Research Article

Adaptive Dynamic Surface Integral Sliding Mode Fault-Tolerant Control for Multimachine Excitation Systems with SVC

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In this paper, an adaptive dynamic surface integral sliding mode fault-tolerant controller is designed for the multimachine power system with static var compensator (SVC) to overcome the problem of actuator failure. The main features of the proposed method are as follows: (1) By combining the dynamic surface control (DSC) method with integral sliding mode (ISM), the tracking errors of the system converge to the neighborhood of zero within a finite time, and the convergence speed, tracking accuracy, and anti-interference ability of the system are also significantly improved. (2) By introducing the failure factors, an adaptive fault-tolerant controller is designed to ensure the stability of the entire system after partial failure of the actuator. (3) By estimating the norm of the ideal weight vector of the radial basis function neural networks (RBFNNs), the computational burden of the controller is reduced. Finally, the simulation results show the effectiveness of the proposed control scheme.

1. Introduction

The modern power system has the characteristics of large power grid, large unit, ultrahigh voltage, long distance power transmission, and high automatic control, which brings about great challenges to the stability operation of the power system [1–4]. The important role of generator excitation control in improving the stable operation of the power system has attracted widespread attention from researchers worldwide [5–8]. The traditional power system stabilizer (PSS) [9, 10] and linear optimal excitation control [11] are based on the approximate linearization model. Although the small disturbance stability problem can be improved, the effective suppression of large disturbances cannot be achieved. Moreover, due to parameter uncertainty, external interference, multidimensional and strong coupling, and strong nonlinear characteristics, designing a control system is a very challenging task. Therefore, advanced control strategies such as backstepping [12–15], sliding mode variable structure [16–18], and feedback linearization [19] have been proposed to solve the problem of power system excitation control.

The adaptive backstepping technique can effectively handle the case where the parameters are unknown [20–22]. In [20], the infinite bus voltage and transmission line parameters of the single-machine infinite-bus (SMIB) power system are regarded as unknown, and an adaptive backstepping excitation controller is proposed. A robust nonlinear adaptive backstepping excitation controller is designed in [21] by considering the influence of external disturbance based on the parameter uncertainty. However, the problem of “explosion of complexity” exists in the backstepping method. In order to solve this problem, the dynamic surface control method is used [23–27]. In [24], for a class of uncertain nonlinear systems with asymmetric dead zone nonlinearity, an antidisturbance dynamic surface control scheme is proposed, which effectively solves the problems of non-matching external disturbance and unknown asymmetric dead zone nonlinearity. A first-order filter is introduced on the traditional backstepping method for the power system, and the controller based on the dynamic surface method is designed in [26]. The device effectively improves the stability of the power system. For large-scale multimachine systems with static var compensator (SVC), the decentralized

dynamic surface quantization control scheme is proposed in [4] and the fuzzy dynamic surface sliding mode controller is designed in [7], which improves the robustness of the system. The partial feedback linearization (PFBL) technique is widely used in the design of excitation control systems by overcoming the limitations of direct feedback linearization (DFBL) and exact feedback linearization (EFBL) on rotor angle measurement problem. In [28], the nonlinear system model is transformed into a reduced-order linear part and a nonlinear dynamic autonomous part. The optimal control theory is used to design a linear state feedback stability controller for the reduced-order linear part, which enhances the transient stability limit of the power system.

However, the feedback linearized excitation controller has a parameter sensitivity problem. Sliding mode control (SMC) overcomes the parameter sensitivity problem due to being less sensitive to changes in parameters and external disturbances [29–34]. In [35], for the multimachine power system with external disturbance, the adaptive method and the sliding mode variable structure method are combined based on the feedback linearization to design a decentralized coordinated adaptive sliding mode stabilizer. The adaptive gain of the super-twist algorithm is constructed by using the equivalent control theory, and the finite time stability of the closed-loop power system is realized in [33]. In [36], by combining adaptive fuzzy control with sliding mode control, the chattering problem caused by system uncertainty and dynamics is overcome, and the tracking error is converged to zero better and faster. In addition, intelligent controllers [37–43] are also widely used. The fuzzy logic rules [40] and the neural networks [44, 45] are utilized to design adaptive controller for nonlinear system with parameters uncertainty and external disturbances; the robustness and anti-interference ability of control system are improved.

The static var compensator (SVC) control is also one of the effective and economical means of improving the stability of power systems. Generally, the generator excitation controller and the SVC controller are designed independently of each other, but the uncoordinated control of the SVC and the excitation will have a negative effect and even lead to system instability. The research on the excitation control problem of SMIB power system with SVC has achieved remarkable results. In [46], the sliding mode dynamic surface method and disturbance attenuation technique are adopted. Considering the external disturbance and parameter uncertainty, a nonlinear adaptive robust coordination controller for SVC and generator excitation is designed. The energy-based coordinated stability controller is constructed by using the Hamiltonian function method in [47, 48], which effectively improves the transient stability and voltage regulation performance of the power systems. Immersion and invariant (I&I) control method is widely used in the coordinated control of SVC and excitation. An I&I adaptive control method is adopted to ensure that all single-machine infinite-bus power system states are globally bounded and converge to a new stable equilibrium [3, 49]. However, in the actual operation of the power grid and power generation system, the system is more complicated and cannot be simply equivalent to a SMIB. Therefore, the excitation control of multimachine

infinite-bus power systems with SVC has become the research emphasis of this paper.

Inspired by the above research works, the objective of this paper is to design a new adaptive controller for generators with SVC to ensure the stability of the system and the performance of the transient power system when the system has parameter uncertainties and actuator failures. The controller design process includes two partial steps. First, the dynamic surface is combined with the integral sliding mode to design the fault-tolerant controller of the generator excitation controller. Second, the SVC controller is designed. The main contributions of the proposed method are summarized as follows: (1) By introducing integral sliding mode surface in the dynamic surface control process, the problem of “differential explosion” in the traditional backstepping method is solved, and the structure of the controller is simplified. The introduction of the integral sliding mode surface makes the tracking error of the system converge to zero within a finite time, thereby ensuring the convergence speed and tracking accuracy of the closed-loop system, and the anti-interference ability of the system is also improved. (2) By introducing the actuator failure factor, an adaptive fault-tolerant controller is designed to solve the problem of actuator failure and ensure that the system can still be stable after partial actuator failure. (3) By adopting the minimum parameter learning method, the norm of ideal weight vector of radial basis function neural networks (RBFNNs) is estimated online, the “dimension disaster” problem caused by the traditional neural network due to the estimated weight vector is avoided, and the calculation burden of the controller is reduced.

The rest of this paper is organized as follows. In Section 2, the mathematical model of the multimachine infinite-bus power systems with SVC is described. Coordination controller for generator excitation and SVC is designed in Section 3. The stability analysis is presented in Section 4. The effectiveness of the proposed scheme is illustrated by simulation in Section 5. The conclusion is drawn in Section 6.

2. System Dynamic Models and Problem Statement

2.1. Mathematical Models. The dynamic model of multimachine infinite-bus power systems with SVC is given in this section, in which the dynamics of the i th generator are described by a third-order differential equation, and the SVC is described by a first-order inertia equation. Then, the mathematical models of power system can be described as follows [3, 5]:

$$\begin{cases} \dot{\delta}_i(t) = \omega_i, \\ \dot{\omega}_i(t) = -\frac{D_i}{2H_i}\omega_i + \frac{\omega_{i0}}{2H_i}(P_{mi} - P_{ei}), \\ \dot{E}'_{qi}(t) = \frac{1}{T'_{d0i}}[E_{fi}(t) - E_{qi}(t)], \end{cases} \quad (1)$$

with a SVC model

$$\dot{B}_{Li} = \frac{1}{T_{Ci}} (-B_{Li} + B_{Ci} + u_{Bi}), \quad (2)$$

and the electrical equations are as follows:

$$E_{qi}(t) = E'_{qi}(t) + (x_{di} - x'_{di})I_{di}(t), \quad (3)$$

$$E_{fi}(t) = k_{ei}u_{fi}(t), \quad (4)$$

$$P_{ei}(t) = \sum_{j=1}^n E'_{qi}(t)E'_{qj}(t)B_{ij} \sin(\delta_i - \delta_j), \quad (5)$$

$$Q_{ei}(t) = -\sum_{j=1}^n E'_{qi}(t)E'_{qj}(t)B_{ij} \cos(\delta_i - \delta_j), \quad (6)$$

$$I_{di}(t) = -\sum_{j=1}^n E'_{qj}(t)B_{ij} \cos(\delta_i - \delta_j), \quad (7)$$

$$I_{qi}(t) = \sum_{j=1}^n E'_{qj}(t)B_{ij} \sin(\delta_i - \delta_j), \quad (8)$$

where the explanation of symbols used in the dynamic model (1)–(8) is given in Table 1.

Remark 1. Generally, in order to accurately describe a large-scale multimachine power system, a high-order complex

nonlinear dynamic equation is required [28], which makes it very difficult to analyze the stability of the power system and design the excitation controller [3, 5]. In order to overcome such difficulties, a third-order power system model simplified by the integral manifold method is proposed in [5, 50]. This model makes the control system design and stability analysis feasible; and it has been widely used in the design of excitation controllers for multimachine power system [7, 26, 51–53]. The third-order power system mode and the first-order static reactive power compensator model adopted in this paper are derived from [3, 5].

In order to reduce the complexity of the controller design process in Section 3, $E'_{qi}(t)$ in the generator electrical dynamics is eliminated by differentiating $P_{ei}(t)$ in (5):

$$\begin{aligned} \dot{P}_{ei}(t) &= \frac{1}{T_{doi}} \left[(E_{fi}(t) - (x_{di} - x'_{di})I_{di}(t))I_{di}(t) - P_{ei}(t) \right] \\ &\quad - Q_{ei}(t)\omega_i + \gamma_i(\delta, \omega). \end{aligned} \quad (9)$$

Let $\Delta P_{ei} = P_{ei} - P_{mi}$; we have

$$\Delta \dot{P}_{ei}(t) = \dot{P}_{ei}(t) = -\frac{1}{T_{doi}} \Delta P_{ei}(t) + \frac{1}{T_{doi}} u_i + \gamma_i(\delta, \omega). \quad (10)$$

The multimachine power systems model can be transformed into the following mathematical model [1, 5]:

$$\begin{cases} \dot{\delta}_i(t) = \omega_i, \\ \dot{\omega}_i(t) = -\frac{D_i}{2H_i}\omega_i + \frac{\omega_{i0}}{2H_i}(P_{mi} - P_{ei}) + d_{i1}, \\ \Delta \dot{P}_{ei}(t) = -\frac{1}{T_{doi}} \Delta P_{ei}(t) + \frac{1}{T_{doi}} u_i + \gamma_i(\delta, \omega) + d_{i2}, \end{cases} \quad (11)$$

where d_{i1} and d_{i2} are bounded uncertainties, including modeling errors, measurement errors, and external disturbances. u_i is the control signal of the generator with

$$u_i = E_{fi}(t)I_{qi}(t) - (x_{di} - x'_{di})I_{di}(t)I_{qi}(t) - P_{mi} - T_{doi}'Q_{ei}(t)\omega_i. \quad (12)$$

By considering the failure fault of the actuator at time t_f , the generator excitation voltage $E_{fi}(t)$ can be defined as

$$E_{fi}(t) = k_{ei}(1 - \beta_i)u_{fi}, \quad (13)$$

where β_i is the failure factor. So

$$\begin{aligned} u_i &= E_{fi}(t)I_{qi}(t) - (x_{di} - x'_{di})I_{di}(t)I_{qi}(t) - P_{mi} - T_{doi}'Q_{ei}(t)\omega_i \\ &\quad - \beta_i E_{fi}(t)I_{qi}(t). \end{aligned} \quad (14)$$

So the multimachine power systems model by considering the failure fault can be described as follows:

$$\begin{cases} \dot{\delta}_i(t) = \omega_i, \\ \dot{\omega}_i(t) = -\frac{D_i}{2H_i}\omega_i + \frac{\omega_{i0}}{2H_i}(P_{mi} - P_{ei}) + d_{i1}, \\ \Delta \dot{P}_{ei}(t) = -\frac{1}{T_{doi}} \Delta P_{ei}(t) + \frac{1}{T_{doi}} u_i + \gamma_i(\delta, \omega) + d_{i2} + F_i, \end{cases} \quad (15)$$

TABLE 1: The notation for multimachine power systems with SVC.

Symbol	Nomenclature
δ_i	The power angle of the i th generator, in rad
ω_i	The relative speed of the i th generator, in rad/s
ω_{i0}	The synchronous machine speed, in rad/s
D_i	The per unit damping constant
H_i	The inertia constant, in s
P_{mi}	The mechanical input power, in p.u.
P_{ei}	The electrical power, in p.u.
E_{qi}'	The transient EMF in the quadrature axis, in p.u.
E_{fi}	The equivalent EMF in the excitation coil, in p.u.
E_{qi}	The EMF in the quadrature axis, in p.u.
x_{di}'	The direct axis reactance, in p.u.
x_{di}	The direct axis transient reactance, in p.u.
I_{di}	The direct axis current, in p.u.
k_{ei}	The gain of the excitation amplifier, in p.u.
u_{fi}	The input of the SCR amplifier, in p.u.
Q_{ei}	The reactive power, in p.u.
I_{qi}	The quadrature axis current, in p.u.
B_{Li}	The adjustable equivalent susceptance in SVC
B_{Ci}	The initial value of adjustable susceptance
u_{Bi}	The input of SVC, in p.u.
T_{Ci}	The time constant of adjusting system and SVC
T_{d0i}'	The direct axis transient short-circuit time constant, in s
B_{ij}	The i th row and j th column element of nodal susceptance matrix at the internal nodes after eliminating all physical buses, in p.u.

where

$$F_i = -\beta_i \frac{1}{T_{d0i}'} E_{fi} I_{qi},$$

$$\gamma_i(\delta, \omega) = \sum_{j=1}^n E_{qi}'(t) \dot{E}_{qj}'(t) B_{ij} \sin(\delta_i - \delta_j) \quad (16)$$

$$- \sum_{j=1}^n E_{qi}'(t) E_{qj}'(t) B_{ij} \cos(\delta_i - \delta_j) \omega_j.$$

Here, the bound of the interconnection term $\gamma_i(\delta, \omega)$ satisfies

$$|\gamma_i(\delta, \omega)| \leq \sum_{j=1}^n \left(\gamma_{i1j} |\sin \delta_j| + \gamma_{i2j} |\omega_j| \right) \leq \sum_{j=1}^n \left(\gamma_{i1j} |\delta_j| + \gamma_{i2j} |\omega_j| \right), \quad (17)$$

where

$$\gamma_{i1j} \triangleq \begin{cases} \frac{4p_{1ij}}{|T_{d0j}'|_{\min}} |P_{ei}|_{\max}, & \text{when } j \neq i, \\ \sum_{j=1, j \neq i}^n \frac{4p_{1ij}}{|T_{d0j}'|_{\min}} |P_{ei}|_{\max}, & \text{when } j = i, \end{cases} \quad (18)$$

$$\gamma_{i2} \triangleq p_{2ij} |Q_{ei}|_{\max},$$

with p_{1ij} and p_{2ij} being the constants with values of either 1 or 0. $P_{ei}(t)$ and $Q_{ei}(t)$ are readily measurable variables. From (5)–(8), we can obtain that

$$\begin{aligned} P_{ei} &= E_{qi}' I_{qi}, \\ Q_{ei} &= -E_{qi}' I_{di}. \end{aligned} \quad (19)$$

Define the following state variables for coordinate transformation:

$$\begin{cases} x_{i1} = \delta_i - \delta_{i0}, \\ x_{i2} = \omega_i - \omega_{i0}, \\ x_{i3} = \Delta P_{ei} = P_{ei} - P_{mi}, \\ x_{i4} = V_{mi} - V_{\text{refi}}, \end{cases} \quad (20)$$

where $P_{mi} = P_{mi0}$ is a constant and

$$V_{mi} = \frac{\sqrt{(X_{2i} E_{qi}')^2 + (X_{1i})^2 + 2X_{1i} X_{2i} E_{qi}' \cos x_{i1}}}{X_d \sum_i'}, \quad (21)$$

where V_{mi} is the accessing point voltage and V_{refi} is the corresponding reference voltage of the SVC:

$$\begin{aligned} X_{1i} &= x_{di}' + X_{Ti}, \\ X_d \sum_i' &= X_{1i} + X_{2i} + X_{1i} X_{2i} (B_{Li} - B_{Ci}), \end{aligned} \quad (22)$$

where X_{2i} and X_{Ti} are the transmission line reactance and the transformer reactance, respectively. According to (2) and

(15) and (20), we can obtain the following mathematical model of multimachine power systems with SVC:

$$\begin{cases} \dot{x}_{i1} = x_{i2}, \\ \dot{x}_{i2} = f_{i2}(\bar{x}_{i2}) - g_{i2}x_{i3} + d_{i1}, \\ \dot{x}_{i3} = f_{i3}(\bar{x}_{i3}) + g_{i3}u_i + \gamma_i(\delta, \omega) + d_{i2} + F_i, \\ y_{i1} = x_{i1}, \end{cases} \quad (23)$$

$$\begin{cases} \dot{x}_{i4} = g_{i4}u_{Bi}' + f_{i4}(\bar{x}_{i4}), \\ y_{i2} = x_{i4}, \end{cases} \quad (24)$$

where y_{i1} is the output of multimachine power systems, y_{i2} is the output of the SVC, and

$$\begin{aligned} f_{i2}(\bar{x}_{i2}) &= -\frac{D_i}{2H_i}x_{i2}, \\ f_{i3}(\bar{x}_{i3}) &= -\frac{1}{T_{d0i}}x_{i3}, \\ f_{i4}(\bar{x}_{i4}) &= -\frac{\sin x_{i1}X_{1i}X_{2i}}{(x_{i4} + V_{\text{refi}})(X_d \sum_i)}x_{i2}E_{qi}' \\ &\quad - \frac{X_{1i}X_{2i}(x_{i4} + V_{\text{refi}})}{X_d \sum_i T_{Ci}}(-B_{Li} + B_{Ci}) \\ &\quad + \frac{X_{2i}^2 E_{qi}' + X_{1i}X_{2i} \cos x_{i1}}{(x_{i4} + V_{\text{refi}})(X_d \sum_i)^2} \\ &\quad \cdot \left(-\frac{X_d \sum_i}{T_{d0i}X_d \sum_i}E_{qi}' + \frac{1}{T_{d0i}} \frac{X_{di} - X_{di}'}{X_d \sum_i} \cos x_{i1} \right) \\ &\quad + \frac{X_{2i}^2 x_{i3} + X_{1i}X_{2i}V_{si} \cos \delta_i}{T_{d0i}V_{mi}(X_d \sum_i)^2}u_i, \\ g_{i2} &= \frac{\omega_{i0}}{2H_i}, \\ g_{i3} &= \frac{1}{T_{d0i}}, \\ g_{i4} &= \frac{X_{1i}X_{2i}}{T_{Ci}X_d \sum_i}, \\ u_{Bi}' &= -x_{i4}u_{Bi}, \end{aligned} \quad (25)$$

with

$$\begin{aligned} X_d \sum_i &= X_{3i} + X_{2i} + X_{3i}X_{2i}(B_{Li} - B_{Ci}), \\ X_{3i} &= x_{di} + X_{Ti}. \end{aligned} \quad (26)$$

Since the damping coefficient D_i is difficult to measure accurately, D_i is treated as an uncertainty parameter, and the nonlinear system with uncertain parameters (1) is

transformed by equation (20) into a feedback form as shown in equation (23), so that the dynamic surface integral sliding mode method can be used to design the controller of the system equation (23). We can make the following two assumptions in this paper.

Assumption 1. The signs of g_{ij} , $i = 1, 2, j = 2, 3, 4$, are unknown bounded positive parameters, and there are known positive constants $g_{\max}$ and $g_{\min}$ such that $g_{\max} \geq g_{ij} \geq g_{\min}$; $f_{i2}(\bar{x}_{i2})$, $f_{i3}(\bar{x}_{i3})$, and $f_{i4}(\bar{x}_{i4})$ are unknown continuous functions.

Assumption 2. The reference signal x_{i1d} is bounded and smooth function, its first and second derivatives both exist, and there is a positive real number B_{i0} that satisfies $x_{i1d}^2 + \dot{x}_{i1d}^2 + \ddot{x}_{i1d}^2 \leq B_{i0}$.

Remark 2. Since g_{ij} , $i = 1, 2, j = 2, 3, 4$, are unknown bounded positive parameters and the reference signal x_{i1d} is a bounded smoothing function, Assumptions 1 and 2 are reasonable and common assumptions in [24, 26].

2.2. Radial Basis Function Neural Networks (RBFNNs). The unknown nonlinear continuous functions are approximated by the RBFNNs in this study. The general form of RBFNNs can be expressed as

$$y(\xi) = W^T \varepsilon(\xi), \quad (27)$$

where $\xi \in R^n$ is the input of RBFNNs, $y(\xi) \in R$ is the output of RBFNNs, $W \in R^N$ is the adjustable weight vector, and $\varepsilon(\xi) \in R^N$ is the nonlinear vector function.

In general, a continuous nonlinear function $F: \Omega_\xi \rightarrow R$ with $\Omega_\xi \in R^n$ being a compact set and an approximation error $\sigma_m > 0$ are given such that $|F(\xi) - W^{*T} \varepsilon(\xi)| \leq \sigma_m, \forall \xi \in \Omega_\xi$. Therefore, $F(\xi)$ can be described as $F(\xi) = W^{*T} \varepsilon(\xi) + \sigma^*, \forall \xi \in \Omega_\xi \in R^n$, where σ^* is the approximation error and satisfies $|\sigma^*| \leq \sigma_m$. The optimal weight vector W^* for analytical purposes can be defined as

$$W^* = \arg \min_{W \in R^N} \left\{ \sup_{\xi \in \Omega_\xi} |F(\xi) - W^T \varepsilon(\xi)| \leq \sigma_m \right\}. \quad (28)$$

3. Process of the Controller Design

The design process of the controller is divided into two parts: the design of control law for multimachine excitation systems and the design of control law for SVC. The detailed design procedure is described in the following steps. Step 1 and 2 apply the dynamic surface method, and Step 3 uses integral sliding mode control. According to (24), we know that the model of SVC is of the first order. Therefore, the dynamic surface control method is used to design the controller of SVC in Step 4. The design scheme of the adaptive dynamic surface integral sliding mode fault-tolerant controller is shown in Figure 1, and the design steps are displayed in Table 2.

FIGURE 1: Schematic diagram of the proposed control scheme.

TABLE 2: Adaptive dynamic surface integral sliding mode fault-tolerant control.

Alternative variables	
Step 1	
$z_{i1} = x_{i1} - x_{i1d}$	(T2.1)
$\bar{x}_{i2} = -c_{i1}z_{i1} + \dot{x}_{i1d}$	(T2.2)
$\tau_{i2}\dot{\bar{x}}_{i2} + \bar{x}_{i2} = \bar{x}_{i2}(0)$	(T2.3)
Step 2	
$z_{i2} = x_{i2} - \bar{x}_{i2}$	(T2.4)
$\bar{x}_{i3} = c_{i2}z_{i2} + (1/2)z_{i2}\epsilon_{i2}^T\hat{v}_{i2}$	(T2.5)
$\hat{v}_{i2} = r_{i2}((1/2)z_{i2}^2\epsilon_{i2}^T\epsilon_{i2} - \lambda_{i2}\hat{v}_{i2})$	(T2.6)
$\tau_{i3}\dot{\bar{x}}_{i3} + \bar{x}_{i3} = \bar{x}_{i3}(0)$	(T2.7)
Step 3	
$z_{i3} = x_{i3} - \bar{x}_{i3}$	(T2.8)
$S_{i3} = z_{i3} + k_{i3} \int_0^t z_{i3}(\tau) d\tau$	(T2.9)
$u_i = -c_{i3}S_{i3} - (1/2)\hat{v}_{i3}\epsilon_{i3}^T\epsilon_{i3}S_{i3} - \hat{\theta}_{gi3}(k_{i3} \cdot z_{i3}) - \eta \text{sgn}(S_{i3})$	(T2.10)
$\hat{v}_{i3} = r_{i3}((1/2)S_{i3}^2\epsilon_{i3}^T\epsilon_{i3} - \lambda_{i3}\hat{v}_{i3})$	(T2.11)
$\hat{\theta}_{gi3} = \rho_{gi3}[S_{i3}(k_{i3} \cdot z_{i3}) - \delta_{i3}\hat{\theta}_{gi3}]$	(T2.12)
Step 4	
$z_{i4} = x_{i4} - V_{ref}$	(T2.13)
$u'_{Bi} = -c_{i4}z_{i4} - (1/2)\hat{v}_{i4}\epsilon_{i4}^T\epsilon_{i4}z_{i4}$	(T2.14)
$\hat{v}_{i4} = r_{i4}((1/2)z_{i4}^2\epsilon_{i4}^T\epsilon_{i4} - \lambda_{i4}\hat{v}_{i4})$	(T2.15)

In Table 2, z_{ij} ($j = 1, 2, 3, 4$) are the j th surface errors with x_{i1d} being the desired power angle of the i th generator. S_{i3} represents the designed integral sliding mode surface. $\bar{x}_{i2}$ and $\bar{x}_{i3}$ are the virtual control laws in Step 1 and Step 2. (T2.3) and (T2.7) are first-order low-pass filters, which are used to overcome the differential explosion problem in backstepping method. τ_{i2} and τ_{i3} are the time constants of (T2.3) and (T2.7). $\hat{v}_{i2}$, $\hat{v}_{i3}$, $\hat{v}_{i4}$, and $\hat{\theta}_{gi3}$ are adaptive laws. u_i and u'_{Bi} are the actual control laws of generator excitation and SVC, respectively. c_{ij} ($j = 1, 2, 3, 4$), r_{il} , λ_{il} ($l = 2, 3, 4$), ρ_{gi3} , δ_{i3} , and k_{i3} are positive design parameters. $\hat{v}_{il} = \hat{v}_{il} - v_{il}^*$ ($l = 2, 3, 4$) and $\hat{v}_{il}$ ($l = 2, 3, 4$) are the estimation of $v_{il}^* = \|W_{il}^*\|^2$ with W_{il}^* being the optimal weight vector of the RBF neural

networks in (A.9), (A.17), and (A.23). $\tilde{\theta}_{gi3} = \hat{\theta}_{gi3} - \theta_{gi3}^*$ with $\hat{\theta}_{gi3}$ being the estimation of $\theta_{gi3}^* = (1/g_{i3})$.

Remark 3. A neural network based adaptive robust controller is developed by using the traditional backstepping design method in [2, 54]. Although the semiglobal ultimate uniform boundedness of all signals in the control system is achieved, there is a problem of “explosion of complexity.” In this paper, the introduction of a first-order low-pass filter overcomes the problem.

Remark 4. The values of time constants τ_{i2} and τ_{i3} should be chosen to be as small as possible. According to the actual condition, their values are usually between 0.001 and 0.1.

Remark 5. In order to achieve better transient performance while maintaining the tracking accuracy of the control, the integral sliding mode surface S_{i3} is adopted in Step 3, which greatly improves the robustness of the system.

Remark 6. The saturation function $\text{sat}(\cdot)$ is used instead of the symbol function $\text{sgn}(\cdot)$ to attenuate the chattering phenomenon of sliding mode control. The expressions of the $\text{sat}(\cdot)$ function can be written as $\text{sat}(S_{i3}) = \text{sign}(S_{i3})$ (if $|S_{i3}| > \varphi$), $\text{sat}(S_{i3}) = S_{i3}/\varphi$ (if $|S_{i3}| \leq \varphi$), where $\varphi > 0$.

Remark 7. The adaptive fault-tolerant controller proposed in this paper is based on the dynamic surface control (DSC) technique [25]. Subsystems (23) and (24) are third-order system and first-order system, respectively. Therefore, the controller design process consists of 4 steps, and the actual control input signals (T2.10) and (T2.14) are obtained in the 3rd and 4th steps. In addition, the detailed information of the DSC method is described in some literatures, such as [13, 15, 24]. In order to make the article more concise, the

specific design process of DSC is omitted, and only the necessary intermediate variables are given in Table 2.

4. Stability Analysis

The stability analysis of the multimachine power systems with SVC will be given in this section. First of all, define the filter errors y_{i2e} and y_{i3e} :

$$y_{i2e} = x_{i2d} - \bar{x}_{i2} = x_{i2d} - (-c_{i1}z_{i1} + \dot{x}_{i1d}), \quad (29)$$

$$y_{i3e} = x_{i3d} - \bar{x}_{i3} = x_{i3d} - \left(c_{i2}z_{i2} + \frac{z_{i2}\hat{v}_{i2}\varepsilon_{i2}^T}{2} \right). \quad (30)$$

From (T2.3) and (29), we have

$$\dot{x}_{i2d} = \frac{\bar{x}_{i2} - x_{i2d}}{\tau_{i2}} = -\frac{y_{i2e}}{\tau_{i2}}. \quad (31)$$

Similarly, from (T2.7) and (30), we have

$$\dot{x}_{i3d} = \frac{\bar{x}_{i3} - x_{i3d}}{\tau_{i3}} = -\frac{y_{i3e}}{\tau_{i3}}. \quad (32)$$

There are nonnegative continuous functions B_{i2} and B_{i3} , and

$$\left| \dot{y}_{i2e} + \frac{y_{i2e}}{\tau_{i2}} \right| \leq B_{i2}(z_{i1}, z_{i2}, y_{i2e}, x_{i1d}, \dot{x}_{i1d}, \ddot{x}_{i1d}), \quad (33)$$

$$\left| \dot{y}_{i3e} + \frac{y_{i3e}}{\tau_{i3}} \right| \leq B_{i3}(z_{i1}, z_{i2}, z_{i3}, y_{i2e}, y_{i3e}, \hat{v}_{i2}, x_{i1d}, \dot{x}_{i1d}, \ddot{x}_{i1d}), \quad (34)$$

where

$$\begin{aligned} B_{i2} &= c_{i1}\dot{z}_{i1} - \ddot{x}_{i1d} = c_{i1}(z_{i2} + y_{i2e} - c_{i1}z_{i1}) - \ddot{x}_{i1d} \\ B_{i3} &= -\left[c_{i2}\dot{z}_{i2} + \frac{\dot{z}_{i2}\hat{v}_{i2}\varepsilon_{i2}^T}{2} + \frac{z_{i2}\dot{\hat{v}}_{i2}\varepsilon_{i2}^T}{2} + \hat{v}_{i2}\varepsilon_{i2}^T \left(\sum_{l=1}^2 \frac{\partial \varepsilon_{i2}}{\partial x_{il}} \dot{x}_{il} + \frac{\partial \varepsilon_{i2}}{\partial z_{i2}} \dot{z}_{i2} \right) \right]. \end{aligned} \quad (35)$$

Consider the following Lyapunov function condition:

$$V = \sum_{k=1}^4 V_{ik} + \sum_{i=1}^n \frac{1}{2} y_{i2e}^2 + \sum_{i=1}^n \frac{1}{2} y_{i3e}^2. \quad (36)$$

Theorem 1. Consider the closed-loop control system, including multimachine systems model with actuator failure (23), SVC system model (24), first-order low-pass filters (T2.3) and (T2.7), actual control laws (T2.10) and (T2.14), and adaptive update laws (T2.6), (T2.11), (T2.12), and (T2.15). If Assumptions 1 and 2 are satisfied and the initial condition satisfies $V(0) \leq p$, where p is arbitrary positive constant, then all closed-loop signals such as $z_{i1}, z_{i2}, z_{i3}, z_{i4}, v_{i2}, v_{i3}, v_{i4}, \theta_{gi3}$ are semiglobally uniformly bounded and the tracking error can converge to an arbitrarily small range by adjusting parameters $c_{i1}, c_{i2}, c_{i3}, c_{i4}, \lambda_{i2}, \lambda_{i3}, \lambda_{i4}, \delta_{i3}, k_{i3}, \tau_{i2}, \tau_{i3}, i = 1, 2$. In addition, the integral sliding mode surface shown in (T2.9) can eliminate the steady-state error of the system tracking and ensure the robustness of the system.

Proof. The specific proof can be seen in the Appendix.

5. Simulation Result and Analysis

Simulation studies are meticulously discussed in this section. In order to verify the control performance of the dynamic surface integral sliding mode coordination controller

designed in this paper, the dynamic simulation of the 2-machine power system with SVC shown in Figure 2 is performed, where XT1 and XT2 represent the transformers and $2X_{L1}$ and $2X_{L2}$ represent the transmission lines. Some simulation parameters are selected as in [26].

The design parameters of the control laws including the virtual control laws and the final control laws are selected as $c_{11} = 8, c_{21} = 8, c_{12} = 3, c_{22} = 3, c_{13} = 60, c_{23} = 60, c_{14} = 20, c_{24} = 20$. The updated laws are chosen as $\lambda_{12} = \lambda_{22} = 0.3, r_{12} = r_{22} = 2, \lambda_{13} = \lambda_{23} = 0.3, r_{13} = r_{23} = 2, \rho_{g13} = \rho_{g23} = 0.6, \delta_{13} = \delta_{23} = 1, \lambda_{14} = \lambda_{24} = 0.5$, and $r_{14} = r_{24} = 1$.

The parameters of the integral sliding mode control are selected as $k_{13} = k_{23} = 0.5$. The time parameters of the low-pass filter are chosen as $\tau_{12} = \tau_{22} = 0.005$ and $\tau_{13} = \tau_{23} = 0.005$. In addition, the interference signals are selected as $d_{i1} = 0.001 \cos(2t)$ and $d_{i2} = 0.001 \sin(t) \cos(2t)$.

In order to verify the effectiveness of the designed controller, the tracking performances of the following four controllers are compared in Figures 3–5 under three conditions. (1) Two generators adopt the excitation controller with SVC designed by the traditional adaptive backstepping control (TABSC) method. (2) Two generators adopt the coordinated controller designed by the adaptive dynamic surface control (DSC) method. (3) Two generators adopt the coordinated controller designed by the adaptive sliding mode control (SMC) method. (4) The two generators adopt the coordination controller designed by dynamic surface integral sliding mode control (DSISMC) method in this paper.

FIGURE 2: The structure of 2-machine power system with SVC.

FIGURE 3: The tracking error of power angles δ_i , $i = 1, 2$ by using four controllers for the two generators in Case 1.

FIGURE 4: The tracking error of power angles δ_i , $i = 1, 2$, by using four controllers for the two generators in Case 2.

Case 1. The operating points are selected as follows:

$$\begin{aligned}
 \delta_{10} &= 40.415^\circ, \\
 \omega_{10} &= 314.06 \text{ rad/s}, \\
 P_{m10} &= 1.02 \text{ p.u.}, \\
 V_{\text{ref}1} &= 1.15 \text{ p.u.}, \\
 \delta_{20} &= 40.285^\circ, \\
 \omega_{20} &= 313.94 \text{ rad/s}, \\
 P_{m20} &= 0.98 \text{ p.u.}, \\
 V_{\text{ref}2} &= 1.05 \text{ p.u.}
 \end{aligned} \tag{37}$$

Figures 3 and 6–11 show the simulation results in Case 1. Figure 3 shows the tracking error of power angle δ_i under four controllers; it can be seen that, compared to the controllers designed by the other three methods, the dynamic surface integral sliding mode method adopted in this paper has better dynamic performance in terms of overshoot and stable operation time. The time required to achieve stabilization is shortened by 1~2 s, and the fluctuation range is also significantly improved. According to Figure 3, the steady state (9~10)

can be selected to obtain the maximum value of tracking error (MVTE) and the root mean square value of tracking error (RMSVTE) for the four control schemes as shown in Table 3. Figures 6–11 show the power angles δ_1, δ_2 , the rotated speeds ω_1, ω_2 , the electrical powers P_{e1}, P_{e2} , the control inputs u_1, u_2 of the excitation system, the accessing voltages V_{m1}, V_{m2} , and control inputs u_{B1}, u_{B2} of SVC. It is proven by Figures 6–11 that the controller designed by combining dynamic surface and integral sliding mode has good control effect.

Case 2. The operating points are selected as follows:

$$\begin{aligned}
 \delta_{10} &= 40.415^\circ, \\
 \omega_{10} &= 314.12 \text{ rad/s}, \\
 P_{m10} &= 1.01 \text{ p.u.}, \\
 V_{\text{ref}1} &= 1.15 \text{ p.u.}, \\
 \delta_{20} &= 40.285^\circ, \\
 \omega_{20} &= 314.16 \text{ rad/s}, \\
 P_{m20} &= 1.018 \text{ p.u.}, \\
 V_{\text{ref}2} &= 1.05 \text{ p.u.}
 \end{aligned} \tag{38}$$

FIGURE 5: The tracking error of power angles δ_i , $i = 1, 2$, by using four controllers for the two generators in Case 3.

FIGURE 6: The power angles δ_i , $i = 1, 2$ of the two generators in Case 1.

FIGURE 7: The rotated speed ω_i , $i = 1, 2$ of the two generators in Case 1.

FIGURE 9: The control input u_i , $i = 1, 2$ of the two generators in Case 1.

FIGURE 8: The electrical power P_{ei} , $i = 1, 2$ of the two generators in Case 1.

In the second case, it is assumed that the short circuit fault occurred on the transmission line at $t = 5$ s and disappeared after 0.2 seconds. Figures 4 and 12–17 show the simulation results in this case. Figure 4 shows the power angle tracking error z_{i1} , $i = 1, 2$, of the four control schemes in the case of the short circuit; it can be seen that, after the short circuit fault disappears, the method adopted in this paper can make the tracking error quickly converge to the

FIGURE 10: The accessing voltage V_{mi} , $i = 1, 2$ of the SVC for the two generators in Case 1.

working point, so as to achieve the expected tracking performance of power angles. Similarly, according to Figure 4, the MVTE and RMSVTE in Case 2 can be given in Table 4. Figures 12–17 illustrate the curves of the power angles δ_1, δ_2 , the rotated speeds ω_1, ω_2 , the electrical powers P_{e1}, P_{e2} , the control inputs u_1, u_2 of the excitation system, the accessing voltages V_{m1}, V_{m2} , and the control inputs u_{B1}, u_{B2} of SVC under the case that the unexpected short circuit fault occurred on the transmission line at $t = 5$ s and disappeared at $t = 5.2$ s.

FIGURE 11: The control input u_{Bi} , $i = 1, 2$ of the SVC in Case 1.

TABLE 3: The MVTE and RMSVTE in Case 1.

Types of error	Proposed scheme	TBSC scheme	DSC scheme	SMC scheme
MVTE of G#1	$3.3449e^{-06}$	$7.9840e^{-06}$	$2.3967e^{-05}$	$6.3628e^{-06}$
MVTE of G#2	$3.3402e^{-06}$	$1.5855e^{-05}$	$2.8119e^{-05}$	$6.6305e^{-06}$
RMSVTE of G#1	$2.8195e^{-06}$	$6.0995e^{-06}$	$1.7739e^{-05}$	$5.3544e^{-06}$
RMSVTE of G#2	$2.8147e^{-06}$	$1.1737e^{-05}$	$2.0606e^{-05}$	$5.5828e^{-06}$

FIGURE 12: The power angles δ_i , $i = 1, 2$, of the two generators in Case 2. FIGURE 13: The rotated speeds ω_i , $i = 1, 2$, of the two generators in Case 2.

FIGURE 14: The electrical powers P_{ei} , $i = 1, 2$, of the two generators in Case 2.

FIGURE 15: The control inputs u_i , $i = 1, 2$, of the two generators in Case 2.

Case 3. The operating points are selected as follows:

$$\begin{aligned}
 \delta_{10} &= 40.4^\circ, \\
 \omega_{10} &= 314.10, \\
 P_{m10} &= 1.02 \text{ p.u.}, \\
 V_{\text{ref}1} &= 1.15 \text{ p.u.}, \\
 \delta_{20} &= 40.2^\circ, \\
 \omega_{20} &= 314.06 \text{ rad/s}, \\
 P_{m20} &= 1.00 \text{ p.u.}, \\
 V_{\text{ref}2} &= 1.05 \text{ p.u.}
 \end{aligned} \tag{39}$$

FIGURE 16: The accessing voltages V_{mi} , $i = 1, 2$, of the SVC for the two generators in Case 2.

FIGURE 17: The control inputs u_{Bi} , $i = 1, 2$, of the SVC in Case 2.

In this case, consider that an actuator failure fault occurs at time $t_f = 4.8$ s, so $\bar{u}_{fi}$ can be assumed such that $\bar{u}_{fi} = (1 - \beta_i)u_{fi}$, $t \geq t_f$, $\bar{u}_{fi}$ is the input of the SCR amplifier when failure occurs, and the multimachine excitation systems models with SVC in the case of failure fault are equations (23) and (24). The failure factors $\beta_1 = 0.2, \beta_2 = 0.4$. Figures 5 and 18–23 show the simulation results in Case 3. Figure 5 illustrates the power angle tracking error z_{i1} , $i = 1, 2$, of the four control schemes in the case of the failure fault; it can be seen that when the failure fault occurs, the method designed in this paper has good tracking performance. Similarly, Table 5 shows the MVTE and RMVSTE in Case 3. Figures 18–21 show the curves of the

TABLE 4: The MVTE and RMSVTE in Case 2.

Types of error	Proposed scheme	TBSC scheme	DSC scheme	SMC scheme
MVTE of G#1	$3.4536e^{-06}$	$7.6832e^{-06}$	$2.4130e^{-05}$	$8.3619e^{-06}$
MVTE of G#2	$3.2387e^{-06}$	$1.5550e^{-05}$	$2.7959e^{-05}$	$6.8147e^{-06}$
RMSVTE of G#1	$2.9299e^{-06}$	$5.8961e^{-06}$	$1.8058e^{-05}$	$5.5876e^{-06}$
RMSVTE of G#2	$2.7118e^{-06}$	$1.0816e^{-05}$	$2.0317e^{-05}$	$5.6189e^{-06}$

FIGURE 18: The power angles δ_i , $i = 1, 2$, of the two generators in Case 3. FIGURE 20: The electrical powers P_{ei} , $i = 1, 2$, of the two generators in Case 3. FIGURE 19: The rotated speeds ω_i , $i = 1, 2$, of the two generators in Case 3. FIGURE 21: The control inputs u_i , $i = 1, 2$, of the two generators in Case 3.

power angles δ_1, δ_2 , the rotated speeds ω_1, ω_2 , the electrical powers P_{e1}, P_{e2} , and the control inputs u_1, u_2 of the excitation system under the case that the failure fault occurred at

$t = 4.8$ s, respectively. Figures 22 and 23 illustrate the curves of the accessing voltages V_{m1}, V_{m2} and the control inputs u_{B1}, u_{B2} of SVC in the third case.

FIGURE 22: The accessing voltages V_{mi} , $i = 1, 2$, of the SVC for the two generators in Case 3.

FIGURE 23: The control inputs u_{Bi} , $i = 1, 2$, of the SVC in Case 3.

TABLE 5: The MVTE and RMSVTE in Case 3.

Types of error	Proposed scheme	TBSC scheme	DSC scheme	SMC scheme
MVTE of G#1	$5.7220e^{-06}$	$4.8496e^{-04}$	$2.2845e^{-04}$	$2.8019e^{-04}$
MVTE of G#2	$8.2102e^{-06}$	$2.5091e^{-03}$	$5.0814e^{-04}$	$5.6473e^{-04}$
RMSVTE of G#1	$5.2248e^{-06}$	$4.8282e^{-04}$	$2.2052e^{-04}$	$2.7854e^{-04}$
RMSVTE of G#2	$7.6584e^{-06}$	$2.5137e^{-03}$	$4.9848e^{-04}$	$5.6299e^{-04}$

6. Conclusion

In this paper, the method of combining adaptive dynamic surface with integral sliding mode fault-tolerant control is proposed to solve the excitation control problem of

multimachine infinite-bus power systems with SVC by considering parameter uncertainties, external disturbances, and actuator failure. Applying the RBFNNs to approximate the unknown nonlinear function not only overcomes the uncertainty of the model but also reduces the computational

burden. The designed controller solves the “explosion of complexity” problem of the traditional backstepping method and makes the tracking error converge to zero in a limited time, thereby improving the steady-state tracking accuracy of the system, while ensuring that the system still has good stability after the failure. Simulation results show the effectiveness of the proposed control algorithm. Future work will focus on the design of a disturbance observer based adaptive output feedback control scheme for multimachine power systems by introducing a fixed-time control method to improve the robustness of the system.

Appendix

Proof of Theorem 1. The time derivative of V is as follows:

$$\dot{V} = \dot{V}_{i1} + \dot{V}_{i2} + \dot{V}_{i3} + \dot{V}_{i4} + \sum_{i=1}^n y_{i2e} \dot{y}_{i2e} + \sum_{i=1}^n y_{i3e} \dot{y}_{i3e}, \quad (\text{A.1})$$

$$V_{i1} = \frac{1}{2} \sum_{i=1}^n z_{i1}^2. \quad (\text{A.2})$$

The time derivative of V_{i1} is

$$\dot{V}_{i1} = \sum_{i=1}^n z_{i1} \dot{z}_{i1}. \quad (\text{A.3})$$

By Formula (29), (T2.2), (T2.4), and (A.3), it can be obtained that

$$\dot{V}_{i1} = \sum_{i=1}^n z_{i1} (z_{i2} + y_{i2e} - c_{i1} z_{i1}). \quad (\text{A.4})$$

By using Young's inequalities, we have

$$\begin{aligned} z_{i1} z_{i2} &\leq \frac{1}{2} z_{i1}^2 + \frac{1}{2} z_{i2}^2, \\ z_{i1} y_{i2e} &\leq \frac{1}{2} z_{i1}^2 + \frac{1}{2} y_{i2e}^2. \end{aligned} \quad (\text{A.5})$$

Substitute (A.5) into (A.4); then, one has

$$\dot{V}_{i1} \leq \sum_{i=1}^n \left[-(c_{i1} - 1) z_{i1}^2 + \frac{1}{2} z_{i2}^2 + \frac{1}{2} y_{i2e}^2 \right], \quad (\text{A.6})$$

$$V_{i2} = \sum_{i=1}^n \left(\frac{1}{2g_{i2}} z_{i2}^2 + \frac{1}{2r_{i2}} \tilde{v}_{i2}^2 \right). \quad (\text{A.7})$$

Then, the time derivative of V_{i2} is

$$\begin{aligned} \dot{V}_{i2} &= \sum_{i=1}^n \left(\frac{1}{g_{i2}} z_{i2} \dot{z}_{i2} + \frac{1}{r_{i2}} \tilde{v}_{i2} \dot{\tilde{v}}_{i2} \right) \\ &= \sum_{i=1}^n \left[z_{i2} \left(-x_{i3} + \frac{1}{g_{i2}} (f_{i2}(\bar{x}_{i2}) + d_{i1} - \dot{x}_{i2d}) \right) + \frac{1}{r_{i2}} \tilde{v}_{i2} \dot{\tilde{v}}_{i2} \right]. \end{aligned} \quad (\text{A.8})$$

Here, the RBF neural network is used to approximate unknown function $(1/g_{i2})(f_{i2}(\bar{x}_{i2}) + d_{i1} - \dot{x}_{i2d})$:

$$\frac{1}{g_{i2}} (f_{i2}(\bar{x}_{i2}) + d_{i1} - \dot{x}_{i2d}) + \frac{1}{2} z_{i2} = W_{i2}^{*T} \varepsilon_{i2}(\xi_{i2}) + \sigma_{i2}^*, \quad (\text{A.9})$$

where $\xi_{i2} = (x_{i1}, x_{i2}, x_{i2d}) \in R^3$, $|\sigma_{i2}^*| \leq \sigma_{i2m}$. According to Young's inequalities, there are

$$z_{i2} W_{i2}^{*T} \varepsilon_{i2}(\xi_{i2}) \leq \frac{1}{2} z_{i2}^2 \varepsilon_{i2}^T \varepsilon_{i2} v_{i2}^* + \frac{1}{2} z_{i2} \sigma_{i2}^* \leq \frac{1}{2} z_{i2}^2 + \frac{1}{2} \sigma_{i2m}^2, \quad (\text{A.10})$$

with σ_{i2m} being the upper boundary of the approximation error. Substituting (A.9) and (A.10) into (A.8), we can obtain that

$$\dot{V}_{i2} \leq \sum_{i=1}^n \left[z_{i2} \left(-x_{i3} + \frac{z_{i2} \varepsilon_{i2}^T \varepsilon_{i2} v_{i2}^*}{2} \right) + \frac{1}{2} + \frac{1}{2} \sigma_{i2m}^2 + \frac{1}{r_{i2}} \tilde{v}_{i2} \dot{\tilde{v}}_{i2} \right]. \quad (\text{A.11})$$

Substituting (T2.5) and (T2.6) into (A.11), one has

$$\dot{V}_{i2} \leq \sum_{i=1}^n \left[z_{i2} (-z_{i3} - y_{i3e} - c_{i2} z_{i2}) + \frac{1}{2} + \frac{1}{2} \sigma_{i2m}^2 - \lambda_{i2} \tilde{v}_{i2} \dot{\tilde{v}}_{i2} \right]. \quad (\text{A.12})$$

By using Young's inequalities, one has

$$-z_{i2} y_{i3e} \leq \frac{1}{2} z_{i2}^2 + \frac{1}{2} y_{i3e}^2. \quad (\text{A.13})$$

Substituting (A.13) into (A.12), we can obtain that

$$\dot{V}_{i2} \leq \sum_{i=1}^n \left[-\left(c_{i2} - \frac{1}{2} \right) z_{i2}^2 - z_{i2} z_{i3} + \frac{1}{2} y_{i3e}^2 + \frac{1}{2} + \frac{1}{2} \sigma_{i2m}^2 - \lambda_{i2} \tilde{v}_{i2} \dot{\tilde{v}}_{i2} \right], \quad (\text{A.14})$$

$$V_{i3} = \sum_{i=1}^n \left(\frac{1}{2g_{i3}} S_{i3}^2 + \frac{1}{2\rho_{gi3}} \tilde{\theta}_{gi3}^2 + \frac{1}{2r_{i3}} \tilde{v}_{i3}^2 \right). \quad (\text{A.15})$$

Then, the time derivative of V_{i3} is

$$\begin{aligned}\dot{V}_{i3} &= \sum_{i=1}^n \left(\frac{1}{g_{i3}} S_{i3} \dot{S}_{i3} + \frac{1}{\rho_{gi3}} \tilde{\theta}_{gi3} \dot{\tilde{\theta}}_{gi3} + \frac{1}{r_{i3}} \tilde{v}_{i3} \dot{\tilde{v}}_{i3} \right) \\ &= \sum_{i=1}^n \left[S_{i3} \left(u_i + \frac{1}{g_{i3}} (f_{i3}(\bar{x}_{i3}) - \dot{x}_{i3d} + d_{i2} + F_i + y_i(\delta, \omega)) + \frac{k_{i3}}{g_{i3}} z_{i3} \right) + \frac{1}{\rho_{gi3}} \tilde{\theta}_{gi3} \dot{\tilde{\theta}}_{gi3} + \frac{1}{r_{i3}} \tilde{v}_{i3} \dot{\tilde{v}}_{i3} \right] \\ &\leq \sum_{i=1}^n \left[S_{i3} \left(u_i + \frac{1}{g_{i3}} \left(f_{i3}(\bar{x}_{i3}) - \dot{x}_{i3d} + d_{i2} + F_i + \sum_{j=1}^n \delta_{ji}(|x_{i1}|, |x_{i2}|) \right) \theta_{gi3}^* \cdot k_{i3} \cdot z_{i3} \right) + \frac{1}{\rho_{gi3}} \tilde{\theta}_{gi3} \dot{\tilde{\theta}}_{gi3} + \frac{1}{r_{i3}} \tilde{v}_{i3} \dot{\tilde{v}}_{i3} \right],\end{aligned}\quad (\text{A.16})$$

where $\sum_{j=1}^n \delta_{ji}(|x_{i1}|, |x_{i2}|) = \sum_{j=1}^n (\gamma_{i1j}|\delta_j| + \gamma_{i2j}|\omega_j|)$. Here, the RBF neural network is used to approximate unknown function

$(1/g_{i3})(f_{i3}(\bar{x}_{i3}) - \dot{x}_{i3d} + d_{i2} + F_i + \sum_{j=1}^n \delta_{ji}(|x_{i1}|, |x_{i2}|))$ with

$$\frac{1}{g_{i3}} \left(f_{i3}(\bar{x}_{i3}) + \sum_{j=1}^n \delta_{ji}(|x_{i1}|, |x_{i2}|) - \dot{x}_{i3d} + d_{i2} + F_i \right) + \frac{1}{2} S_{i3} = W_{i3}^{*T} \varepsilon_{i3}(\xi_{i3}) + \sigma_{i3}^*, \quad (\text{A.17})$$

where $\xi_{i3} = (x_{i1}, x_{i2}, x_{i3}, x_{i3d}) \in R^4$, $|\sigma_{i3}^*| \leq \sigma_{i3m}$. According to Young's inequalities, there are

$$S_{i3} W_{i3}^{*T} \varepsilon_{i3}(\xi_{i3}) \leq \frac{1}{2} S_{i3}^2 \varepsilon_{i3}^T \varepsilon_{i3} v_{i3}^* + \frac{1}{2} S_{i3} \sigma_{i3}^* \leq \frac{1}{2} S_{i3}^2 + \frac{1}{2} \sigma_{i3m}^2, \quad (\text{A.18})$$

with σ_{i3m} being the upper boundary of the approximation error. Substituting (A.17) and (A.18) into (A.16), we can obtain that

$$\dot{V}_{i3} \leq \sum_{i=1}^n \left[S_{i3} \left(u_i + \frac{v_{i3}^* \varepsilon_{i3}^T S_{i3}}{2} + \theta_{gi3}^* \cdot k_{i3} \cdot z_{i3} \right) + \frac{1}{2} + \frac{1}{2} \sigma_{i3m}^2 + \frac{1}{\rho_{gi3}} \tilde{\theta}_{gi3} \dot{\tilde{\theta}}_{gi3} + \frac{1}{r_{i3}} \tilde{v}_{i3} \dot{\tilde{v}}_{i3} \right]. \quad (\text{A.19})$$

Similarly, substituting (T2.10)–(T2.12) into (A.19), one has

$$\dot{V}_{i3} \leq \sum_{i=1}^n \left(-c_{i3} S_{i3}^2 + \frac{1}{2} + \frac{1}{2} \sigma_{i3m}^2 - \delta_{i3} \tilde{\theta}_{gi3} \dot{\tilde{\theta}}_{gi3} - \lambda_{i3} \tilde{v}_{i3} \dot{\tilde{v}}_{i3} - \eta |S_{i3}| \right), \quad (\text{A.20})$$

$$V_{i4} = \sum_{i=1}^n \left(\frac{1}{2g_{i4}} z_{i4}^2 + \frac{1}{2r_{i4}} \tilde{v}_{i4}^2 \right). \quad (\text{A.21})$$

Then, the time derivative of V_{i4} is

$$\begin{aligned}\dot{V}_{i4} &= \sum_{i=1}^n \left(\frac{1}{g_{i4}} z_{i4} \dot{z}_{i4} + \frac{1}{r_{i4}} \tilde{v}_{i4} \dot{\tilde{v}}_{i4} \right) \\ &= \sum_{i=1}^n \left[z_{i4} \left(u_{Bi}' + \frac{1}{g_{i4}} (f_{i4}(\bar{x}_{i4}) - \dot{V}_{\text{refi}}) \right) + \frac{1}{r_{i4}} \tilde{v}_{i4} \dot{\tilde{v}}_{i4} \right].\end{aligned}\quad (\text{A.22})$$

Similar to the above steps, the RBF neural network is used to approximate unknown function $(1/g_{i4})(f_{i4}(\bar{x}_{i4}) - \dot{V}_{\text{refi}})$ with

$$\frac{1}{g_{i4}} (f_{i4}(\bar{x}_{i4}) - \dot{V}_{\text{refi}}) + \frac{1}{2} z_{i4} = W_{i4}^{*T} \varepsilon_{i4}(\xi_{i4}) + \sigma_{i4}^*, \quad (\text{A.23})$$

where $\xi_{i4} = (x_{i1}, x_{i2}, x_{i3}, x_{i4}, V_{\text{refi}}) \in R^5$, $|\sigma_{i4}^*| \leq \sigma_{i4m}$. According to Young's inequalities, there are

$$z_{i4} W_{i4}^{*T} \varepsilon_{i4}(\xi_{i4}) \leq \frac{1}{2} z_{i4}^2 \varepsilon_{i4}^T \varepsilon_{i4} v_{i4}^* + \frac{1}{2} z_{i4} \sigma_{i4}^* \leq \frac{1}{2} z_{i4}^2 + \frac{1}{2} \sigma_{i4m}^2, \quad (\text{A.24})$$

with σ_{i4m} being the upper boundary of the approximation error. Substituting (A.23) and (A.24) into (A.22), we can obtain that

$$\dot{V}_{i4} \leq \sum_{i=1}^n \left[z_{i4} \left(u_{Bi}' + \frac{v_{i4}^* \varepsilon_{i4}^T S_{i4}}{2} \right) + \frac{1}{2} + \frac{1}{2} \sigma_{i4m}^2 + \frac{1}{r_{i4}} \tilde{v}_{i4} \dot{\tilde{v}}_{i4} \right]. \quad (\text{A.25})$$

Substituting (T2.14) and (T2.15) into (A.25), one has

$$\dot{V}_{i4} \leq \sum_{i=1}^n \left(-c_{i4} z_{i4}^2 + \frac{1}{2} + \frac{1}{2} \sigma_{i4m}^2 - \lambda_{i4} \tilde{v}_{i4} \hat{v}_{i4} \right), \quad (\text{A.26})$$

and consider the sets

$$\begin{aligned} Y_1 &:= \{(x_{i1d}, \dot{x}_{i1d}, \ddot{x}_{i1d}) : x_{i1d}^2 + \dot{x}_{i1d}^2 + \ddot{x}_{i1d}^2 \leq B_{i0}\}, \\ Y_2 &:= \left\{ \sum_{k=1}^4 V_{ik} + \sum_{i=1}^n \frac{1}{2} y_{i2e}^2 + \sum_{i=1}^n \frac{1}{2} y_{i3e}^2 \leq p \right\}. \end{aligned} \quad (\text{A.27})$$

The continuous functions B_{i2} and B_{i3} have maximums in the compact set $Y_1 \times Y_2$. According to Young's inequalities, we have the following inequalities:

$$\begin{aligned} |y_{i2e} B_{i2}| &\leq \frac{y_{i2e}^2 B_{i2}^2}{2\mu} + \frac{\mu}{2} \leq \frac{y_{i2e}^2 M_{i2}^2}{2\mu} + \frac{\mu}{2}, \\ |y_{i3e} B_{i3}| &\leq \frac{y_{i3e}^2 B_{i3}^2}{2\mu} + \frac{\mu}{2} \leq \frac{y_{i3e}^2 M_{i3}^2}{2\mu} + \frac{\mu}{2}, \end{aligned} \quad (\text{A.28})$$

where μ is any positive constant and M_{i2} and M_{i3} are the maximums of B_{i2} and B_{i3} , respectively. According to Young's inequalities, we have

$$\begin{aligned} -\lambda_{i2} \tilde{v}_{i2} \hat{v}_{i2} &\leq -\frac{\lambda_{i2} \tilde{v}_{i2}^2}{2} + \frac{\lambda_{i2} v_{i2}^{*2}}{2}, \\ -\lambda_{i3} \tilde{v}_{i3} \hat{v}_{i3} &\leq -\frac{\lambda_{i3} \tilde{v}_{i3}^2}{2} + \frac{\lambda_{i3} v_{i3}^{*2}}{2}, \\ -\lambda_{i4} \tilde{v}_{i4} \hat{v}_{i4} &\leq -\frac{\lambda_{i4} \tilde{v}_{i4}^2}{2} + \frac{\lambda_{i4} v_{i4}^{*2}}{2}, \\ -\delta_{i3} \tilde{\theta}_{gi3} \hat{\theta}_{gi3} &\leq -\frac{\delta_{i3} \tilde{\theta}_{gi3}^2}{2} + \frac{\delta_{i3} \theta_{gi3}^{*2}}{2}. \end{aligned} \quad (\text{A.29})$$

Substituting (33), (34), and (A.6), as well as (A.14), (A.20), and (A.26) into (A.1), it follows that

$$\dot{V} \leq \sum_{i=1}^n \left[\begin{aligned} &-(c_{i1} - 1)z_{i1}^2 - (c_{i2} - 1)z_{i2}^2 - z_{i2}z_{i3} - c_{i3}S_{i3}^2 - c_{i4}z_{i4}^2 + \frac{1}{2}y_{i2e}^2 + \frac{1}{2}y_{i3e}^2 \\ &+ \frac{3}{2} + \frac{1}{2}\sigma_{i2m}^2 + \frac{1}{2}\sigma_{i3m}^2 + \frac{1}{2}\sigma_{i4m}^2 - \lambda_{i2}\tilde{v}_{i2}\hat{v}_{i2} - \lambda_{i2}\tilde{v}_{i2}\hat{v}_{i2} - \lambda_{i2}\tilde{v}_{i2}\hat{v}_{i2} \\ &- \delta_{i3}\tilde{\theta}_{gi3}\hat{\theta}_{gi3} + y_{i2e}\left(-\frac{y_{i2e}}{\tau_{i2}} + B_{i2}\right) + y_{i3e}\left(-\frac{y_{i3e}}{\tau_{i3}} + B_{i3}\right) \end{aligned} \right]. \quad (\text{A.30})$$

From (A.30), we can know that if z_{i3} converges to zero, $-z_{i2}z_{i3}$ will be eliminated. The integral sliding surface is designed to ensure that z_{i3} converges to zero in a finite time.

Substituting (A.28) and (A.29) into (A.30), it follows that

$$\dot{V} \leq \sum_{i=1}^n \left[\begin{aligned} &-(c_{i1} - 1)z_{i1}^2 - (c_{i2} - 1)z_{i2}^2 - c_{i3}S_{i3}^2 - c_{i4}z_{i4}^2 + y_{i2e}\left(\frac{1}{2} - \frac{1}{\tau_{i2}} + \frac{M_{i2}^2}{2\mu}\right) \\ &+ y_{i3e}\left(\frac{1}{2} - \frac{1}{\tau_{i3}} + \frac{M_{i3}^2}{2\mu}\right) + \mu + \frac{3}{2} + \frac{1}{2}\sigma_{i2m}^2 + \frac{1}{2}\sigma_{i3m}^2 + \frac{1}{2}\sigma_{i4m}^2 - \frac{\lambda_{i2}\tilde{v}_{i2}^2}{2} \\ &- \frac{\lambda_{i3}\tilde{v}_{i3}^2}{2} - \frac{\lambda_{i4}\tilde{v}_{i4}^2}{2} - \frac{\delta_{i3}\tilde{\theta}_{gi3}^2}{2} + \frac{\lambda_{i2}v_{i2}^{*2}}{2} + \frac{\lambda_{i3}v_{i3}^{*2}}{2} + \frac{\lambda_{i4}v_{i4}^{*2}}{2} + \frac{\delta_{i3}\theta_{gi3}^{*2}}{2} \end{aligned} \right]. \quad (\text{A.31})$$

Let

$$\frac{1}{\tau_{i2}} \geq \frac{1}{2} + \frac{M_{i2}^2}{2\mu} + a_0, \quad (\text{A.32})$$

$$\frac{1}{\tau_{i3}} \geq \frac{1}{2} + \frac{M_{i3}^2}{2\mu} + a_0, \quad (\text{A.33})$$

where a_0 is a positive design parameter. Substituting (A.32) and (A.33) into (A.31), one has

$$C^* = \sum_{i=1}^n \left[\mu + \frac{3}{2} + \frac{1}{2}\sigma_{i2m}^2 + \frac{1}{2}\sigma_{i3m}^2 + \frac{1}{2}\sigma_{i4m}^2 + \frac{\lambda_{i2}}{2}v_{i2}^{*2} + \frac{\lambda_{i3}}{2}v_{i3}^{*2} + \frac{\lambda_{i4}}{2}v_{i4}^{*2} + \frac{\delta_{i3}}{2}\theta_{gi3}^{*2} \right]. \quad (\text{A.35})$$

Here, a_0 satisfies

$$a_0 \leq \min \left\{ g_{\min}(c_{i1} - 1), g_{\min}(c_{i2} - 1), c_{i3}, c_{i4}, \frac{r_{i2}\lambda_{i2}}{2}, \frac{r_{i3}\lambda_{i3}}{2}, \frac{r_{i4}\lambda_{i4}}{2}, \frac{\rho_{gi3}\delta_{i3}}{2} \right\}. \quad (\text{A.36})$$

Then there is

$$\dot{V} \leq -2a_0V + C^*. \quad (\text{A.37})$$

By selecting a_0 to make $a_0 \geq (C^*/2p)$ established, when $V = p$, $\dot{V} \leq 0$. So $V \leq p$ is an invariant set; that is, for all $t > 0$, $V(t) \leq p$ if $V(0) \leq p$. The solution of inequality (A.37) is

$$0 \leq V \leq \frac{C^*}{2a_0} + \left(V(0) - \frac{C^*}{2a_0} \right) e^{-2a_0t}. \quad (\text{A.38})$$

Obviously, all error signals in the closed-loop system are semiglobally uniformly bounded within the compact set below.

$$\Theta = \left\{ (z_{i1}, z_{i2}, z_{i3}, z_{i4}, \tilde{v}_{i2}, \tilde{v}_{i3}, \tilde{v}_{i4}, \tilde{\theta}_{gi3}, y_{i2e}, y_{i3e}) : V \leq \frac{C^*}{2a_0} \right\}. \quad (\text{A.39})$$

It implies that the compact set Θ can be arbitrarily small by adjusting parameters $c_{i1}, c_{i2}, c_{i3}, c_{i4}, r_{i2}, r_{i3}, r_{i4}, \lambda_{i2}, \lambda_{i3}, \lambda_{i4}, k_{i3}, \delta_{i3}, \rho_{gi3}$. This completes the proof of Theorem 1.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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$$\dot{V} \leq \sum_{i=1}^n \left[- (c_{i1} - 1)z_{i1}^2 - (c_{i2} - 1)z_{i2}^2 - c_{i3}S_{i3}^2 - c_{i4}z_{i4}^2 - a_0y_{i2e}^2 - a_0y_{i3e}^2 - \frac{\lambda_{i2}}{2}\tilde{v}_{i2}^2 - \frac{\lambda_{i3}}{2}\tilde{v}_{i3}^2 - \frac{\lambda_{i4}}{2}\tilde{v}_{i4}^2 - \frac{\delta_{i3}}{2}\tilde{\theta}_{gi3}^2 \right] + C^*, \quad (\text{A.34})$$

with

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