Chaos Control in Memristor-Based Oscillators Using Intelligent Terminal Sliding Mode Controller

Amir Hossein Abolmasoumi and Somayeh Khosravinejad

Abstract—**The problem of terminal sliding mode controller design for chaos control in memristor-based oscillators is investigated. The main goal is to stabilize the chaotic Chua's memristor-based oscillator and to track the sinusoidal reference input. The stability of the oscillator with terminal sliding mode control is analyzed using Lyapunov criteria. Moreover, by defining a new objective function, genetic algorithm optimization is used to reduce the chattering effect and to decrease the convergence time of terminal sliding mode controller. Simulation results demonstrate the usefulness of the proposed control method.**

Index Terms—**Chaos, memristor-based oscillator, terminal sliding mode control, genetic algorithm.**

I. Introduction

There has been some increasing interest in recent years in the studies regarding modeling the chaos and controlling chaotic systems. So far, various methods are used to control chaos such as feedback control [1], adaptive control [2], impulsive control [3], backstepping control [4] and many others. One of the major methods in nonlinear chaos control is Sliding Mode Control (SMC).

Sliding mode control method is a nonlinear control which is used in nonlinear problems to achieve the goals such as stabilization, tracking the reference input and controlling the systems with uncertainties. A standard sliding mode controller design consists of two phases. The first phase, which is called the reaching mode, is when the initial state trajectory of the system is approaching to the arbitrary sliding surface (chosen by the designer). In the second phase, which is called the sliding mode, the system state after reaching the desired surface, it starts sliding on the surface and stay on that. Chattering phenomenon will occur after the first time state hits the sliding surface [5].Conventional sliding mode control (SMC), however, encounters two important issues, i.e. infinite-time convergence and chattering phenomenon. To resolve the first problem, terminal sliding mode control (TSMC) method can be used that is capable of finite-time convergence. To handle the second problem, by the control input can be modified in a way that it would decrease the effect of chattering phenomenon. Chattering reduction and hitting time shortening, in SMC and TSMC can be directly improved by choosing the optimal controller parameters using intelligent optimization methods such as Genetic Algorithm (GA) [6], Particle Swarm Optimization (PSO) [7], [8], etc.

Electronic oscillators are the initial and basic signal generators. They are electrical circuits that produce sine or square wave in their output. Among different kinds of oscillators there are memristor-based oscillators which are achieved by replacing one or more elements of conventional oscillator circuits with a memristive system, such as memristor-based Wien-oscillator [9], memristor-based relaxation oscillator [10], Op-Amps memristor Based oscillator [11] and Chua's memristor- based oscillator [12]. Memristor was proposed by Leon Chua in 1971 [13] and mentioned as the fourth element of electrical circuits. It was fabricated as a nanometer-size solid-state two-terminal device in 2008[14]. Because of the nonlinear nature of the memristive systems, they could cause the chaos in the oscillators they are being used in. So, it is essential to analyze the stability of such oscillator circuits. Moreover, applying nonlinear control methods such as SMC could be a solution to such nonlinear oscillators to be able to track the desired sinusoidal and to control their possibly chaotic behavior. So far, various methods have been used to control chaos in the chaotic oscillators and memristor-based chaotic oscillators [15]-[19].

To the best knowledge of authors, the problem of chaos control in Chua's oscillator circuit including memristive elements is under study by several disciplines as a hot topic. Moreover, the application of terminal sliding mode controllers, such as TSMC, with specifically optimized gains and especial sliding surfaces is not fully investigated in the literature. In this paper, we design anintelligent terminal sliding mode control to control chaos in Chua's memristor-based oscillator for stabilization and being able to track the sinusoidal reference input. To this aim, the dynamic behaviour of the oscillator is firstly formulated and the chaos occurrence is verified. Then by designing the TSMC, the sinusoidal tracking is achieved in finite time. Afterwards, proposing an appropriate performance index, genetic algorithm optimization is applied to adjust the controller parameters in way that the chattering problems would be suppressed and the hitting time is shortened to possible extent so that the tracking quality would be improved .

The rest of paper is organized as follows: Section II briefly represents the basics of TSMC design. Section III introduces the appropriate target function to be minimized in order to improve the performance of TSMC in terms of chattering reduction and tracking time shortening. Section IV gives the essential to model the memristor-based chaotic oscillator. Section V explains the TSMC design procedure for Chua's oscillator in presence of memristive element. Section VI verifies the effectiveness of the proposed method via simulation and finally Section VII concludes the paper.

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II. TERMILNAL SLIDING MODE CONTROL

There are different methods to define the sliding surface in SMC, it can be considered as a convex function of the error, integral function of the error or as a function of the error derivatives. In conventional SMC, the sliding surface is a linear hyperplane composed of the system states [5]. TSMC method, however, uses the sliding surface in the form of nonlinear functions. Thus, in TSMC, the tracking errors on the sliding surface converge to zero in a finite time.

Consider system (1) described as a canonical model of states as follows:

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = F(\mathbf{x}) + G(\mathbf{x})u \end{cases} \qquad (1)$$
$$y_{\text{out}}(t) = x_1(t)$$

where $y_{\text{out}}(t)$ is the output, $\mathbf{x} = [x_1(t), x_2(t)]^T$ is the states vector, $u(t)$ is the control input, $F(\mathbf{x})$ and $G(\mathbf{x})$ are nonlinear function, $d(t)$ is the external disturbance which is constrained as $|d(t)| \le L$. The terminal sliding hyperplane for the system (1) is proposed as follows:

$$s(t) = \dot{x}_1 + \beta x_1^{\frac{q}{p}} = x_2 + \beta x_1^{\frac{q}{p}} \qquad (2)$$

where $\beta_i > 0$ is a design constant,*p*and*q*are positive odd integers satisfying $p > q$. By straight calculations, the convergence time of TSMC can be obtained as follows:

$$t_s = \frac{p}{\beta(p-q)} |x_1(t_r)|^{1-\frac{q}{p}} \qquad (3)$$

where t_r is reaching time. To ensure that the TSMC exists on the switching surface, and this switching surface can be reached in finite time, one has to satisfy Equation (4) [5].

$$\frac{1}{2}\frac{d}{dt}s^2 \le -\eta|s| = \qquad (4)$$

where η is a positive constant. Now, we can design control law that satisfies (4) and also using $\dot{s} = 0$, for system (1) as follows:

$$u = -G^{-1}(\mathbf{x})(\mathrm{F}(\mathbf{x}) + \beta \frac{q}{p} x_1^{\frac{q}{p}-1} x_2 + \eta sign(s)). \qquad (5)$$

Consider the following Lyapunov function as $V = \frac{1}{2}S^2$, we have

$$\dot{V} = s\dot{s} = s(F(\mathbf{x}) + G(\mathbf{x})\mathrm{u} + \beta \frac{q}{p} x_1^{\frac{q}{p}-1} x_2) \qquad (6)$$

Next, by substituting (5) into (6), we have

$$\dot{V} = s\dot{s} = -(\eta)|s| \le 0, \qquad (7)$$

From (7), we find that the Lyapunov condition is satisfied.

III. INTELLIGENT TERMINAL SLIDING MODE CONTROL

Improvingtheperformanceof TSMC method can be achieved by choosing the optimal parameters of the controller using optimization methods. We can defineparameters*k* and β_i, $(i = 1, 2, 3)$ in terminal sliding mode controller as a set of parameters (R_i) that are used to form a chromosome in genetic algorithms. Fitness function is defined as follows:

$$f\,(R_i) = \int S\, dt + \int (-\mathrm{G}^{-1}(\mathbf{x})\,\mathrm{ksgn(s)})^2\, dt \qquad (8)$$
$$R_i = (\beta_i, k)$$

The proposed fitness function (Equation (8)) can providethe shorter hitting time and the smaller chattering magnitudeby minimizing the area under the curvediagram of the sliding surface (the first part) and by optimizing the controller gain parameter *k*, (the second part).

IV. MEMRISTOR- BASED CHUA'S OSCILLATOR

Chua's oscillator circuit is known as a primary source for studying and generating chaos in electronic circuits. Chua's circuit consists of a linear inductor, two capacitors, a linear resistance and nonlinear Chua's diode. Memristor- based Chua's oscillator is evolved from Chua's chaotic circuit by replacing the Chua's diode with a two terminal circuit consisting of a negative conductance and a flux-controlled memristor [12] (Fig. 1).

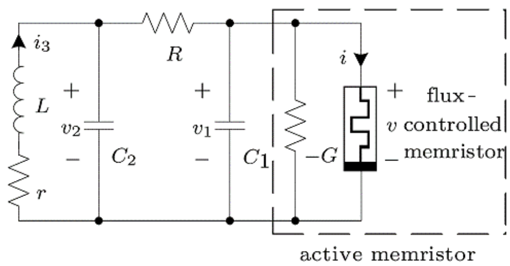

Fig. 1. Memristor- based Chua's circuit.

AFlux-controlled memristordescribed by the function $W(\phi)$, called as memristance, has the mathematical relationship between flux and charge as:

$$W(\phi) = dq(\phi)/d\phi \qquad (9)$$

where $q = q(\varphi)$ is a smooth continuous cubic monotone-increasing nonlinear function as follows:

$$q(\varphi) = a\varphi + b\varphi^3 \qquad (10)$$

Consequently, the memristance $W(\phi)$ is defined by $W(\phi) = dq(\phi)/d\phi = a + 3b\phi^2$. The relationship between the voltage across and the current through the memristor is thus given by:

$$i(t) = W(\phi).v(t) \qquad (11)$$

From Fig. 1, we can obtain a set of four first-orderdifferential equations, which defines the relationship between four circuit variables (v_1, v_2, i_3, φ):

$$\begin{cases} \dfrac{dv_1}{dt} = \dfrac{1}{RC_1}[v_2 - v_1 + GRv_1 - RW(\phi)v_1] \\ \dfrac{dv_2}{dt} = \dfrac{1}{RC_2}[v_1 - v_2 + Ri_3] \\ \dfrac{di_3}{dt} = -\dfrac{1}{L}v_2 - \dfrac{r}{L}i_3 \\ \dfrac{d\phi}{dt} = v_1 \end{cases} \tag{12}$$

To simplify the equations, variables and parameters can be named as follows:

$$x_1 = \phi, x_2 = v_1, x_3 = v_2, x_4 = i_3, \alpha = 1/C_1,$$
$$\beta = 1/L, \gamma = r/L, \xi = G, C_2 = 1, \text{ and } R = 1$$

with these changes, the state equation could be rewritten in the form below:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \alpha(x_3 - x_2 + \xi x_2 - W(x_1)x_2) \\ \dot{x}_3 = x_2 - x_3 + x_4 \\ \dot{x}_4 = -(\beta x_3 + \gamma x_4) \end{cases} \tag{13}$$

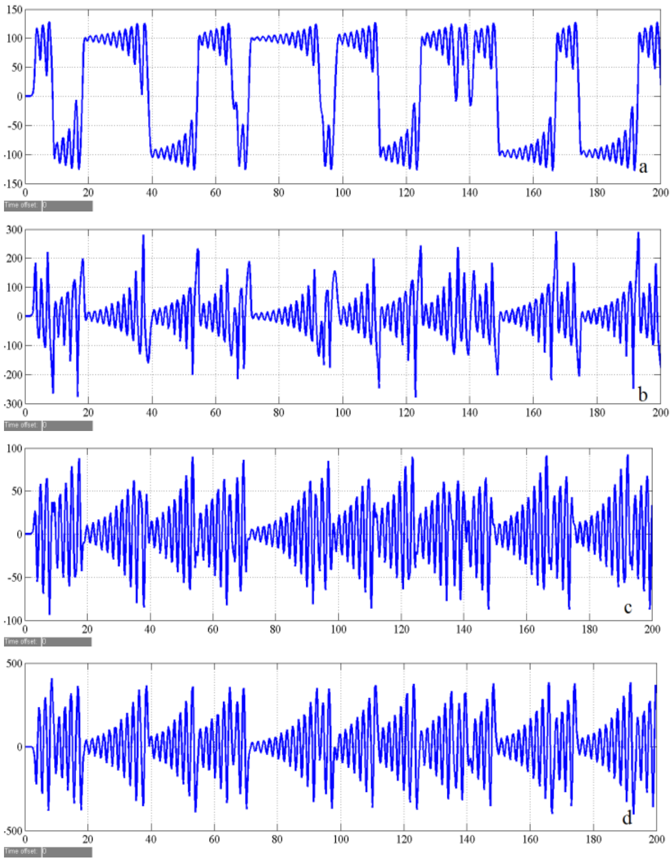

Fig. 2. States of system (13) for initial conditions $(10^{-3}, 10^{-3}, 10^{-10}, 10^{-4})$, a) x_1, b) x_2, c) x_3 and d) x_4.

For the parameter values chosen as $\alpha = 9.8$, $\beta = 100/7$, $\gamma = 0$, $\xi = 9/7$, $a = -0.667 \times 10^{-3}$, $b = 0.029 \times 10^{-3}$ and for the initial conditions $(10^{-3}, 10^{-3}, 10^{-10}, 10^{-4})$, system (13) is chaotic (Fig. 2) and represents a symmetrical 2-scroll chaotic attractor as shown in (Fig. 3). After applying an input to state linearization transformation on the system equations of Memristor- based Chua's oscillator, we would have

$$\begin{cases} \dot{z}_1 = z_2 \\ \dot{z}_2 = z_3 \\ \dot{z}_3 = z_4 \\ \dot{z}_4 = v = f(\mathbf{x}) + g(\mathbf{x})u \end{cases} \tag{14}$$

in which

$$\begin{aligned} f(\mathbf{x}) = & -6\alpha b x_2^3 - 12\alpha^2 b x_1 x_2 (x_3 - x_2 + \xi x_2 - W(x_1)x_2) \\ & + \alpha^2(-1 + \xi - W(x_1))[x_2 - x_3 + x_4 \\ & - \alpha(-1 + \xi - W(x_1))(x_3 - x_2 + \xi x_2 - W(x_1)x_2) \\ & - 6bx_1 x_2^2] + \alpha^2(-6bx_1x_2)(x_3 - x_2 + \xi x_2 - W(x_1)x_2) \\ & + \alpha^2(x_3 - x_2 + \xi x_2 - W(x_1)x_2) - \alpha(x_2 - x_3 + x_4) \\ & + \alpha(-\beta x_3 - \gamma x_4). \end{aligned}$$

$$g(\mathbf{x}) = \alpha,\ W(x_1) = a + 3bx_1^2$$

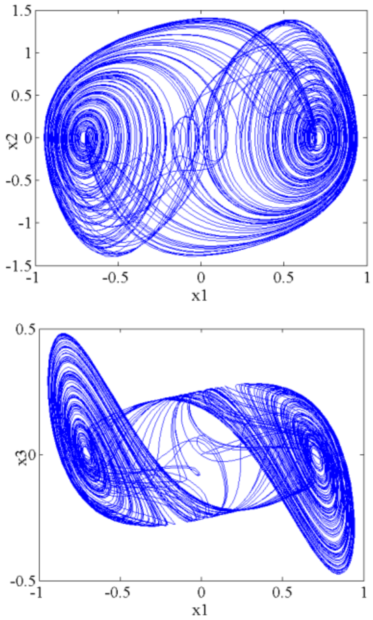

Fig. 3. Chaotic attractor of Memristor- based Chua's oscillator.

V. TSMC Design for Chaotic Memristor-Based Chua's Oscillator

In this section, we design TSMC and intelligent TSMC controllers for chaos control in the Memristor-based Chua's oscillator. The tracking error used in sliding surface is defined as:

$$\begin{cases} e_1 = z_1 - y_d \\ e_2 = z_2 - \dot{y}_d \\ e_3 = z_3 - \ddot{y}_d \\ e_4 = z_4 - y_d^{(3)} \end{cases} \Rightarrow \begin{cases} \dot{e}_1 = e_2 \\ \dot{e}_2 = e_3 \\ \dot{e}_3 = e_4 \\ \dot{e}_4 = f(\mathbf{x}) + g(\mathbf{x})u - y_d^{(4)} \end{cases} \tag{15}$$

According to (2), sliding surface is defined as

$$\begin{aligned} s_0 &= e_1, \\ s_1 &= e_2 + \beta_1 e_1^{\alpha_1}, \\ s_2 &= e_3 + \beta_1 \alpha_1 e_1^{\alpha_1 - 1} e_2 + \beta_2 (e_2 + \beta_1 e_1^{\alpha_1})^{\alpha_2} \\ s_3 &= e_4 + \beta_1 \alpha_1 ((\alpha_1 - 1) e_1^{\alpha_1 - 2} e_2^{\,2} + e_1^{\alpha_1 - 1} e_3) \\ &\quad + \beta_2 \alpha_2 (e_2 + \beta_1 e_1^{\alpha_1})^{\alpha_2 - 1} (e_3 + \beta_1 \alpha_1 e_1^{\alpha_1 - 1} e_2) \\ &\quad + \beta_3 (e_3 + \beta_1 \alpha_1 e_1^{\alpha_1 - 1} e_2 + \beta_2 (e_2 + \beta_1 e_1^{\alpha_1})^{\alpha_2})^{\alpha_3}. \end{aligned} \tag{16}$$

where $\alpha = \frac{q}{p}$. Using $\dot{s}_3 = 0$ and according to (5) control law is defined as

$$u = -g^{-1}(\mathbf{x})[f(\mathbf{x}) + A + \mathrm{ksgn}(s_3)], \qquad \mathrm{k} = \mathrm{L} + \eta. \tag{17}$$

where

$$\begin{aligned} A = {} & \beta_1 \alpha_1 [(\alpha_1 - 1)(\alpha_1 - 2) e_1^{\alpha_1 - 3} e_2^{\,3} \\ & + 2(\alpha_1 - 1) e_1^{\alpha_1 - 2} e_2 e_3 + (\alpha_1 - 1) e_1^{\alpha_1 - 2} e_2 e_3 \\ & + e_1^{\alpha_1 - 1} e_4] + \beta_2 \alpha_2 (\alpha_2 - 1)(e_2 + \beta_1 e_1^{\alpha_1})^{\alpha_2 - 2} \\ & \times (e_3 + \beta_1 \alpha_1 e_1^{\alpha_1 - 1} e_2)^2 + \beta_2 \alpha_2 (e_2 + \beta_1 e_1^{\alpha_1})^{\alpha_2 - 1} \\ & \times (e_4 + \beta_1 \alpha_1 ((\alpha_1 - 1) e_1^{\alpha_1 - 2} e_2^{\,2} + e_1^{\alpha_1 - 1} e_3)) \\ & + \beta_3 \alpha_3 [e_3 + \beta_1 \alpha_1 e_1^{\alpha_1 - 1} e_2 + \beta_2 (e_2 + \beta_1 e_1^{\alpha_1})^{\alpha_2}]^{\alpha_3 - 1} \\ & \times [e_4 + \beta_1 \alpha_1 ((\alpha_1 - 1) e_1^{\alpha_1 - 2} e_2^{\,2} + e_1^{\alpha_1 - 1} e_3) \\ & + \beta_2 \alpha_2 (e_2 + \beta_1 e_1^{\alpha_1})^{\alpha_2 - 1} (e_3 + \beta_1 \alpha_1 e_1^{\alpha_1 - 1} e_2)] \end{aligned}$$

In the stabilization problem and tracking problem, y_d in (15) is set equal to zero and $10^{-3}\sin(t)$, respectively.

VI. Simulation Results

In this section, the effectiveness of the proposed method is validated via simulations. The simulation results of both methods are compared with each other. To avoid the chattering phenomenon, saturation function with threshold parameter equal to 0.02 instead of sign function is used incontrol.

Parameter values of the sliding surface and controller areinitially selectedby designerto achieve appropriate convergence rate and the reasonable magnitude of chattering.

The selected values of the parameters in both stabilization and tracking problem ofTSMCare as follows:

$$\alpha_1 = \frac{q_1}{p_1} = \frac{7}{9},\ \alpha_2 = \frac{q_2}{p_2} = \frac{9}{11},\ \alpha_3 = \frac{q_3}{p_3} = \frac{11}{13},\ \beta_1 = 0.15,$$
$$\beta_2 = 0.1,\ \ \beta_3 = 0.25,\ \ k = 17.$$

For modification of the control gains via optimization, we set GA parameters as follows:

Population size = 50, Number of generations = 100, Crossover rate = 0.8 and Mutation rate = 0.04.

In intelligent TSMC, we set $\beta_i \in [0,20]$ and $k \in [0,20]$ as the searching range of β_i and k. Based on the proposed intelligent method, the optimized value of all parameters are obtained as follows:

- In stabilization problem:

$$\beta_1 = 0.385, \beta_2 = 0.159, \beta_3 = 0.473,\ k = 0.951$$

- In tracking problem:

$$\beta_1 = 0.386, \beta_2 = 0.328, \beta_3 = 0.473,\ k = 1.397$$

The simulation results of stabilization using GA-based intelligent TSMC and TSMC methods are shown in Fig. 4.

As shown in Fig. 4, the system states of Memristor-based Chua's oscillator have been stabilized using TSMC and intelligent TSMC.Given Fig. 4, it is obvious that the hitting time has been decreased by using the intelligent TSMC compared with TSMC.

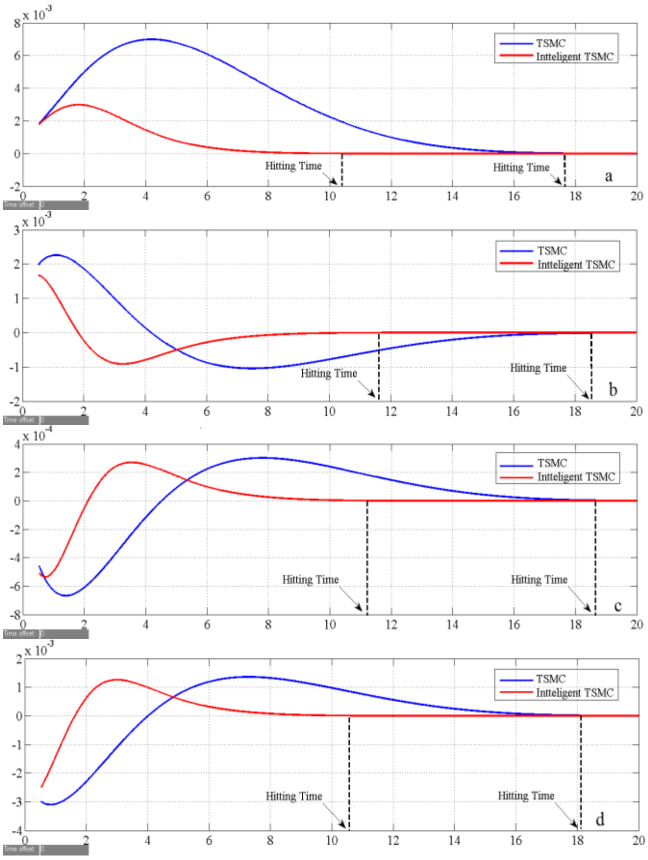

Fig. 4. The simulation results of stabilization of system states using intelligentTSMC and TSMC, a) x_1 , b) x_2 , c) x_3 and d) x_4

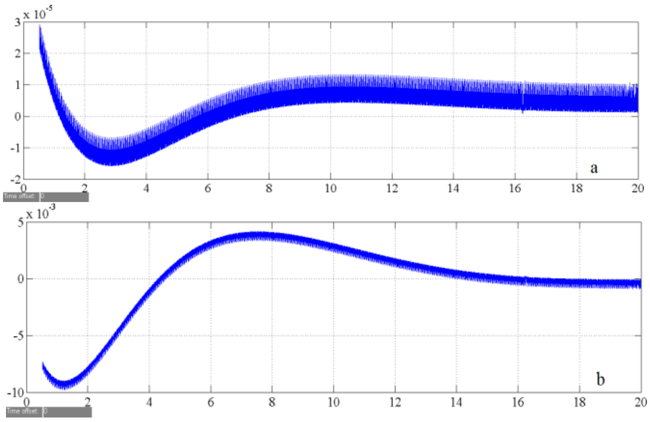

Fig. 5. The time response of sliding surface and control signal in stabilization problem using TSMC. a) Surface *S* and b) Control input *u*.

In Fig. 5 and Fig. 6, we can see the time response of the surface S and control u in stabilization problem using TSMC and intelligent TSMC.

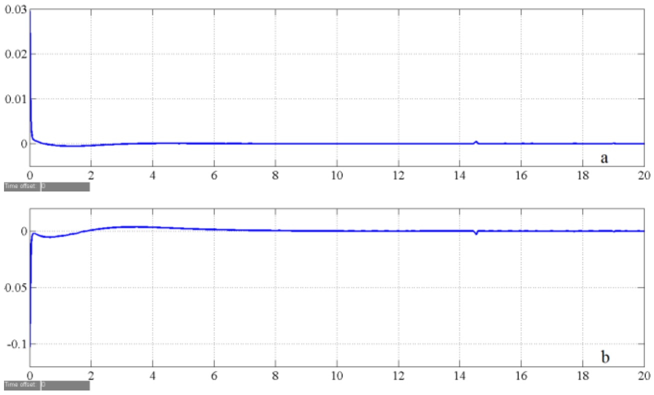

Fig. 6. The time response ofsliding surface and control signalinstabilization problem usingintelligent TSMC. a)Surface$S$ and b)Control input$u$.

As shown in Fig. 5, chattering phenomenon could be a problem when usingTSM controller but as can be seen in Fig. 6, this problemis solvedby GA optimization in the intelligent TSMC method. Fig. 7 shows the tracking of a sinusoidal input using intelligent TSMC and TSMC methods. In Fig. 8 and Fig. 9, the time response of sliding surface S and control u in tracking problem using intelligent TSMC and TSMC are shown.

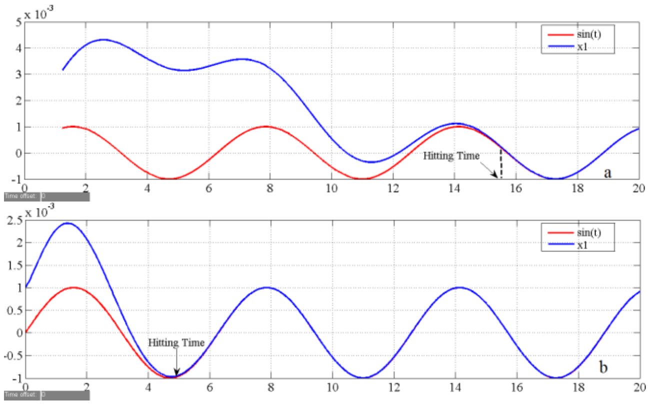

Fig. 7. Tracking of a sinusoidal input using. a) TSMC and b) intelligent TSMC.

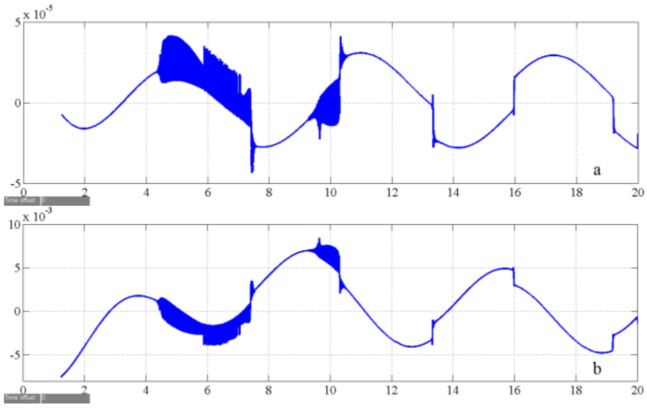

Fig. 8. The time response of S and u in tracking problem using TSMC. a) Sliding surface S and b) Control input$u$.

As shown in Fig. 7, the output of system (12) tracks the sinusoidal input using both TSMC and intelligent TSMC methods. However, the hitting time in intelligent TSMC is much shorter than that ofTSMC. Also chattering is improved by GA optimization of TSMC, unlike the conventional TSMC method which shows a considerable chattering in its control (see Fig. 8 and Fig. 9).

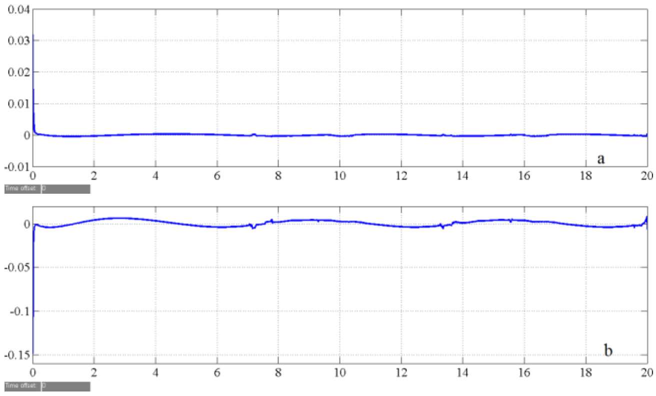

Fig. 9. The time response of sliding surface S and control input u in tracking problem using intelligent TSMC. a) Surface S and b) Control input u.

VII. Conclusion

Chaos control problem in a memristor-based oscillator to track the sinusoidal input using intelligent terminal sliding mode control wasconsidered.By defining a nonlinear hyperplane as the sliding surface and using Lyapunov stability criteria the initial TSMC is designed and tuned for a dynamically modelled Chua's oscillator including a memristive system in its circuit. Although enjoying a finite-time convergence of sliding surface, TSMC suffers from the chattering issue; also the overall hitting time in sinusoidal tracking problem could be regarded as a matter of improvement. Introducing an appropriate nonlinear target functional and performing optimization by the intelligent GA method was ended in extraction of modified control gains so that the modified intelligently tuned TSMC could overcome the problem of chattering in control. Moreover, appropriately selecting the performance index to be optimized via GA, the hitting time in tracking sinusoidal inputs by the oscillator was considerably decreased which could be seen from simulation results.

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