the gain of interval observer which needs to be defined in advance.

Theorem 1. *Supposing that Assumptions 1 and 2 are held and a system without sensor faults, if the initial states of the proposed interval observer (10) meet the following inequalities,*

$$\hat{x}_i^-(0) \leq x_i(0) \leq \hat{x}_i^+(0), \quad (11)$$

then (10) is an interval observer for system (8) with $-L_i$ designed as Metzler and Hurwitz.

Proof. Denote estimation errors of the interval observer as $e_{1i}(t) = \hat{x}_i^+(t) - x_i(t)$ and $e_{2i}(t) = x_i(t) - \hat{x}_i^-(t)$. If the system runs normally without any sensor fault, from (8) and (10), the error dynamics system can be obtained as follows:

$$\begin{aligned}\dot{e}_{1i}(t) &= A_{ii}(C_i - I)x_i(t) + \sum_{j \neq i}^N A_{ij}(C_i - I)x_j(t) \\ &\quad + d_i^+ - d_i^- - d_i(t) - L_iC_ie_{1i}(t), \\ \dot{e}_{2i}(t) &= A_{ii}(C_i - I)x_i(t) + \sum_{j \neq i}^N A_{ij}(C_i - I)x_j(t) \\ &\quad - d_i^- + d_i^+ + d_i(t) - L_iC_ie_{2i}(t).\end{aligned}\quad (12)$$

Recalling $C_i = I_n$,

$$\begin{aligned}\dot{e}_1(t) &= d_i^+ - d_i^- - d_i(t) - L_ie_1(t), \\ \dot{e}_2(t) &= -d_i^- + d_i^+ + d_i(t) - L_ie_2(t).\end{aligned}\quad (13)$$

According to Assumption 2, it can be obtained that

$$\begin{aligned}d_i^+ - d_i^- - d_i(t) &\geq 0, \\ -d_i^- + d_i^+ + d_i(t) &\geq 0.\end{aligned}\quad (14)$$

Choosing $-L_i$ as a Metzler and Hurwitz matrix, we can obtain that $\hat{x}_i^-(t) \leq x_i(t) \leq \hat{x}_i^+(t)$, for $t \geq 0$ from Lemma 1, and the condition of Hurwitz ensures the system is stable when operating. $\square$

3.2. Disturbance Reconstruction. From Theorem 1, we can get $\hat{x}_i^-(t) \leq x_i(t) \leq \hat{x}_i^+(t)$, for all $t \geq 0$, so it is reasonable to obtain the following equation:

$$x_i(t) = \Phi_i(t)\hat{x}_i^+(t) + (I - \Phi_i(t))\hat{x}_i^-(t), \quad (15)$$

where $\Phi_i(t) = \text{diag}\{a_1(t), a_2(t), \dots, a_n(t)\}$ and $0 \leq a_i(t) \leq 1, i = 1, 2, \dots, n$.

After obtaining the interval observer according to Theorem 1, the following theorem is proposed in combination with (15), which is used to reconstruct the load disturbance.

Theorem 2. For an LFC model (8) satisfying Assumptions 1 and 2 and an interval observer satisfying Theorem 1, the external load disturbance can be reconstructed by the following algebraic computation:

$$\hat{d}_i(t) = \hat{M}_1\hat{x}_i^+ - \hat{M}_1\hat{x}_i^- + \hat{M}_2(d_i^+ - d_i^-), \quad (16)$$

where $\hat{M}_1$ and $\hat{M}_2$ are defined as

$$\hat{M}_1 = \hat{\Phi}_i(t)\hat{N}_1 + (I - \hat{\Phi}_i(t))\hat{N}_2 + \dot{\hat{\Phi}}_i(t) - A_{ii}\hat{\Phi}_i(t), \quad (17)$$

$$\hat{M}_2 = 2\hat{\Phi}_i(t) - I,$$

with $\hat{N}_1 = A_{ii}\hat{\Phi}_i(t) + L_i\hat{\Phi}_i(t) - L_i$ and $\hat{N}_2 = A_{ii}\hat{\Phi}_i(t) + L_i\hat{\Phi}_i(t)$.

Proof. According to (15) and (10), we can obtain

$$\begin{aligned} \hat{x}_i^+(t) &= N_1\hat{x}_i^+ + (A_{ii} - N_1)\hat{x}_i^- + B_i u_i(t) + d_i^+ - d_i^- \\ &\quad + \sum_{j \neq i}^N A_{ij}(\Phi_j(t)\hat{x}_j^+(t) + (I - \Phi_j(t))\hat{x}_j^-(t)), \\ \hat{x}_i^-(t) &= N_2\hat{x}_i^+ + (A_{ii} - N_2)\hat{x}_i^- + B_i u_i(t) + d_i^- - d_i^+ \\ &\quad + \sum_{j \neq i}^N A_{ij}(\Phi_j(t)\hat{x}_j^+(t) + (I - \Phi_j(t))\hat{x}_j^-(t)), \end{aligned} \quad (18)$$

where $N_1 = A_{ii}\Phi_i(t) + L_i\Phi_i(t) - L_i$ and $N_2 = A_{ii}\Phi_i(t) + L_i\Phi_i(t)$.

According to (15), the first derivative of $x_i(t)$ is

$$\begin{aligned} \dot{x}_i(t) &= (\dot{\Phi}_i(t)N_1 + (I - \dot{\Phi}_i(t))N_2 + \dot{\Phi}_i(t))\hat{x}_i^+ + B_i u_i(t) \\ &\quad + (A_{ii} - \dot{\Phi}_i(t)N_1 - (I - \dot{\Phi}_i(t))N_2 - \dot{\Phi}_i(t))\hat{x}_i^- \\ &\quad + \sum_{j \neq i}^N A_{ij}(\Phi_j(t)\hat{x}_j^+(t) + (I - \Phi_j(t))\hat{x}_j^-(t)) \\ &\quad + (2\Phi_i(t) - I)(d_i^+ - d_i^-). \end{aligned} \quad (19)$$

Substituting (8) and (15) into (19), we can obtain the reconstruction of $d_i(t)$:

$$d_i(t) = M_1\hat{x}_i^+ - M_1\hat{x}_i^- + M_2(d_i^+ - d_i^-), \quad (20)$$

where $M_1 = \Phi_i(t)N_1 + (I - \Phi_i(t))N_2 + \dot{\Phi}_i(t) - A_{ii}\Phi_i(t)$ and $M_2 = 2\Phi_i(t) - I$.

Then, the external disturbance can be reconstructed by using (20). As for the computation of $\Phi_i(t)$, we can convert (15) to the following equality to calculate $\Phi_i(t)$:

$$x_i(t) = \begin{bmatrix} \hat{x}_{i1}^+ & & & \\ & \hat{x}_{i2}^+ & & \\ & & \ddots & \\ & & & \hat{x}_{in}^+ \end{bmatrix} \begin{bmatrix} a_1(t) \\ a_2(t) \\ \vdots \\ a_n(t) \end{bmatrix} + \begin{bmatrix} \hat{x}_{i1}^- & & & \\ & \hat{x}_{i2}^- & & \\ & & \ddots & \\ & & & \hat{x}_{in}^- \end{bmatrix} \begin{bmatrix} 1 - a_1(t) \\ 1 - a_2(t) \\ \vdots \\ 1 - a_n(t) \end{bmatrix}. \quad (21)$$

Define

$$\begin{aligned} Q_1(t) &= \text{diag}\{\hat{x}_{i1}^+, \hat{x}_{i2}^+, \dots, \hat{x}_{in}^+\}, \\ Q_2(t) &= \text{diag}\{\hat{x}_{i1}^-, \hat{x}_{i2}^-, \dots, \hat{x}_{in}^-\}, \\ a_v(t) &= [a_1(t), a_2(t), \dots, a_n(t)]^T. \end{aligned} \quad (22)$$

Then, we can obtain

$$\begin{aligned} (Q_1(t) - Q_2(t))a_v(t) &= x_i(t) - \hat{x}_i^-(t), \\ a_v(t) &= (Q_1(t) - Q_2(t))^{-1}(x_i(t) - \hat{x}_i^-(t)). \end{aligned} \quad (23)$$

Consequently, the disturbance can be reconstructed by using (16). $\square$

3.3. Sliding Mode Load Frequency Controller Design. In order to maintain the system frequency stable when load disturbances occur, a new-type load frequency controller is designed and applied in this subsection which is used in the integral-type sliding mode technique. The integral-type switching surfaces can be designed as

$$s_i(t) = G_i y_i(t) - \int_0^t G_i (A_{ii} + B_i K_i) y_i(\theta) d\theta, \quad (24)$$

where G_i and K_i are constant matrices with appropriate dimension.

Traditional SMC utilizes the boundary value of load disturbance to design a control law. However, the uncertain term $d_i(t)$ always changes in actual engineering. The controller based on the boundary value ξ_i may not perform very well, so we redesigned the controller by using the reconstructed value $\hat{d}_i(t)$ and the adaptive law as follows:

$$\left\{ \begin{array}{l} u_i(t) = K_i y_i(t) - ((G_i B)_i)^{-1} [G_i \hat{d}_i(t) + \kappa_i s_i(t) \\ \quad + G_i \sum_{j \neq i}^N A_{ij} y_j(t) + \tilde{\tau}_i \|G_i\| \text{sat}(s_i(t))] \\ \text{sat}(s_i(t)) = \begin{cases} \frac{s_i(t)}{\varepsilon_i}, & \|s_i(t)\| \leq \varepsilon_i \\ \text{sign}(s_i(t)), & \|s_i(t)\| > \varepsilon_i \end{cases} \end{array} \right. , \quad (25)$$

where $\hat{d}_i(t)$ is the reconstruction of $d_i(t)$ from (16) and $\|d_i(t) - \hat{d}_i(t)\| < \tau_i$, in which τ_i is the positive constant, and we define the following adaptive law of $\tilde{\tau}_i$:

$$\dot{\tilde{\tau}}_i = n_i \|G_i\| \|s_i(t)\|. \quad (26)$$

Theorem 3. *The closed-loop control system will remain asymptotically stable under the load frequency controller (25) based on load disturbance reconstruction with adaptive law (26).*

Proof. Define a Lyapunov function as

$$V_i(t) \triangleq 0.5 s_i^2(t) + 0.5 \frac{1}{n_i} \tilde{\tau}_i^2, \quad (27)$$

where $\tilde{\tau}_i = \tau_i - \hat{\tau}_i$ and $\dot{\tilde{\tau}}_i = \dot{\tau}_i - \dot{\hat{\tau}}_i = -\dot{\hat{\tau}}_i$.

According to the switching surface (24), we can obtain

$$\begin{aligned} \dot{V}_i(t) &= s_i(t) \dot{s}_i(t) - \frac{1}{n_i} \tilde{\tau}_i \dot{\tilde{\tau}}_i \\ &= s_i(t) [G_i C_i A_{ii} x_i(t) + G_i C_i B_i u_i(t) + G_i C_i d_i(t) \\ &\quad + G_i C_i \sum_{j \neq i}^N A_{ij} x_j(t) - G_i A_{ii} C_i x_i(t) \\ &\quad - G_i B_i K_i C_i x_i(t)] - \frac{1}{n_i} \tilde{\tau}_i \dot{\tilde{\tau}}_i. \end{aligned} \quad (28)$$

Recalling $C_i = I_n$,

$$\begin{aligned} \dot{V}_i(t) &= s_i(t) \left[G_i B_i u_i(t) + G_i \sum_{j \neq i}^N A_{ij} x_j(t) + G_i d_i(t) \right. \\ &\quad \left. - G_i B_i K_i C_i x_i(t) \right] - \frac{1}{n_i} \tilde{\tau}_i \dot{\tilde{\tau}}_i \\ &= s_i(t) [G_i (d_i(t) - \hat{d}_i(t)) - \kappa_i s_i(t) \\ &\quad - \hat{\tau}_i \|G_i\| \text{sat}(s_i(t))] - \frac{1}{n_i} \tilde{\tau}_i \dot{\tilde{\tau}}_i \\ &\leq \|G_i\| \|s_i(t)\| \tau_i - \kappa_i \|s_i(t)\|^2 - \|G_i\| \|s_i(t)\| \hat{\tau}_i \\ &\quad - \frac{1}{n_i} \tilde{\tau}_i \dot{\tilde{\tau}}_i \\ &= \|G_i\| \|s_i(t)\| (\tau_i - \hat{\tau}_i - \tilde{\tau}_i) - \kappa_i \|s_i(t)\|^2 \\ &= -\kappa_i \|s_i(t)\|^2 < 0. \end{aligned} \quad (29)$$

Consequently, it can be concluded that the system state will eventually remain stable under the proposed controller, which implies the new-type LFC controller can ensure the stability of each control area in power system. $\square$

4. Sensors Fault Diagnosis and Estimation and FTC Strategy

The closed-loop control of the system requires precise measurements. However, any fault that may affect the sensor

will inevitably lead to performance degradation and cause system damage. Therefore, to ensure the stability and reliability when the system is operating, it is necessary to perform fault detection and fault tolerance control when faults occur. In this section, the fault diagnosis based on interval residual errors, sensor fault estimation based on the augmented observer, and FTC strategy are defined, and the whole control strategy is redesigned as shown in Figure 2.

4.1. Fault Diagnosis. According to the interval observer designed in Section 3, the following interval residual errors are designed for sensor fault diagnosis:

$$\begin{aligned} r_i^+(t) &= y_i(t) - \hat{y}_i^-(t), \\ r_i^-(t) &= y_i(t) - \hat{y}_i^+(t), \end{aligned} \quad (30)$$

where

$$\begin{aligned} \hat{y}_i^+(t) &= C_i^+ \hat{x}_i^+(t) - C_i^- \hat{x}_i^-(t), \\ \hat{y}_i^-(t) &= C_i^+ \hat{x}_i^-(t) - C_i^- \hat{x}_i^+(t). \end{aligned} \quad (31)$$

According to Theorem 1, if $-L_i$ is designed as a Metzler matrix, then under the initial condition $\hat{x}_i^-(0) \leq x_i(0) \leq \hat{x}_i^+(0)$ and without sensor faults, we can get

$$\begin{aligned} \hat{x}_i^-(t) &\leq x_i(t) \leq \hat{x}_i^+(t), \\ \hat{y}_i^-(t) &\leq y_i(t) \leq \hat{y}_i^+(t), \end{aligned} \quad (32)$$

$$0 \in [r_{is}^-(t), r_{is}^+(t)], s = 1, 2, \dots, 4.$$

In case of faults, even if $-L_i$ is designed as Metzler and Hurwitz, the nonnegativity of the error dynamics cannot be guaranteed. Therefore, $0 \in [r_{is}^-(t), r_{is}^+(t)]$ will not be guaranteed at this time, which can be used for detecting faults.

4.2. Fault Estimation. The following augmented system (33) is designed which is equivalent to the original dynamic system (8). This equivalent transformation treats the sensor failure $f_{si}(t)$ in the original system (8) as a state one, so that an effective state observer strategy can be designed, while estimating the states and sensor faults.

$$\begin{cases} \dot{\bar{x}}_i(t) = \bar{A}_{ii}\bar{x}_i(t) + \bar{B}_i u_i(t) + w_i(t) + \sum_{j \neq i}^N \bar{A}_{ij} \bar{x}_j(t) \\ y_i(t) = \bar{C}_i \bar{x}_i(t) \end{cases}, \quad (33)$$

where

$$\begin{aligned} \bar{x}_i &\triangleq \begin{bmatrix} x_i \\ f_{si} \end{bmatrix}, \bar{A}_{ii} \triangleq \begin{bmatrix} A_{ii} & 0 \\ 0 & 0_{p \times p} \end{bmatrix}, \bar{B}_i \triangleq \begin{bmatrix} B_i \\ 0_{p \times m} \end{bmatrix} \\ \bar{C}_i &\triangleq [C_i \ I_p], \bar{A}_{ij} \triangleq \begin{bmatrix} A_{ij} & 0 \\ 0 & 0_{p \times p} \end{bmatrix}, w_i = \begin{bmatrix} d_i \\ \dot{f}_{si} \end{bmatrix}. \end{aligned} \quad (34)$$

For the augmented system (33), a state observer for i th subsystem is constructed as follows:

$$\begin{cases} \dot{\hat{\bar{x}}}_i(t) = \bar{A}_{ii}\hat{\bar{x}}_i(t) + \bar{B}_i u_i(t) + L_{pi}(y_i(t) - \hat{y}_i(t)) \\ + \sum_{j \neq i}^N \bar{A}_{ij} \hat{\bar{x}}_j, \\ \hat{y}_i(t) = \bar{C}_i \hat{\bar{x}}_i(t), \end{cases} \quad (35)$$

where $\hat{\bar{x}}_i(t)$ is the estimation of $\bar{x}_i(t)$ by the augmented observer and L_{pi} is a constant matrix with appropriate dimension.

Define the state estimate error and sensor fault estimate error as $e_x(t) = \hat{x}_i(t) - x_i(t)$, $e_{fsi}(t) = \hat{f}_{si}(t) - f_{si}(t)$, and $\bar{e}_i(t) = [e_x^T(t) \ e_{fsi}^T(t)]^T$. From (33) and (35), the error dynamic system is obtained as

$$\begin{cases} \dot{\bar{e}}_i(t) = (\bar{A}_i - L_{pi}\bar{C}_i)\bar{e}_i(t) + \sum_{j \neq i}^N \bar{A}_{ij}\bar{e}_j - w_i(t) \\ e_{fsi}(t) = \bar{I}_p^T \bar{e}_i(t) \quad i = 1, 2, \dots, N \end{cases}, \quad (36)$$

where $\bar{I}_p = [0 \ I_p]^T$.

Theorem 4. Given a H_∞ performance level ρ , if there exist matrix $W_i \in \mathbb{R}^{(n+p)N \times pN} > 0$ and symmetric matrices $P_i \in \mathbb{R}^{(n+p)N \times (n+p)N} > 0$ such that condition (37) is satisfied,

$$\begin{bmatrix} \Gamma_1 & -P & I_N \otimes \bar{I}_p \\ * & -\rho I_{(n+p)N} & 0 \\ * & * & -\rho I_{pN} \end{bmatrix} < 0, \quad (37)$$

where

$$\begin{aligned} \Gamma_1 &= P\bar{A} - W\bar{C} + (P\bar{A} - W\bar{C})^T, \\ P &= \text{diag}\{P_1, P_2, \dots, P_N\}, \\ W &= \text{diag}\{W_1, W_2, \dots, W_N\}, \\ \bar{C} &= \text{diag}\{\bar{C}_1, \bar{C}_2, \dots, \bar{C}_N\}, \\ \bar{A} &= \begin{bmatrix} \bar{A}_{11} & \bar{A}_{12} & \dots & \bar{A}_{1N} \\ \bar{A}_{21} & \bar{A}_{21} & \dots & \bar{A}_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \bar{A}_{N1} & \bar{A}_{N2} & \dots & \bar{A}_{NN} \end{bmatrix}, \end{aligned} \quad (38)$$

then the error dynamics of the whole interconnected power system satisfies the H_∞ performance. Also, we can calculate the gain matrices L_p by $L_{pi} = P_i^{-1}W_i$.

Proof. Define augmented vectors and matrices as follows:

$$\begin{aligned} L_p &= \text{diag}\{L_{p1}, L_{p2}, \dots, L_{pN}\}, \\ \bar{e}(t) &= [\bar{e}_1^T(t) \ \bar{e}_2^T(t) \ \dots \ \bar{e}_N^T(t)]^T, \\ e_{fs}(t) &= [e_{fs1}^T(t) \ e_{fs2}^T(t) \ \dots \ e_{fsN}^T(t)]^T, \\ w(t) &= [w_1^T(t) \ w_2^T(t) \ \dots \ w_N^T(t)]^T. \end{aligned} \quad (39)$$

So, we can get the global error dynamics of power grid as follows:

FIGURE 2: The structure of the proposed control approach.

$$\begin{cases} \dot{\bar{e}}(t) = (\bar{A} - L_p \bar{C}) \bar{e}(t) - w(t) \\ e_{fs}(t) = I_N \otimes \bar{I}_p^T \bar{e}(t) \end{cases} \quad (40)$$

From the global view, $W = PL_p$, so (37) can be rewritten as

$$\begin{bmatrix} \Gamma_2 & -P & I_N \otimes \bar{I}_p \\ * & -\rho I_{(n+p)N} & 0 \\ * & * & -\rho I_{pN} \end{bmatrix} < 0, \quad (41)$$

where

$$\Gamma_2 = P\bar{A} - PL_p\bar{C} + (P\bar{A} - PL_p\bar{C})^T. \quad (42)$$

According to Lemma 2, if (37) is satisfied, the global error dynamics system (40) will satisfy the H_∞ performance $\| - (I_N \otimes \bar{I}_p^T)(sI - (\bar{A} - L_p\bar{C}))^{-1} \|_\infty < \rho$. $\square$

Remark 1. The H_∞ performance in Theorem 4 can inhibit the influence of $w(t)$ on sensor failure estimation error $e_{fs}(t)$. The condition in (37) is in the form of LMI which can make the design of the gain matrix L_{pi} more convenient.

4.3. Fault Compensation. According to the augmented observer designed in the previous section, the online sensor failure estimations can be obtained by

$$\hat{f}_{si}(t) = \bar{I}_p^T \hat{x}_i(t). \quad (43)$$

To keep the system stable when operating, the signals of system output are compensated accordingly by using the sensor fault estimation information, when faults occur.

$$\begin{aligned} y_{ci}(t) &= y_i(t) - \hat{f}_{si}(t) \\ &= C_i x_i(t) + f_{si}(t) - \hat{f}_{si}(t) \\ &= C_i x_i(t) + e_{fsi}(t), \end{aligned} \quad (44)$$

where $y_{ci}(t)$ is the compensated output signal.

Remark 2. The H_∞ performance used in Theorem 4 can inhibit the influence of $w(t)$ on sensor failure estimation error $e_{fs}(t)$. We can obtain accurate sensor fault estimations as long as we choose appropriate H_∞ performance level γ . Therefore, the fault compensation part can use the sensor fault estimations, which greatly eliminate the interference of the sensor faults on the system performance and guarantee the reliability and stability when the system is running.

4.4. Fault-Tolerant Control. Once the sensor faults occur, the compensation signal described in (44) is used to replace the output signal of the system measurement. Therefore, the

DR-SMC-LFC controller proposed in this paper can be redefined as

$$\begin{aligned}
 s_i(t) &= G_i y_{ci}(t) - \int_0^t G_i (A_{ii} + B_i K_i) y_{ci}(\theta) d\theta, \\
 \left\{ \begin{aligned}
 u_i(t) &= K_i y_{ci}(t) - (G_i B_i)^{-1} \left[G_i \hat{d}_i(t) + \kappa_i s_i(t) \right. \\
 &\quad \left. + G_i \sum_{j \neq i}^N A_{ij} y_{cj}(t) + \hat{\tau}_i \|G_i\| \text{sat}(s_i(t)) \right] \\
 \text{sat}(s_i(t)) &= \begin{cases} \frac{s_i(t)}{\varepsilon_i}, & \|s_i(t)\| \leq \varepsilon_i \\ \text{sign}(s_i(t)), & \|s_i(t)\| > \varepsilon_i \end{cases}
 \end{aligned} \right. \quad (45)
 \end{aligned}$$

In this way, it can not only keep the system frequency stable when the load changes in the power system but also timely compensate the measurement signal when the faults occur and realize FTC.

5. Simulation Results

To investigate the performance of the proposed method in a multiarea LFC, a three-area interconnected power grid model was built on the MATLAB/Simulink environment. Two cases with or without sensor faults under load disturbance are simulated, and the simulation results are demonstrated in Figures 3–5. The system model parameters are standardized with 100 MW as the reference value, and the established system parameters [15] are shown in Table 1. The purpose of LFC is to maintain the frequency within the nominal range and minimize the connection power between different control areas. Therefore, $\Delta f_i(t)$ and $\Delta P_{tie,i}$ can be used to compare the quality of different control strategies.

5.1. Case 1. In this case, fully considering the interconnectivity of the multiarea power grid, different load disturbances are applied in the three areas, respectively.

In order to realize the estimation of the bound values of the state in each control area by the designed interval observer, take area 1 as an example and design the parameters and initial values of the interval observer (10) as follows:

$$\begin{aligned}
 \hat{x}_1^+(0) &= [0.005; 0.005; 0.005; 0.005], \hat{x}_1^-(0) = -\hat{x}_1^+(0), \\
 d_1^+(0) &= [0.01; 0.01; 0.01; 0.01], d_1^-(0) = -d_1^+(0), \\
 L_1 &= \begin{bmatrix} 10 & -2 & -2 & -2 \\ -2 & 10 & -2 & -2 \\ -2 & -2 & 10 & -2 \\ -2 & -2 & -2 & 10 \end{bmatrix}. \quad (46)
 \end{aligned}$$

Taking the deviation of system frequency and tie-line power as an example, the real-time boundary estimations'

effect of frequency deviation is shown in Figure 3(a) and the real-time boundary estimations' effect of tie-line power deviation is shown in Figure 3(b). From the simulation results, it can be seen that the estimations of the bound values of the state can respond rapidly from its initial state, quickly follow the change of the state in each control area, and ensure the state condition of $\hat{x}_i^-(t) \leq x_i(t) \leq \hat{x}_i^+(t)$.

By using the real-time boundary estimations obtained by using the interval observer combined with the interval disturbance reconstruction technology proposed in this paper, the load disturbances in the three areas are reconstructed in real time. Figure 3(c) shows the reconstruction effect of interval disturbances which is compared with actual load disturbances. The advantage of interval disturbance reconstruction is that it does not need to obtain the precise boundary value of disturbance. The key of disturbance reconstruction is to ensure $d_i^- \leq d_i(t) \leq d_i^+$, which leaves some leeway for the designer to select the appropriate disturbance boundary. The simulation results show that although the three areas are interconnected, the interval disturbance reconstruction technology can still quickly and accurately decouple and reconstruct the load disturbances in each area, which provides an important basis for the design of the subsequent sliding mode load frequency controller.

The real-time disturbance reconstruction value obtained through interval disturbance reconstruction is used to design the new load frequency controller. To achieve control performance, take area 1 as an example; the parameters of controller (25) are designed as follows:

$$K_1 = [6, 1, 0, 3], G_1 = B_1^+, \kappa_1 = 0.02, n_1 = 0.03. \quad (47)$$

To further study the effectiveness of the designed interval disturbance reconstruction based sliding mode load frequency control strategy, the control effect is compared with the PI-type load frequency controller (PI-LFC) and the traditional sliding mode controller (SMC-LFC). The design parameters of the PI load frequency controller are obtained through repeated experiments, and the traditional sliding mode controller is selected as follows with disturbance boundary value $\xi_i = 0.01$:

FIGURE 3: Simulation performance. (a) The interval estimation for $\Delta f_i(t)$ of each power grid. (b) The interval estimation for $\Delta P_{tie,i}(t)$ of each power grid. (c) The reconstruction of the load disturbance $\Delta P_{di}(t)$ of each power grid. (d) $\Delta f_i(t)$ of each power grid under load disturbance.

FIGURE 4: Simulation performance. (a) $\Delta P_{tie,i}(t)$ of each power grid under load disturbance. (b) Interval residual errors of $\Delta f_i(t)$ of each power grid. (c) Interval residual errors of $\Delta P_{tie,i}(t)$ of each power grid. (d) The estimation of $f_{si}(t)$ of each power grid.

FIGURE 5: Simulation performance. (a) $\Delta f_i(t)$ and (b) $\Delta P_{tie,i}(t)$ of each power grid under load disturbance and sensor fault.

TABLE 1: The parameters of the three-area power grid.

	Area 1	Area 2	Area 3
D_i (p.u./Hz)	0.025	0.025	0.025
H_i (p.u. s)	0.3708	0.2708	0.2708
T_{ti} (s)	0.19	0.23	0.23
T_{gi} (s)	0.05	0.05	0.05
R_i (Hz/p.u.)	2.15	2.45	2.45
$T_{12} = 0.13, T_{13} = 0.12, T_{23} = 0.10$ (p.u./Hz)			

$$u_i(t) = K_i x_i(t) - (G_i B_i)^{-1} \left[G_i \xi_i + \kappa_i s_i(t) + G_i \sum_{j \neq i}^N A_{ij} x_j(t) + m_i \text{sign}(s_i(t)) \right]. \quad (48)$$

The comparison simulation results of the three control strategies are shown in Figures 3(d)–4(a). Figure 3(d) shows the frequency deviation of each area under different control strategies; Figure 4(a) shows the power deviation on the tie line between each area and the other areas under different control strategies.

The simulation results show that, under the influence of the same load disturbances, the PI-type load frequency controller cannot quickly respond to the change of the load disturbances, resulting in a large system frequency deviation and tie-line power deviation, and it is difficult to maintain the stability of the grid. The traditional sliding mode controller has a better control effect by virtue of its own sliding mode variable structure, but its control performance is slightly lacking due to the difficulty of setting the appropriate disturbance boundary value. The interval disturbance

reconstruction based sliding mode load frequency control strategy can effectively and quickly respond to load changes and maintain the system frequency deviation within a small range of changes.

5.2. Case 2. In actual engineering, the power grid is not only affected by load disturbances in different areas but also faces the problem of sensor fault due to the different characteristics of the sensor itself and the interference of the operating environment. Therefore, in this case, in addition to the different load disturbances in the three areas in Case 1, the problem of sensor fault in the system is also considered, and simulation experiments are carried out. For the sake of simplicity, suppose the form of sensor fault signal is as follows and sensor fault occurs after 50 s:

$$\begin{aligned}
f_{s1}(t) &= [f_{s1,1}(t) \ 0 \ 0 \ 0]^T, \\
f_{s2}(t) &= [f_{s2,1}(t) \ 0 \ 0 \ 0]^T, \\
f_{s3}(t) &= [f_{s3,1}(t) \ 0 \ 0 \ 0]^T,
\end{aligned} \tag{49}$$

where $f_{s1,1}(t)$, $f_{s2,1}(t)$, and $f_{s3,1}(t)$ are shown in Figure 4(d).

Interval residual errors based on interval observers have considered system disturbances, so there will be no false alarms due to external disturbances, which can be used for fault diagnosis. Figures 4(b) and 4(c) show the interval residual errors of $\Delta f_i(t)$ and $\Delta P_{tie,i}(t)$, respectively. When the system is operating normally, the interval residual errors satisfy $0 \in [r_{is}^-(t), r_{is}^+(t)]$, but when faults occur, there are $0 \notin [r^-[\Delta f_i], r^+[\Delta f_i]]$ and $0 \in [r^-[\Delta P_{tie,i}], r^+[\Delta P_{tie,i}]]$, from which the fault locations can be diagnosed.

The sensor fault signals will be estimated by the augmented observer online, once the fault is detected. The estimated value of the sensor faults is shown in Figure 4(d), from which we can find that the augmented observer can well track and estimate the sensor fault signals quickly.

Figures 5(a) and 5(b) show $\Delta f_i(t)$ and $\Delta P_{tie,i}(t)$ response, respectively, in each area after sensor faults occur. It can be seen from the simulation experiment that, in the case of the same fault, the controller without considering the fault compensation is difficult to avoid the interference of sensor fault, so that the system frequency and the tie-line power have a large deviation, and it is difficult to maintain the stability of the grid. However, the controller based on fault compensation can well reduce the influence of faults on the system, so that the system frequency and the deviation of tie-line power can be kept within a small range and the stability of the grid can be maintained.

6. Conclusion

A new LFC scheme based on load disturbance reconstruction is proposed for the multiarea power grid, and the corresponding FTC strategy is also developed in this paper. The conclusions of this paper are as follows:

- (1) The disturbance is reconstructed based on interval estimation, which solves the problem of decoupling and reconstruction of load disturbance.
- (2) An integral sliding mode controller based on disturbance reconstruction is designed to ensure that the frequency deviation of the system is small. The simulation results show that the proposed controller can respond to the load changes effectively and quickly and the system frequency deviation can be kept in a small range.
- (3) Sensor faults are diagnosed by interval residual. An augmented observer is designed to estimate sensor faults. The results show that the influence of sensor faults on system performance is greatly eliminated by using sensor fault estimation to compensate the system, and the system runs reliably and stably.

In the future research work, we will also study how to reduce the influence of malicious attacks on the power grid and ensure the stable operation of the power grid.

Data Availability

The data used to support the findings of this study cannot be made freely available. Access to the data is restricted.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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