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Designing Full-Order Sliding Mode Controller Based on ANFIS Approximator for Uncertain Nonlinear Chaotic Systems

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ABSTRACT

In this paper, a full-order sliding mode controller, based on adaptive neuro-fuzzy inference system (ANFIS) as approximator, is proposed for controlling nonlinear chaotic systems in presence of uncertainty. At first, the full-order sliding mode controller is designed for the system in the absence of uncertainty such that the system states are converged to the sliding surface. Then, adding uncertainty to system equations, convergence of the method is illustrated using simulations. By assuming that a part of the system dynamics is uncertain and only input-output data is partly available, ANFIS is used in off-line mode to approximate the uncertain dynamics of the system based on input-output data. The proposed method can effectively solve the problems of the sliding-based methods, such as chattering phenomenon and singularity. The simulation results, applied to the well-known nonlinear systems namely permanent magnet synchronous motor (Asus) and plasma torch systems when they behave in chaotic mode, demonstrate effectiveness and fidelity of the proposed control method.

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ANFIS, Full order sliding mode control, PMSM, Plasma torch chaotic system

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I. INTRODUCTION

Chaos phenomenon can be observed in behavior of lots of nonlinear systems with certain dynamics and many natural and artificial systems with this property are being explored gradually. Among these systems, one can refer to identification of chaotic model in economic transactions [1], materials and biotechnology [2], oscillatory circuit [3] and so on. These systems can be expressed by ordinary or partial differential equations including time-independent or time-dependent, discrete-time or continuous-time and energy storage or waste systems [4].

Some hyperchaotic systems have also been introduced in literature. For example, one can refer to hyperchaotic complex Lorenz system [5], Wang and Chen systems [6] and integrated hyperchaotic system. The most underlying feature of such chaotic systems is their sensitiveness to change in initial conditions. This means that change in system behavior is made per slight change in initial conditions of chaotic system [7]. In general case, a continuous system with nonlinear structure, certain dynamics and long-term unpredictable behavior can be chaotic by changing some parameters [8].

Chaos control has attracted attention of many scholars over the decades and different methods have been proposed for controlling chaotic behaviors. The first group includes control methods use internal features of chaotic system [9] and second group controls chaos utilize control techniques. One of the most effective methods for chaos control is sliding mode control (SMC) method. Conventional SMC has some problems such as slow convergence, singularity and chattering [10].

One of the effective SMC methods to control chaotic systems is integral SMC (ISMC) in which proportional integral sliding surface is used to determine general stability for desired equilibrium point. The advantage of using the integral sliding surface is that in addition to providing zero error convergence, integral of error also becomes zero. This can decrease steady state error and also increases the system stability threshold [11]. Other sliding methods such as high-order SMC (HOSMC), terminal SMC (TSMC) and non-singular SMC (NSMC) methods have been also proposed for chaotic systems [12]-[13]. These methods provide partly some advantages such as reduced chattering, non-singularity and finite-time convergence. However, the

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main problem of the existing SMC-based methods is that because of using discrete control input, chattering phenomenon occurs and some additional methods are needed to meet the problem. In this study, full-order sliding model control (FOSMC) has been applied to control the chaos. This method provides more general solution in which the singularity and chattering problems have been solved to high extent.

In this paper, FOSMC has been firstly designed for two well-known nonlinear systems namely permanent magnet synchronous motor (PMSM) and plasma torch systems. By applying the proposed control plan on the systems in chaotic mode, the ability of proposed method to control chaotic behavior of system has been demonstrated adequately even in presence of uncertainty. Then, with the assumption that some part of system dynamics is uncertain and only some input-output data is partly available, adaptive neuro-fuzzy inference system (ANFIS) is used to estimate unknown part of the system dynamics based on the off-line input-output data. The main contributions and innovations of the present work which has not been investigated in the existing studies is as follows:

- Applying FOSMC to uncertain chaotic systems, PMSM and plasma torch systems, for the first time
- Combining ANFIS approximator with FOSMC method to control the system with unknown parts

The organization of this paper is as follows. In Section 2, the system equations and the problem statement are presented. In Section 3, the FOSMC method is firstly introduced and then ANFIS approximator is proposed to estimate control law. In Section 4, the simulation results are presented and the conclusion are drawn in Section 5.

II. System Equations and Problem Statement

The proposed FOSMC method is designed for two nonlinear chaotic systems namely PMSM and plasma torch system. In this section, we introduce the dynamics of these systems.

A. Permanent Magnet Synchronous Motor (PMSM)

Because of high efficiency and power of PMSM and its low construction cost, it has been widely used in industry. In this system, by changing some parameters, system stability may be destroyed and the system may encounter chaotic behavior. In this study, SMC is applied, as one of the most applicable techniques of robust control, for controlling chaotic systems in presence of uncertainty [14]. PMSM chaotic system, introduced in [15], is described as:

$$\begin{aligned}\frac{di_d}{dt} &= -i_d + \omega i_q + u_d \\ \frac{di_q}{dt} &= -i_q - \omega i_d + \gamma\omega + u_q \\ \frac{d\omega}{dt} &= \sigma(i_q - \omega) - T_L\end{aligned} \tag{1}$$

where i_d, i_q and ω, as system state variables, respectively refer to direct axial current, quadrature axis current and angle speed. Moreover, u_d, u_q and T_L respectively refer to direct axial axis voltage, quadrature axis voltage and external load torque. In addition, γ and σ are positive but uncertain parameters. If initial conditions and parameters are chosen as follows:

$$\begin{aligned}&(i_d(0), i_q(0), \omega(0)) = (20, 0.01, -5) \\ &u_d = u_q = T_L = 0 \\ &\gamma = 20 \\ &\sigma = 5.46\end{aligned} \tag{2}$$

then, the system behaves chaotically [16]. The chaotic attractor is depicted in Fig. 1.

Assuming $x_1 = \omega$, $x_2 = i_q$ and $x_3 = i_d$, the system can be recomposed as:

where x_1, x_2 and x_3 refer to state variables and u refers to control signal.

$$\begin{aligned}\dot{x}_1 &= \sigma(x_2 - x_1) \\ \dot{x}_2 &= -x_2 - x_1 x_3 + \gamma x_1 + u \\ \dot{x}_3 &= -x_3 + x_1 x_2\end{aligned} \tag{3}$$

where x_1, x_2 and x_3 refer to state variables and u refers to control signal.

For ease of designing controller, PMSM system is divided to two subsystems. The first subsystem consists of two first equation of (3). The second subsystem includes third equation of (3). It should be noted that the second subsystem, i.e., $\dot{x}_3 = -x_3 + x_1 x_2$, can be considered as dynamical equation inside the system. If x_1 and x_2 converge to zero, the second subsystem is converted to $\dot{x}_3 = -x_3$, which asymptotically converges to zero. Therefore, the aim of control system is to design the control input u in the second subsystem, so that x_1 and x_2 are converged to 0. Changing variables in the following form:

$$\begin{aligned}y_1 &= x_1 \\ y_2 &= \sigma(x_2 - x_1)\end{aligned} \tag{4}$$

Thus, the second subsystem can be written as:

$$\begin{aligned}\dot{y}_1 &= y_2 \\ \dot{y}_2 &= a(x) + bu\end{aligned} \tag{5}$$

Where b and $a(x)$ are as follows:

$$a(x)=\sigma[-x_2-x_1x_3+\gamma x_1-\sigma(x_2-x_1)]$$
$$b=\sigma \tag{6}$$

Where the system can contain a bounded uncertainty due to the existence of uncertainty in its parameters. Also, external disturbance can also be considered in this system. Thus, we have:

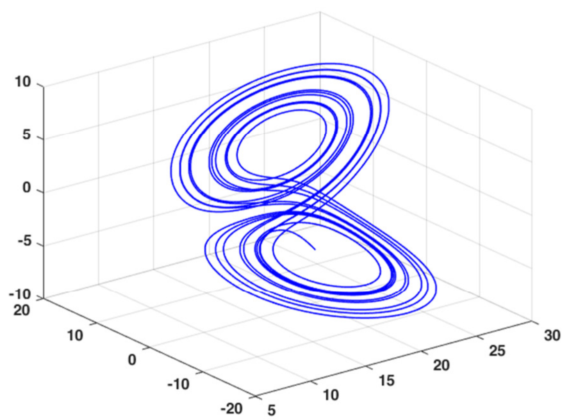

Fig. 1. The phase portrait of PMSM system.

$$\dot{y}_1=y_2$$
$$\dot{y}_2=a(x)+\Delta a+d_1+bu \tag{7}$$

Where d_1 refers to external disturbance satisfying $|d_1|<\gamma_1$ for $\gamma_1\in R$ and Δa refers to uncertainty where $|\Delta a|<\delta_1$ for $\delta_1\in R$.

B. Plasma Torch System

Rod-type plasma torch system is an example of chaotic system used widely in industrial applications. Mathematical model of the system, described in [17], is as follows:

$$\dddot{F}+\mu_2\ddot{F}+\mu_1\dot{F}+\mu F=\pm F^3 \tag{8}$$

where $F,\dot{F},\ddot{F}\in R$ and $\mu,\mu_1,\mu_2\in R$ are the system parameters. Parameters are depended on thermophysical properties such as electric art current and plasma gas flow rate. In this paper, without loss of generality, only $-F_3$ is considered. In this equation, the parameters have been considered as $\mu_1=100$ and $\mu_2=1$. Assuming $F=x_1$, $\dot{F}=x_2$ and $\ddot{F}=x_3$, (8) can be written as:

$$\dot{x}_1=x_2$$
$$\dot{x}_2=x_3 \tag{9}$$
$$\dot{x}_3=-\mu x_1-50x_2-x_3-x_1^3$$

It has been shown that for $\mu=-130$, the system (9) performs chaotic behavior [18]. Chaotic behavior of plasma torch system is illustrated in Fig. 2.

By adding disturbance and uncertainty to the model of system, the equation becomes:

$$\dot{x}_1=x_2$$
$$\dot{x}_2=x_3$$
$$\dot{x}_3=-\mu x_1-50x_2-x_3-x_1^3+\Delta f+d_2+u \tag{10}$$
$$=f(x)+\Delta f+d_2+u$$

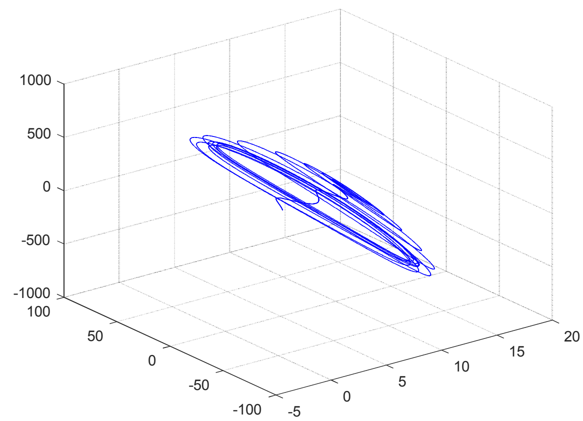

Fig. 2. The phase portrait of Plasma torch system.

Where d_2 refers to external disturbance satisfying $|d_2|<\gamma_2$ for $\gamma_2\in R$ and Δa refers to uncertainty where $|\Delta f|<\delta_2$ for $\delta_2\in R$.

C. Problem Statement

Consider a high-order nonlinear system in the following canonical form:

$$\dot{x}_1=x_2$$
$$\dot{x}_2=x_3$$
$$\dots \tag{11}$$
$$\dot{x}_n=f(x,t)+d(x,t)+b(x,t)u$$

Where n refers to the system order; $x=[x_1,x_2,...,x_n]^T\in R^n$ is the system state vector; $b(x,t)\neq 0$ is a continuous function; $f(x,t)$ refers to continuous and differentiable nonlinear function and $u\in R$ is the control input. Moreover, $d(x,t):R^n\to R$ is a partially known function representing uncertainty and external disturbance which satisfies the following condition:

$$|d(x,t)|\leq I_d \tag{12}$$

Where $I_d>0$ is a known limited constant.

At the first, FOSMC method is designed for PMSM and plasma torch systems. Then, by assuming uncertainty in the system dynamics, input-output data is given and the system is approximated using ANFIS and it is utilized in control input.

III. Proposed Method

A. Full-Order Sliding Mode Controller

Designing SMC basically includes two steps, selecting sliding surface and designing sliding controller. Sliding surface should be selected in such way that system can behave desirably. The control aim is to guarantee that the system reaches sliding surface in finite-time and remain on it thereafter [19].

FOSMC can be considered for the systems in canonical form of Brunowski, similar to (11). In this method, sliding surface is defined as:

$$\begin{aligned} S &= \dot{x}_n + c_n \operatorname{sgn}(x_n)|x_n|^{\alpha_n} + \ldots + c_1 \operatorname{sgn}(x_1)|x_1|^{\alpha_1} \\ &= f(x,t) + d(x,t) + b(x,t)u + c_n \operatorname{sgn}(x_n)|x_n|^{\alpha_n} \\ &+ \ldots + c_1 \operatorname{sgn}(x_1)|x_1|^{\alpha_1} \end{aligned} \tag{13}$$

Where c_i and α_i (for $i = 1,\ldots,n$) are constant design parameters. The parameters c_i are chosen such that $p^{(n)} + c_n p^{(n-1)} + \cdots + c_2 \dot{p} + c_1$ is Hurwitz, and α_i can be determined according to the following conditions:

$$\begin{aligned} &\alpha_{n+1} = 1 \\ &\alpha_n = \alpha \\ &\alpha_{i-1} = \frac{\alpha_i \alpha_{i+1}}{2\alpha_{i+1} - \alpha_i}, i = 2,3,..,n \end{aligned} \tag{14}$$

Where $\alpha \in (1-\delta, 1)$ for $\delta \in (0,1)$. The control input is chosen as:

$$u = b^{-1}(x,t)(u_{eq} + u_n) \tag{15}$$

Assuming $b(x,t) = 1$, we have:

$$u = u_{eq} + u_n \tag{16}$$

where:

$$u_{eq} = -f(x,t) - c_n \operatorname{sgn}(x_n)|x_n|^{\alpha_n} - \ldots - c_1 \operatorname{sgn}(x_1)|x_1|^{\alpha_1} \tag{17}$$

$$\dot{u}_n + T u_n = \upsilon,\ u_n(0) = 0 \tag{18}$$

$$\upsilon = -(k_d + k_T + \eta)\operatorname{sgn}(S) \tag{19}$$

Where η is a positive constant and k_T and k_d are selected in such way that following conditions are provided [20].

$$\begin{aligned} &\left|\dot{d}(x,t)\right| \le k_d \\ &k_T \ge T I_d \end{aligned} \tag{20}$$

Where T is a non-negative constant. We have the following theorem:

Theorem 1 [20]. If the sliding surface S is selected as (13) and the control input is considered as (16), then the nonlinear system (11) will reach $S = 0$ in finite-time and thereby converge to zero along with $S = 0$ in finite-time.

B. The Proposed Controller

In majority of problems, especially in field of control engineering, mathematical model is usually unavailable or inaccurate due to the existence of presumptions. Control methods are highly depended on exact mathematical model and solving problems using these methods is always along with some difficulties. However, intelligent controllers as model-free methods and can reduce the dependency to the model. Hence, these methods can be adequately used in problems in which no mathematical model is available. The methods are also robust to model uncertainties and because of independence on mathematical model, they have usually more adequate performance than classic methods. Another advantage of these methods is their high compatibility, which allows the model to combine them with existing methods to create new combined methods to achieve reasonable solution [21]-[23]. Nowadays, fuzzy logic has become one of the most successful methods for development of complex control systems. The theory of fuzzy logic has been provided by Zadeh in 1965 [24]. With the growth of computer sciences, the fuzzy logic has been widely used in different fields such as control engineering, qualitative modeling, model identification, signal processing, artificial intelligence and so on [25]. Fuzzy approximation is an approach analyzing how to describe complicated functions by means of fuzzy (IF-THEN) rules.

In this paper, ANFIS is used to approximate the uncertain part of the system dynamics. ANFIS consists of a knowledge base including a collection of M fuzzy rules with the following form:

$$\begin{aligned} &\text{Rule } i: \text{ IF } x_1 \text{ is } A_1^i \text{ and } x_2 \text{ is } A_2^i \text{ and } \ldots \text{ and } x_n \text{ is } A_n^i \\ &\qquad \text{THEN } \hat{f}_i = p_1^i x_1 + p_2^i x_2 + \cdots + p_n^i x_n + q^i \end{aligned} \tag{21}$$

Where A_j^i is a fuzzy set in Rule i associated with the membership function of $\mu_{A_j^i}(x_j)$, for $i = 1,\ldots,M$ and $j = 1,\ldots,n$. Total function of ANFIS with n-input and single output can be written as:

$$\begin{aligned} \hat{f}(x) &= \frac{\sum_{i=1}^{M} w_i \hat{f}_i}{\sum_{i=1}^{M} w_i} \\ &= \frac{\sum_{i=1}^{M} w_i (p_1^i x_1 + p_2^i x_2 + \cdots + p_n^i x_n + q^i)}{\sum_{i=1}^{M} w_i} \end{aligned} \tag{22}$$

Where a_j^i and b^i are the parameters of ANFIS and w_i is the weight of Rule i which is calculated by multiplying membership functions of IF part of Rule i, i.e.,

$$w_i = \underset{j=1}{\overset{n}{\pi}} \mu_{A_j^i}(x_j) \tag{23}$$

The membership functions $\mu_{A_j^i}$, are chosen as generalized bell function, which is described as $\mu_{A_j^i}(x_j; a_j^i, b_j^i, c_j^i) = 1/[1 + \left|(x_j - c_j^i)/b_j^i\right|^{2b_j^i}]$. The parameters of ANFIS, i.e., p_j^i,

q^i and the parameters of these membership functions, a_j^i, b_j^i and c_j^i are adjusted using a hybrid learning algorithm (which is a combination of least-squares and backpropagation gradient descent methods,) to model a given set of off-line input-output data. By having off-line input-output data, the learning process can automatically be performed using Fuzzy toolbox of MATLAB software. It should be noticed that ANFIS parameters are constant during the control action. In the proposed method, ANFIS is used to approximate the unknown function using a set of off-line input-output data. After off-line training of the ANFIS, the parameters of ANFIS are considered as fixed values during control operation.

Theorem 2 [26]. Let $f(x)$ be a continuous function defined on a compact set Ω. Then for any constant $\varepsilon > 0$, there exists an ANFIS as (22), such that $\sup_{x\in\Omega}\left|f(x)-\hat{f}(x)\right| \le \varepsilon$.

The inputs of inference system are considered as states x_1, x_2 and … and x_n and the output can be $\hat{f}(x)$. By assuming system uncertainty in (11), a new control law called u_{anfis} is added to (16) and new control law is given as:

$$u = u_{eq} + u_n + u_{anfis} \tag{24}$$

where u_{eq} and u_{anfis} are considered as follows:

$$u_{eq} = -c_1\,\mathrm{sgn}(x_1)\left|x_1\right|^{\alpha_1} - \ldots - c_n\,\mathrm{sgn}(x_n)\left|x_n\right|^{\alpha_n} \tag{25}$$

$$u_{anfis} = -\hat{f} \tag{26}$$

In addition, u_n is the solution of (18) and by assuming $u_n(0)=0$, we have:

$$u_n(t) = (1/T)(k_d + k_T + \eta)(e^{-Tt} - 1)\,\mathrm{sgn}(S) \tag{27}$$

According to universal approximation theorem, ANFIS defined as $\hat{f}$ described by (22) has the capability to approximate every desired continuous function f defined on a compacted set with favorable accuracy [27]. Similarly, the continuous function, $\dot{f}$, can be approximated with an ANFIS defined as $\dot{\hat{f}}$. Therefore, there exist known constants ϕ and β such that:

$$\begin{aligned} &\left|f-\hat{f}\right| < \phi \\ &\left|\dot{f}-\dot{\hat{f}}\right| < \beta \end{aligned} \tag{28}$$

Where ϕ and β are known constants defined as accuracies of approximations.

We have the following theorem:

Theorem 3. Assume that the system is in form of (11), the sliding surface S is selected as (13) and the control law is presented as (24). The system states converge to zero in finite-time if $T\phi + \beta < \eta$ is satisfied.

Proof. Consider a Lyapunov function as:

$$V = \frac{1}{2}S^2 \tag{29}$$

By taking derivative of (29), wet have:

$$\dot{V} = S\dot{S} \tag{30}$$

Replacing (24) into (13), we have:

$$S = (f - \hat{f}) + u_n + d \tag{31}$$

Where d satisfies (12) and (20).

By taking derivative of (31) and replacing into (30), we have:

$$\dot{V} = S[(\dot{f} - \dot{\hat{f}}) + \dot{u}_n + \dot{d}] \tag{32}$$

Considering the solution of (18) as (27), from (12), (20) and (31), we can write the following inequality:

$$Tu_n(t) \le T\left|u_n(t)\right| \le T\left|u_n(t)\right|_{\max} \le TI_d + T\phi \le k_T + T\phi \tag{33}$$

Considering (20) and (28) in (32), we have:

$$\dot{V} \le S\beta + S\dot{u}_n + S\dot{d} \tag{34}$$

On the other hand, we have:

$$\begin{aligned} S\dot{u}_n + S\dot{d} &= -(k_d + k_T + \eta)\left|S\right| - STu_n + S\dot{d} \\ &= (S\dot{d} - k_d\left|S\right|) + (-STu_n - k_T\left|S\right|) - \eta\left|S\right| < (T\phi - \eta)\left|S\right| \end{aligned} \tag{35}$$

Therefore, we can conclude that:

$$\dot{V} \le \beta\left|S\right| + T\varepsilon\left|S\right| - \eta\left|S\right| \le \left|S\right|(T\phi + \beta - \eta) \tag{36}$$

Thus, to make $\dot{V}$ negative, we must have:

$$T\phi + \beta < \eta \tag{37}$$

which completes the proof.

This theorem shows that the proposed method can provide the stability for the system (11) with unknown part and the effect of approximation error can be compensated by appropriate selection of control parameter η.

IV. Simulations

A. PMSM System

In this section, simulation results are illustrated by applying the proposed controller to PMSM system. In order to compare the results of the proposed method with similar methods, we firstly apply a TSMC method [13] to PMSM system. The results are shown in Fig. 3.

Now, we apply the proposed FOSMC technique to PMSM system. The initial states of (20, 0.01, -5) are assumed. In addition, the coefficients and parameters in the sliding surface and the control law are considered as follows:

$$c_1 = 100,\ c_2 = 50,\ \alpha_1 = 1/3,\ \alpha_2 = 5/10 \tag{38}$$

$$T = 0.1,\ (k_d + k_T + \eta) = 10 \tag{39}$$

The states and the control law are converged to zero as shown in Fig. 4.

By considering chaotic condition and applying uncertainty as (40), it could be observed that the controller is able to control the chaotic system similar to previous case and perform a good convergence.

$$\Delta f = 0.2\sin(\pi x_1)\sin(\pi x_2)\sin(\pi x_3), \quad |\Delta f| \le 0.2 \qquad (40)$$

When a part of system dynamics is uncertain, it is approximated using ANFIS, system behavior is depicted in Fig. 5.

It can be seen that FOSMC provides better response compared with TSMC. The use of ANFIS can also improve the results. The existence of uncertainty has not affected on the results and the proposed ANFIS-based FOSMC technique has a satisfactory performance.

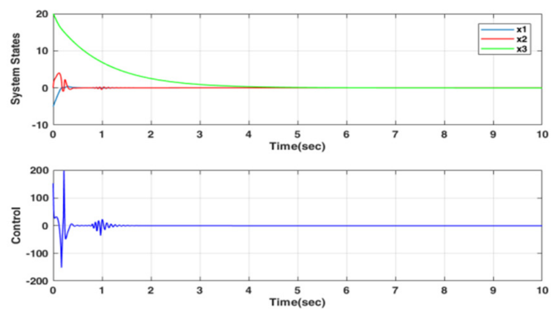

Fig. 3. Time response of states and control signal with TSMC for PMSM system.

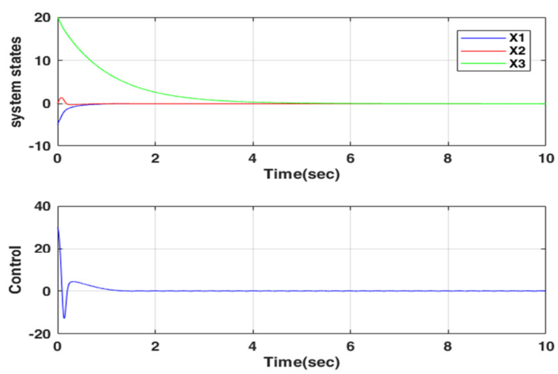

Fig. 4. Time response of states and control signal with FOSMC for PMSM system.

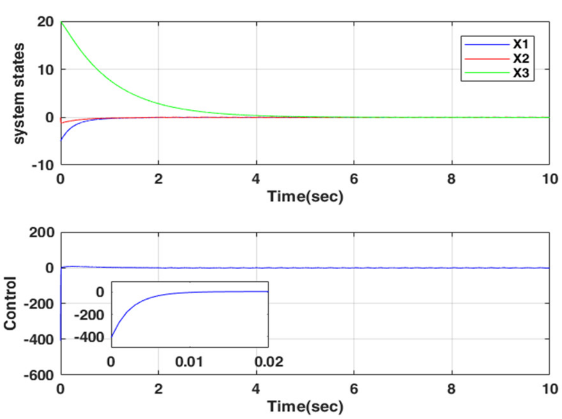

Fig. 5. Time response of states and control signal with ANFIS-based FOSMC in the presence of uncertainty for PMSM system.

B. *Plasma Torch System*

Applying TSMC method [13] to plasma torch system, the results are depicted in Fig. 6.

Now, by applying the proposed FOSMC technique to plasma torch system with regard to exiting parameters of controller as (41) and (42), the states and the control law are shown in Fig. 7.

$$\begin{aligned} &c_1 = 300,\ c_2 = 150,\ c_3 = 50, \\ &\alpha_1 = 9/12,\ \alpha_2 = 9/11,\ \alpha_3 = 9/10 \end{aligned} \qquad (41)$$

$$T = 0.1,\ (k_d + k_T + \eta) = 10 \qquad (42)$$

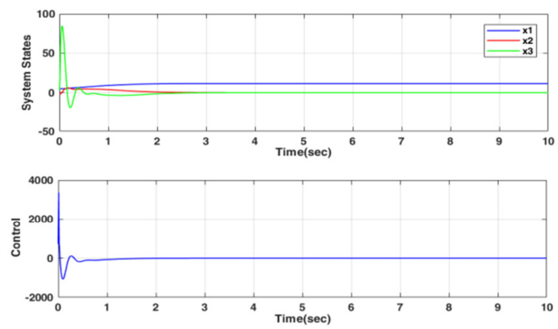

Fig. 6. Time response of states and control signal with TSMC for rod-type plasma torch system.

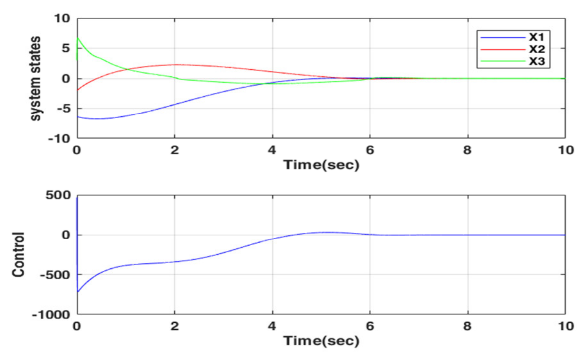

Fig. 7. Time response of states and control signal with FOSMC for rod-type plasma torch system.

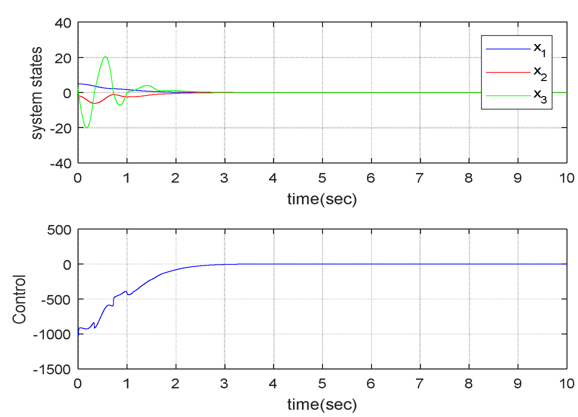

Fig. 8. Time response of states and control signal with ANFIS-based FOSMC in the presence of uncertainty for rod-type plasma torch system.

It can be observed that using TSMC, although the convergence is acceptable, but due to existence of steady state error, the results are not satisfactory. By utilizing FOSMC the stabilization has been improved. When a part of the system is unknown, the results are shown in Fig. 8. It is also seen that using the proposed ANFIS-based FOSMC, the effects of uncertainty are in acceptable range.

V. Conclusions

In this study, FOSMC method based on ANFIS has been applied for controlling chaotic nonlinear systems. The proposed method provides both FOSMC and ANFIS advantages simultaneously. A nonsingular design and chattering-free response together with finite-time robustness against uncertainty is gained while the model of the system includes unknown parts. The method has been applied to well-known chaotic nonlinear systems, i.e., PMSM and plasma torch systems, and the simulation results show the effectiveness of the proposed technique. At first, regardless of uncertainty, it has been observed that the FOSMC method has the ability to meet uncertain chaotic nonlinear systems. Then, the situation for which the system dynamics includes unknown parts, is considered and it has been found that ANFIS has the ability to approximate the unknown part such that the responses of FOSMC has not been affected. Although the method is applicable to the other chaotic systems and also to chaotic neural networks, but at this stage, our aim is to apply the proposed method to some well-known chaotic systems in which SMC-based methods have been studied in the literature and therefore, the comparison on the effects of chaos and uncertainty can be investigated. However, it is the goal of our future research work to apply the proposed method to the other systems.

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