

Research Article

Adaptive Neural Networks Synchronization of a Four-Dimensional Energy Resource Stochastic System

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An adaptive neural networks chaos synchronization control method is proposed for a four-dimensional energy resource demand-supply system with input constraints. Assuming the response system contains unknown uncertain nonlinearities and unknown stochastic disturbances, the neural networks and robust terms are used to identify the nonlinearities and overcome the stochastic disturbances, respectively. Based on stochastic Lyapunov stability and robust adaptive theories, an adaptive neural networks synchronization control method is developed. In the design process, an auxiliary design system is employed to address input constraints. Simulation results, which fully coincide with theoretical results, are presented to demonstrate the obtained results.

1. Introduction

Energy resource system is a kind of complex nonlinear system. Over the last two decades, much attention has been paid to the chaos synchronization in this class system. Reference [1] established a three-dimensional energy resource demand-supply system based on the real energy resources demand-supply system in the East and the West of China. By adding a new variable to consider the renewable resources, a four-dimensional energy resource system was proposed in [2]. The dynamics behaviors of the four-dimensional energy resource system have been analyzed by means of the Lyapunov exponents and bifurcation diagrams. Also the same as the above-mentioned power systems, this four-dimensional energy resource system is with rich chaos behaviors. The problem of chaotic control for the energy resource system was considered in [3]. Feedback control and adaptive control methods were used to suppress chaos to unstable equilibrium or unstable periodic orbits, where only three of the system's parameters were supposed to be unknown. Reference [4] investigated the robust chaos synchronization problem for the four-dimensional energy resource systems based on the sliding mode control technique. The control of energy resource chaotic system was investigated by time-delayed feedback control method in [5]. Four linear control

schemes are proposed to a four-dimensional energy resource system in [6]. Based on stability criterion of linear system and Lyapunov stability theory, respectively, the chaos synchronization problems for energy resource demand-supply system were discussed using two novel different control methods in [7].

In many practical dynamic systems (including the energy resource demand-supply system), physical input saturation on hardware dictates that the magnitude of the control signal is always constrained. Saturation is a potential problem for actuators of control systems. It often severely limits system performance, giving rise to undesirable inaccuracy or leading instability [8, 9]. The development of control schemes for systems with input saturation has been a task of major practical interest as well as theoretical significance. The proposed approaches in [1–7] assume that all the components of the considered energy resource demand-supply systems are in good operating conditions and do not consider the problem of saturation. Reference [10] proposed two different chaos synchronization methods for a class of energy resource demand-supply systems with input saturation, but the response system in [10] did not contain unknown uncertain nonlinearities and unknown stochastic disturbances. It is well known that stochastic disturbances also often exist in many practical systems. Their existence is a source of

instability of the control systems; thus, the investigations on stochastic control systems have received considerable attention in recent years [11–22]. Since the emergence of the stochastic stabilization theory in the 1960s, the progress has been constructed by a fundamental technical Itô lemma, and the control design for stochastic systems is more difficult compared with deterministic systems.

Motivated by the above observations, an adaptive neural networks chaos synchronization method is proposed for a four-dimensional energy resource demand-supply system with input constraints. Assume that the response system contains unknown uncertain nonlinearities and unknown stochastic disturbances. In the design, the neural networks and robust terms are used to identify the nonlinearities and overcome the stochastic disturbances, respectively. Based on Lyapunov stability, an adaptive synchronization method is developed in order to make the states of two chaotic systems asymptotically synchronized. The new auxiliary design system is employed to address input constraints. Numerical simulations are provided to illustrate the effectiveness of the proposed approach.

Compared with the existing results, the main contributions of the proposed method are as follows: (i) the controlled response system of this paper contains unknown nonlinearities, and the proposed method can solve the unknown nonlinearity problem by neural networks, but the methods of [1–8, 10] cannot solve this problem; (ii) the controlled response system of this paper contains stochastic disturbances, and the proposed method can solve the stochastic disturbances problem based on Itô's lemma and stochastic LaSalle's theorem, but the methods of [1–8, 10] cannot solve this problem; (iii) an auxiliary design system is employed to address input constraints problem, and the methods of [1–8] can solve this problem.

2. Energy Resource Chaotic System

The four-dimensional energy resource system can be expressed as follows (see [2, 4, 6]):

$$\begin{aligned}\dot{x} &= a_1 x \left(1 - \frac{x}{M}\right) - a_2 (y + z) - d_3 w, \\ \dot{y} &= -b_1 y - b_2 z + b_3 x [N - (x - z)], \\ \dot{z} &= c_1 z (c_2 x - c_3), \\ \dot{w} &= d_1 x - d_2 w,\end{aligned}\quad (1)$$

where $x(t)$ is the energy resource shortage in A region, $y(t)$ is the energy resource supply increment in B region, and $z(t)$ and $w(t)$ are energy resource import in A region and renewable energy resource in A region, respectively; M , N , a_i , b_j , c_j , and d_j ($i = 1, 2$, $j = 1, 2, 3$) are parameters that are all positive real. The dynamics of this system has been extensively studied in [2, 4, 6].

When the system parameters are taken as the following values, this system exhibits chaotic behavior: $M = 1.8$, $N = 1$, $a_1 = 0.1$, $a_2 = 0.15$, $b_1 = 0.06$, $b_2 = 0.082$, $b_3 = 0.07$, $c_1 = 0.2$, $c_2 = 0.5$, $c_3 = 0.4$, $d_1 = 0.1$, $d_2 = 0.06$, and $d_3 = 0.07$.

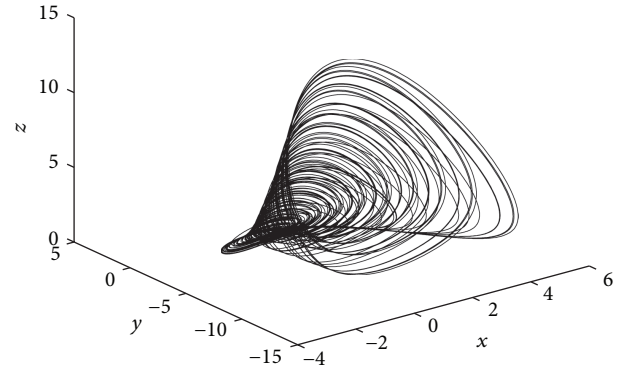


FIGURE 1: Three-dimensional view $x - y - z$.

Without the particular statement, these values are adopted in this whole paper. Figures 1, 2, and 3 show the phase portraits with initial conditions of $x(0) = 0.82$, $y(0) = 0.29$, $z(0) = 0.48$, and $w(0) = 0.1$.

3. Synchronization of the Energy Resource System

In this section, a controller will be designed in order to make the response system track the drive system. The drive system with subscript 1 is written as

$$\begin{aligned}\dot{x}_1 &= a_1 x_1 \left(1 - \frac{x_1}{M}\right) - a_2 (y_1 + z_1) - d_3 w_1, \\ \dot{y}_1 &= -b_1 y_1 - b_2 z_1 + b_3 x_1 [N - (x_1 - z_1)], \\ \dot{z}_1 &= c_1 z_1 (c_2 x_1 - c_3), \\ \dot{w}_1 &= d_1 x_1 - d_2 w_1.\end{aligned}\quad (2)$$

Assume that the controlled response system with subscript 2 contained uncertain nonlinearities (unknown smooth nonlinear functions) and unknown external stochastic disturbance, and it can be expressed as the following dynamics:

$$\begin{aligned}dx_2 &= \left[a_1 x_2 \left(1 - \frac{x_2}{M}\right) - a_2 (y_2 + z_2) - d_3 w_2 \right. \\ &\quad \left. + f_1(x_2) + u_1(v_1(t)) \right] dt + p_1(e_1) dW, \\ dy_2 &= \left[-b_1 y_2 - b_2 z_2 + b_3 x_2 [N - (x_2 - z_2)] \right. \\ &\quad \left. + f_2(y_2) + u_2(v_2(t)) \right] dt + p_2(e_2) dW, \\ dz_2 &= \left[c_1 z_2 (c_2 x_2 - c_3) + f_3(z_2) + u_3(v_3(t)) \right] dt \\ &\quad + p_3(e_3) dW, \\ dw_2 &= \left[d_1 x_2 - d_2 w_2 + f_4(w_2) + u_4(v_4(t)) \right] dt \\ &\quad + p_4(e_4) dW,\end{aligned}\quad (3)$$

where v_i is the actual controller to be designed and $u_i(v_i(t))$ ($i = 1, 2, 3, 4$) is the plant input subject to saturation

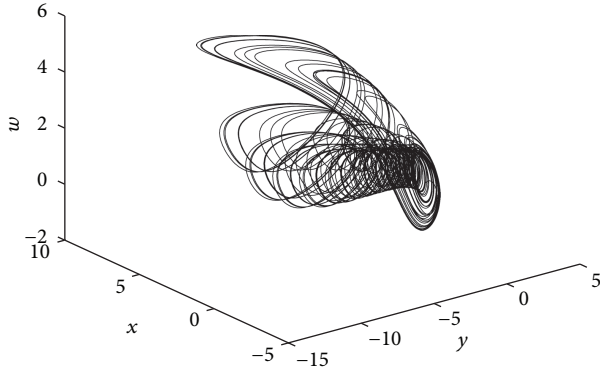


FIGURE 2: Three-dimensional view $y - x - w$.

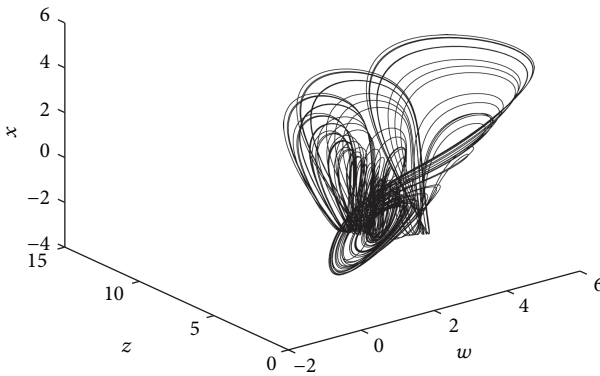


FIGURE 3: Three-dimensional view $w - z - x$.

type nonlinearly. $p_i(e_i)$, $i = 1, 2, 3, 4$, are uncertain functions, and $W \in R^n$ is an independent standard Brownian motion defined on a complete probability space, with the incremental covariance $E\{dW \cdot dW^T\} = \sigma(t)\sigma(t)^T dt$.

Remark 1. If no input saturation, uncertain nonlinearities, and unknown external stochastic disturbance (i.e., $u_i(v_i(t)) = v_i(t)$, $p_i(t) = 0$, and $f_i(\cdot) = 0$ ($i = 1, 2, 3, 4$)) are included in (3), then (3) becomes the chaotic systems studied widely, see [8, 10], where $u_i(v_i(t))$ can be described as

$$u_i(v_i(t)) = \text{sat}(v_i(t)) = \begin{cases} \text{sign}(v_i(t)) u_{iM}, & |v_i(t)| \geq u_{iM}, \\ v_i(t), & |v_i(t)| < u_{iM}, \end{cases} \quad (4)$$

where u_{iM} is a known bound of $u_i(v_i(t))$.

To design an adaptive controller, the following basic assumption is made for the system (3).

Assumption 2. The disturbance covariance $P^T \sigma \sigma^T P \leq \sum_{i=1}^4 e_i \bar{\sigma}_i(e_i)$, where $P = [p_1(e_1) \ p_2(e_2) \ p_3(e_3) \ p_4(e_4)]^T$ and $\bar{\sigma}_i(e_i)$ is a known function.

To establish stochastic stability as a preliminary, consider a stochastic nonlinear system:

$$dx = f(x, t) dt + g(x, t) dW, \quad (5)$$

where $x \in R^n$, W is an independent r -dimensional Wiener process, defined on the probability space (Ω, F, P) , with the incremental covariance $E\{dW, dW^T\} = \sigma(t)\sigma(t)^T de$, and $f : R^n \times R \rightarrow R^n$ and $g : R^n \times R \rightarrow R^{n \times r}$ are locally Lipschitz continuous in x , uniformly in $t \in R$, with $f(0, t) = 0$ and $g(0, t) = 0$, for all $t \geq 0$.

Lemma 3 (see [16, 17] (stochastic LaSalle's theorem)). Consider (5) and suppose that there exists a twice continuously differentiable function $V(x, t)$, which is positive definite, decrescent, and radially unbounded, and another nonnegative continuous function $Q(x) \geq 0$ such that the infinitesimal generator $V(x, t)$ along (5) satisfies

$$\ell V := \frac{\partial V}{\partial t} + \frac{\partial V}{\partial x} f(x) + \frac{1}{2} \text{Tr} \left\{ \sigma^T g^T \frac{\partial^2 V}{\partial x^2} g \sigma \right\} \leq -Q(x), \quad \forall x \in R^n, t \geq 0, \quad (6)$$

where Tr denotes the matrix trace. Then, the equilibrium $x = 0$ is globally stable in probability and

$$P \left\{ \lim_{t \rightarrow \infty} Q(x(t)) = 0 \right\} = 1, \quad \forall x(0) \in R^n. \quad (7)$$

In order to solve the unknown nonlinear $f_i(\cdot)$ ($i = 1, 2, 3, 4$), the following radial basis function neural networks (RBFNNs) [23] are used to identify them similar to fuzzy logic systems [24–27].

An RBFNN can approximate a continuous function $h(X) : R^q \rightarrow R$,

$$h_{nn}(X) = W^T \varphi(X), \quad (8)$$

where the input vector $X \in \Omega \subset R^q$, weight vector $W = [W_1, \dots, W_m]^T \in R^m$, the NN node number $m > 1$, and $\varphi(X) = [\varphi_1(X) \cdots \varphi_m(X)]^T$, with $\varphi_i(X)$ being Gaussian functions, which have the form

$$\varphi_i(X) = \exp \left[\frac{-(X - \mu_i)^T (X - \mu_i)}{\eta^2} \right], \quad i = 1, 2, \dots, m, \quad (9)$$

where $\mu_i = [\mu_{i1}, \dots, \mu_{iq}]^T$ is the center of the receptive field and η is the width of the Gaussian function.

According to the literatures [23], the neural network (8) can approximate any continuous function $h(X)$ over a compact set $D \subset R^q$ to arbitrary accuracy as

$$h(X) = W^{*T} \varphi(X) + \varepsilon(X), \quad \forall X \in D, \quad (10)$$

where W^* is an ideal constant weight, $\varepsilon(X)$ is the bounded approximation error, and W^* is defined as

$$W^* = \arg \min_{W \in \Omega} \left\{ \sup_{X \in D} |h(X) - W^T \varphi(X)| \right\}. \quad (11)$$

4. Adaptive Synchronization of the Energy Resource System

For different initial conditions of systems (2) and (3), the two coupled systems can achieve synchronization by designing an appropriate control input $u_i(t)$. First, we define the synchronization error vector between systems (2) and (3) as

$$\begin{aligned} e_1 &= x_2 - x_1 - h_1, & e_2 &= y_2 - y_1 - h_2, \\ e_3 &= z_2 - z_1 - h_3, & e_4 &= w_2 - w_1 - h_4, \end{aligned} \quad (12)$$

where h_i ($i = 1, 2, 3, 4$) is filter signal and will be given later.

From (2), (3), and (12), the error dynamical system can be written as

$$\begin{aligned} de_1 &= \left[-\dot{h}_1 + a_1 e_1 - a_2 (e_2 + e_3) - \frac{a_1 x_2^2}{M} + \frac{a_1 x_1^2}{M} - d_3 e_4 \right. \\ &\quad \left. + a_1 h_1 - a_2 (h_2 + h_3) - d_3 h_4 + f_1(x_2) \right. \\ &\quad \left. + u_1(v_1(t)) \right] dt + p_1(e_1) dW, \\ de_2 &= \left[-\dot{h}_2 - b_1 e_2 - b_2 e_3 + b_3 N e_1 - b_3 x_2^2 + b_3 x_1^2 + b_3 x_2 z_2 \right. \\ &\quad \left. - b_3 x_1 z_1 - b_1 h_2 - b_2 h_3 + b_3 N h_1 \right. \\ &\quad \left. + f_2(y_2) + u_2(v_2(t)) \right] dt + p_2(e_2) dW, \\ de_3 &= \left[-\dot{h}_3 - c_1 c_3 e_3 + c_1 c_2 x_2 z_2 - c_1 c_2 x_1 z_1 - c_1 c_3 h_3 \right. \\ &\quad \left. + f_3(z_2) + u_3(v_3(t)) \right] dt + p_3(e_3) dW, \\ de_4 &= \left[-\dot{h}_4 + d_1 e_1 - d_2 e_4 + d_1 h_1 - d_2 h_4 + f_4(w_2) \right. \\ &\quad \left. + u_4(v_4(t)) \right] dt + p_4(e_4) dW. \end{aligned} \quad (13)$$

RBFNNs are used to identify $f_i(\cdot)$ ($i = 1, 2, 3, 4$), and (13) can be rewritten as

$$\begin{aligned} de_1 &= \left[-\dot{h}_1 + a_1 e_1 - a_2 (e_2 + e_3) - \frac{a_1 x_2^2}{M} + \frac{a_1 x_1^2}{M} - d_3 e_4 \right. \\ &\quad \left. + a_1 h_1 - a_2 (h_2 + h_3) - d_3 h_4 + W_1^{*T} \varphi_1(x_2) + \varepsilon_1(x_2) \right. \\ &\quad \left. + u_1(v_1(t)) \right] dt + p_1(e_1) dW, \\ de_2 &= \left[-\dot{h}_2 - b_1 e_2 - b_2 e_3 + b_3 N e_1 - b_3 x_2^2 + b_3 x_1^2 \right. \\ &\quad \left. + b_3 x_2 z_2 - b_3 x_1 z_1 - b_1 h_2 - b_2 h_3 + b_3 N h_1 \right. \\ &\quad \left. + W_2^{*T} \varphi_2(y_2) + \varepsilon_2(y_2) + u_2(v_2(t)) \right] dt + p_2(e_2) dW, \end{aligned}$$

$$\begin{aligned} de_3 &= \left[-\dot{h}_3 - c_1 c_3 e_3 + c_1 c_2 x_2 z_2 - c_1 c_2 x_1 z_1 - c_1 c_3 h_3 \right. \\ &\quad \left. + W_3^{*T} \varphi_3(z_2) + \varepsilon_3(z_2) + u_3(v_3(t)) \right] dt + p_3(e_3) dW, \\ de_4 &= \left[-\dot{h}_4 + d_1 e_1 - d_2 e_4 + d_1 h_1 - d_2 h_4 + W_4^{*T} \varphi_4(w_2) \right. \\ &\quad \left. + \varepsilon_4(w_2) + u_4(v_4(t)) \right] dt + p_4(e_4) dW, \end{aligned} \quad (14)$$

where $|\varepsilon_i| \leq \varepsilon_i^*$ ($i = 1, 2, 3, 4$) and ε_i^* is a positive constant.

In this section, we assume that all the parameters of the energy resource system are unknown. For convenience, similar to [7], we define $a_3 = a_1/M$, $b_4 = b_3N$, $q_1 = c_1c_2$, and $q_2 = c_1c_3$; the system (14) can be rewritten as

$$\begin{aligned} de_1 &= \left[-\dot{h}_1 + a_1 e_1 - a_2 (e_2 + e_3) - a_3 x_2^2 + a_3 x_1^2 - d_3 e_4 \right. \\ &\quad \left. + a_1 h_1 - a_2 (h_2 + h_3) - d_3 h_4 + W_1^{*T} \varphi_1(x_2) + \varepsilon_1(x_2) \right. \\ &\quad \left. + u_1(v_1(t)) \right] dt + p_1(e_1) dW, \\ de_2 &= \left[-\dot{h}_2 - b_1 e_2 - b_2 e_3 + b_4 e_1 - b_3 x_2^2 \right. \\ &\quad \left. + b_3 x_1^2 + b_3 x_2 z_2 - b_3 x_1 z_1 - b_1 h_2 \right. \\ &\quad \left. - b_2 h_3 + b_4 h_1 + W_2^{*T} \varphi_2(y_2) + \varepsilon_2(y_2) \right. \\ &\quad \left. + u_2(v_2(t)) \right] dt + p_2(e_2) dW, \\ de_3 &= \left[-\dot{h}_3 - q_2 e_3 + q_1 x_2 z_2 - q_1 x_1 z_1 - q_2 h_3 + W_3^{*T} \varphi_3(z_2) \right. \\ &\quad \left. + \varepsilon_3(z_2) + u_3(v_3(t)) \right] dt + p_3(e_3) dW, \\ de_4 &= \left[-\dot{h}_4 + d_1 e_1 - d_2 e_4 + d_1 h_1 - d_2 h_4 + W_4^{*T} \varphi_4(w_2) \right. \\ &\quad \left. + \varepsilon_4(w_2) + u_4(v_4(t)) \right] dt + p_4(e_4) dW. \end{aligned} \quad (15)$$

Define the dynamic system as

$$\dot{h}_i = -h_i + (u_i - v_i), \quad i = 1, 2, 3, 4. \quad (16)$$

Choose the following Lyapunov function candidate V as

$$\begin{aligned} V &= \frac{1}{2} (e_1^2 + e_2^2 + e_3^2 + e_4^2) + \widetilde{W}_1^T \widetilde{W}_1 + \widetilde{W}_2^T \widetilde{W}_2 + \widetilde{W}_3^T \widetilde{W}_3 \\ &\quad + \widetilde{W}_4^T \widetilde{W}_4 + \widetilde{a}_1^2 + \widetilde{a}_2^2 + \widetilde{a}_3^2 + \widetilde{b}_1^2 + \widetilde{b}_2^2 + \widetilde{b}_3^2 + \widetilde{b}_4^2 \\ &\quad + \widetilde{d}_1^2 + \widetilde{d}_2^2 + \widetilde{d}_3^2 + \widetilde{q}_1^2 + \widetilde{q}_2^2, \end{aligned} \quad (17)$$

where $\widetilde{a}_i = a_i - \widehat{a}_i$, $\widetilde{d}_i = d_i - \widehat{d}_i$ ($i = 1, 2, 3$), $\widetilde{W}_j = W_j^* - \widehat{W}_j$, $\widetilde{b}_j = b_j - \widehat{b}_j$ ($j = 1, 2, 3, 4$), and $\widetilde{q}_k = q_k - \widehat{q}_k$ ($k = 1, 2$).

Similar to [16, 17], the ℓ infinitesimal generator of V along with the solutions of (15) is

$$\begin{aligned} \ell V = & e_1 \left[h_1 + v_1 + a_1 \hat{e}_1 - \hat{a}_2 (e_2 + e_3) - \hat{a}_3 x_2^2 + \hat{a}_3 x_1^2 \right. \\ & \left. - \hat{d}_3 e_4 + \hat{a}_1 h_1 - \hat{a}_2 (h_2 + h_3) - \hat{d}_3 h_4 + p_1(t) \right. \\ & \left. + \widehat{W}_1^T \varphi_1(x_2) + \varepsilon_1(x_2) \right] \\ & + e_2 \left[h_2 + v_2 - \hat{b}_1 e_2 - \hat{b}_2 e_3 + \hat{b}_4 e_1 - \hat{b}_3 x_2^2 \right. \\ & \left. + \hat{b}_3 x_1^2 + \hat{b}_3 x_2 z_2 - \hat{b}_3 x_1 z_1 - \hat{b}_1 h_2 - \hat{b}_2 h_3 \right. \\ & \left. + \hat{b}_4 h_1 + p_2(t) + \widehat{W}_2^T \varphi_2(y_2) + \varepsilon_2(y_2) \right] \\ & + e_3 \left[h_3 + v_3 - \hat{q}_2 e_3 + \hat{q}_1 x_2 z_2 - \hat{q}_1 x_1 z_1 - \hat{q}_2 h_3 \right. \\ & \left. + p_3(t) + \widehat{W}_3^T \varphi_3(z_2) + \varepsilon_3(z_2) \right] \\ & + e_4 \left[h_4 + v_4 + \hat{d}_1 e_1 - \hat{d}_2 e_4 + \hat{d}_1 h_1 - \hat{d}_2 h_4 \right. \\ & \left. + p_4(t) + \widehat{W}_4^T \varphi_4(w_2) + \varepsilon_4(w_2) \right] \\ & + \widehat{W}_1^T \left[e_1 \varphi_1(x_2) - \dot{\widehat{W}}_1 \right] + \widehat{W}_2^T \left[e_2 \varphi_2(y_2) - \dot{\widehat{W}}_2 \right] \\ & + \widehat{W}_3^T \left[e_3 \varphi_3(z_2) - \dot{\widehat{W}}_3 \right] + \widehat{W}_4^T \left[e_4 \varphi_4(w_2) - \dot{\widehat{W}}_4 \right] \\ & + \tilde{a}_1 \left[e_1^2 + e_1 h_1 - \dot{\hat{a}}_1 \right] \\ & + \tilde{a}_2 \left[e_1 (e_2 + e_3) - e_1 (h_2 + h_3) - \dot{\hat{a}}_2 \right] \\ & + \tilde{a}_3 \left[-e_1 x_2^2 + e_1 x_1^2 - \dot{\hat{a}}_3 \right] + \tilde{b}_1 \left[-e_2^2 - e_2 h_2 - \dot{\hat{b}}_1 \right] \\ & + \tilde{b}_2 \left[-e_2 e_3 - e_2 h_3 - \dot{\hat{b}}_2 \right] \\ & + \tilde{b}_3 \left[-e_2 x_2^2 + e_2 x_1^2 + e_2 x_2 z_2 - e_2 x_1 z_1 - \dot{\hat{b}}_3 \right] \\ & + \tilde{b}_4 \left[e_2 e_1 + e_2 h_1 - \dot{\hat{b}}_4 \right] + \tilde{d}_1 \left[e_4 e_1 + e_4 h_4 + e_4 h_1 - \dot{\hat{d}}_1 \right] \\ & + \tilde{d}_2 \left[-e_4^2 - \dot{\hat{d}}_2 \right] + \tilde{d}_3 \left[-e_1 (e_4 + h_4) - \dot{\hat{d}}_3 \right] \\ & + \tilde{q}_1 \left[e_3 x_2 z_2 - e_3 x_1 z_1 - \dot{\hat{q}}_1 \right] + \tilde{q}_2 \left[-e_3^2 - e_3 h_3 - \dot{\hat{q}}_2 \right] \\ & + \sum_{i=1}^4 e_i \bar{\sigma}_i(e_i). \end{aligned} \tag{18}$$

Design the actual controllers v_j and parameters update laws of \widehat{W}_j , \hat{a}_i , \hat{d}_i ($i = 1, 2, 3$), \hat{b}_j ($j = 1, 2, 3, 4$), and \hat{q}_k ($k = 1, 2$) as follows:

$$\begin{aligned} v_1 = & -l_1 e_1 - \bar{\sigma}_1(e_1) - h_1 - \hat{a}_1 e_1 + \hat{a}_2 (e_2 + e_3) \\ & + \hat{a}_3 x_2^2 - \hat{a}_3 x_1^2 + \hat{d}_3 e_4 - \hat{a}_1 h_1 + \hat{a}_2 (h_2 + h_3) \\ & + \hat{d}_3 h_4 - \widehat{W}_1^T \varphi_1(x_2) - \text{sgn}(e_1) (\varepsilon_1^* + \alpha_1), \end{aligned} \tag{19}$$

$$\begin{aligned} v_2 = & -l_2 e_2 - \bar{\sigma}_2(e_2) - h_2 + \hat{b}_1 e_2 + \hat{b}_2 e_3 - \hat{b}_4 e_1 \\ & + \hat{b}_3 x_2^2 - \hat{b}_3 x_1^2 - \hat{b}_3 x_2 z_2 + \hat{b}_3 x_1 z_1 + \hat{b}_1 h_2 + \hat{b}_2 h_3 \\ & - \hat{b}_4 h_1 - \widehat{W}_2^T \varphi_2(y_2) - \text{sgn}(e_2) (\varepsilon_2^* + \alpha_2), \end{aligned} \tag{20}$$

$$\begin{aligned} v_3 = & -l_3 e_3 - \bar{\sigma}_3(e_3) - h_3 + \hat{q}_2 e_3 - \hat{q}_1 x_2 z_2 + \hat{q}_1 x_1 z_1 \\ & + \hat{q}_2 h_3 - \widehat{W}_3^T \varphi_3(z_2) - \text{sgn}(e_3) (\varepsilon_3^* + \alpha_3), \end{aligned} \tag{21}$$

$$\begin{aligned} v_4 = & -l_4 e_4 - \bar{\sigma}_4(e_4) - h_4 - \hat{d}_1 e_1 + \hat{d}_2 e_4 - \hat{d}_1 h_1 \\ & + \hat{d}_2 h_4 - \widehat{W}_4^T \varphi_4(w_2) - \text{sgn}(e_4) (\varepsilon_4^* + \alpha_4), \end{aligned} \tag{22}$$

where l_i ($i = 1, 2, 3, 4$) are positive design parameters. Consider the following:

$$\dot{\widehat{W}}_1 = e_1 \varphi_1(x_2), \tag{23}$$

$$\dot{\widehat{W}}_2 = e_2 \varphi_2(y_2), \tag{24}$$

$$\dot{\widehat{W}}_3 = e_3 \varphi_3(z_2), \tag{25}$$

$$\dot{\widehat{W}}_4 = e_4 \varphi_4(w_2), \tag{26}$$

$$\dot{\hat{a}}_1 = e_1^2 + e_1 h_1, \tag{27}$$

$$\dot{\hat{a}}_2 = e_1 (e_2 + e_3) - e_1 (h_2 + h_3), \tag{28}$$

$$\dot{\hat{a}}_3 = -e_1 x_2^2 + e_1 x_1^2, \tag{29}$$

$$\dot{\hat{b}}_1 = -e_2^2 - e_2 h_2, \tag{30}$$

$$\dot{\hat{b}}_2 = -e_2 e_3 - e_2 h_3, \tag{31}$$

$$\dot{\hat{b}}_3 = -e_2 x_2^2 + e_2 x_1^2 + e_2 x_2 z_2 - e_2 x_1 z_1, \tag{32}$$

$$\dot{\hat{b}}_4 = e_2 e_1 + e_2 h_1, \tag{33}$$

$$\dot{\hat{d}}_1 = e_4 e_1 + e_4 h_4 + e_4 h_1, \tag{34}$$

$$\dot{\hat{d}}_2 = -e_4^2, \tag{35}$$

$$\dot{\hat{d}}_3 = -e_1 (e_4 + h_4), \tag{36}$$

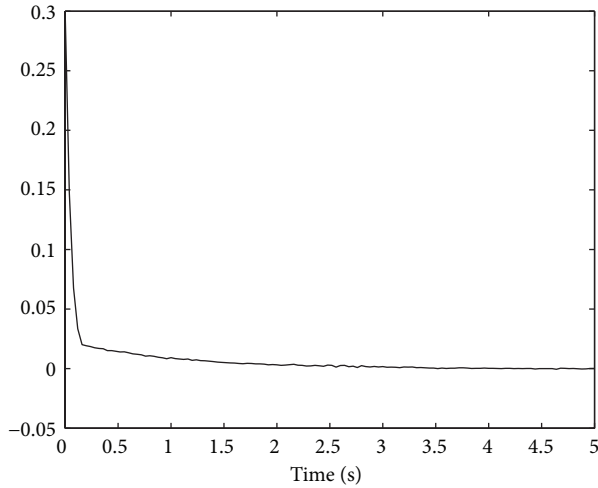
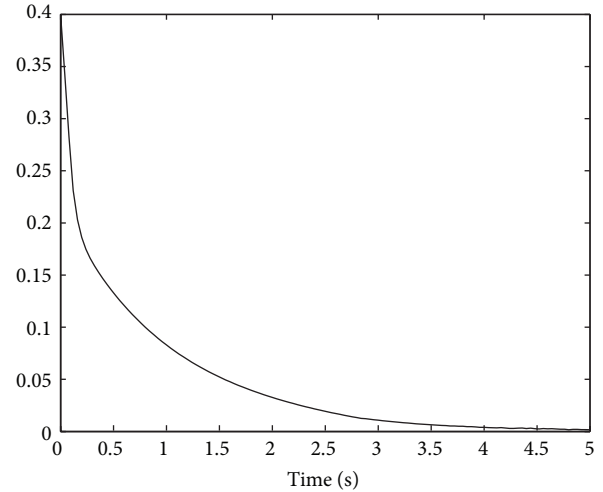
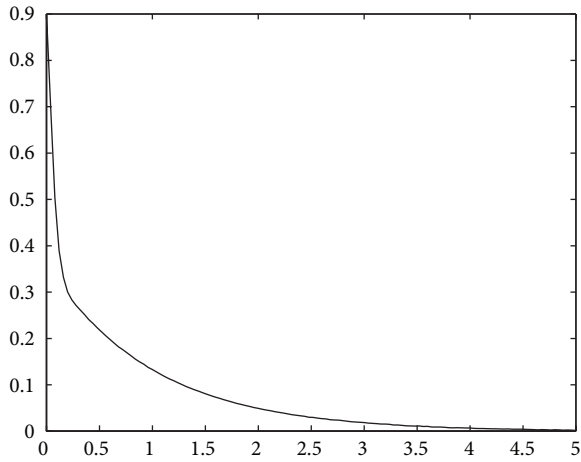
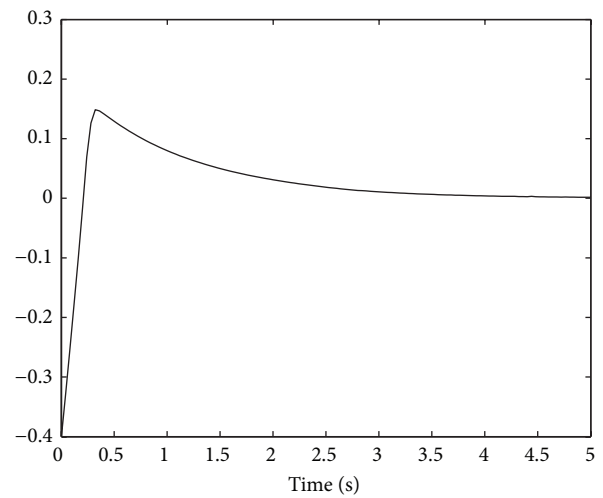
$$\dot{\hat{q}}_1 = e_3 x_2 z_2 - e_3 x_1 z_1, \tag{37}$$

$$\dot{\hat{q}}_2 = -e_3^2 - e_3 h_3. \tag{38}$$

Substituting (19)–(38) into (18) results in

$$\ell V \leq -l_1 e_1^2 - l_2 e_2^2 - l_3 e_3^2 - l_4 e_4^2. \tag{39}$$

From (39) and Lemma 3, we can conclude that the states x_2 , y_2 , z_2 , and w_2 of response system (2) and the states x_1 , y_1 , z_1 , and w_1 of drive system (3) are ultimately synchronized asymptotically in probability.

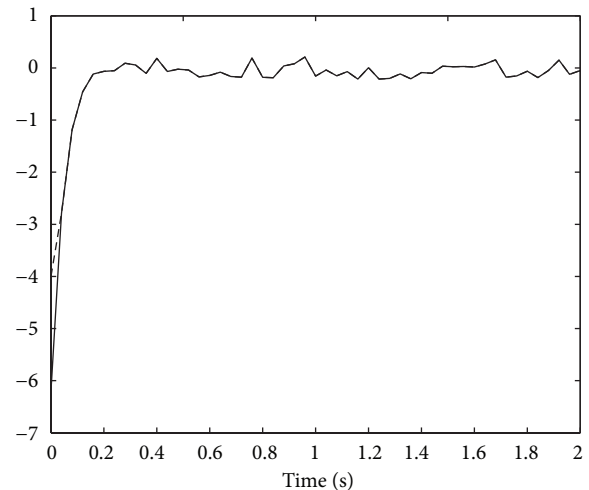
FIGURE 4: The trajectory of e_1 .FIGURE 6: The trajectory of e_3 .FIGURE 5: The trajectory of e_2 .FIGURE 7: The trajectory of e_4 .

5. Simulation Results

In this section, external perturbations $p_i(e_i) = e_i$; uncertain nonlinear $f_1(x_2) = 0.1x_2^2$, $f_2(y_2) = 0.1y_2^2$, $f_3(z_2) = z_2$, and $f_4(w_2) = w_2$. Consider $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = 0.1$ and $\varepsilon_1^* = \varepsilon_2^* = \varepsilon_3^* = \varepsilon_4^* = 0.1$. RBFNNs, $\widehat{W}_i^T \varphi_i(\cdot)$, contain 25 nodes, with centers evenly spaced in $[-4, 4]$ and width is 2. $\dot{W}(t)$ is assumed to be Gaussian white noise with zero mean and variance 1.0.

The initial values are chosen as $x_1(0) = 0.1$, $y_1(0) = -0.8$, $z_1(0) = 0.2$, $w_1(0) = 0.1$, $x_2(0) = 0.4$, $y_2(0) = 0.1$, $z_2(0) = 0.6$, and $w_2(0) = -0.3$, and the other initial values are chosen as zeros. The saturation values are $u_{2M} = 5$, $u_{3M} = 2$, and $u_{4M} = 2$. Design parameters in controllers are $l_1 = 20$, $l_2 = 20$, $l_3 = 20$, and $l_4 = 20$. The simulation results are shown in Figures 4, 5, 6, 7, 8, 9, 10, and 11.

Remark 4. It is worth pointing out that the method of [10] cannot be used to control the systems of this paper. There exist three reasons: (i) the system of this paper is four dimensional

FIGURE 8: The trajectories of v_1 (solid line) and u_1 (dash-dotted line).

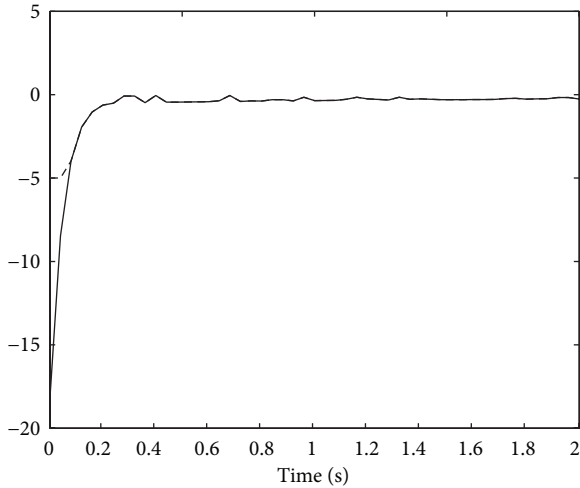


FIGURE 9: The trajectories of v_2 (solid line) and u_2 (dash-dotted line).

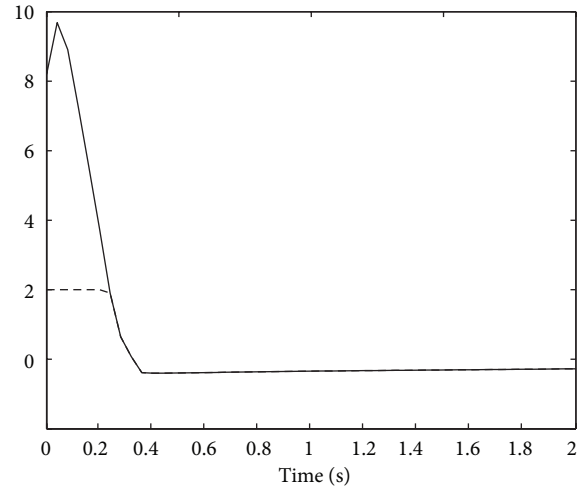


FIGURE 11: The trajectories of v_4 (solid line) and u_4 (dash-dotted line).

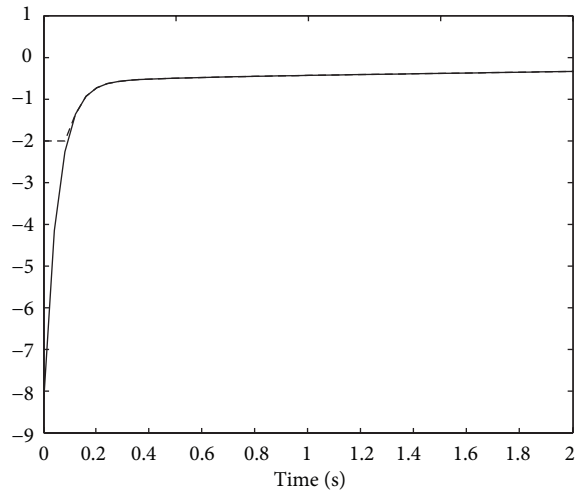


FIGURE 10: The trajectories of v_3 (solid line) and u_3 (dash-dotted line).

and the system in [10] is three dimensional; (ii) the system of this paper contains stochastic disturbances, and the system in [10] does not contain them; (iii) the controlled response system of this paper contains unknown nonlinearities, and [10] does not contain them.

6. Conclusions

This paper has solved the synchronization problems of a class of unknown parameters four-dimensional energy resource system. The main features of the proposed algorithm are that (i) the problems of the input constraint have been solved by employing a new auxiliary system; (ii) the unknown nonlinearities and stochastic disturbances that existed in the response system have been overcome by the neural networks and some special robust terms, respectively; (iii) the stability

of the energy resource demand-supply system has been guaranteed based on stochastic Lyapunov theory.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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