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CHAOS SYNCHRONIZATION USING SUPER-TWISTING SLIDING MODE CONTROL APPLIED ON CHUA'S CIRCUIT

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Abstract. *Chua's circuit is the classic chaotic system and the most widely used in serval areas due to its potential for secure communication. However, developing an accurate chaos control strategy is one of the most challenging works for Chua's circuit. This study proposes a new application of super twisting algorithm (STC) based on sliding mode control (SMC) to eliminate or synchronize the chaos behavior in the circuit. Therefore, the proposed control strategy is robust against uncertainty and effectively regulates the system with a good regulation tracking task. Using the Lyapunov stability, the property of asymptotical stability is verified. The whole of the system including the (control strategy, and Chua's circuit) is implemented under a suitable test setup based on dSpace1104 to validate the effectiveness of our proposed control scheme. The experimental results show that the proposed control method can effectively eliminate or synchronize the chaos in the Chua's circuit.*

Key words: *Chaos control, Chua's circuit, Control design Super-twisting*

1. INTRODUCTION

In a natural phenomenon, such as varied weather, chaos is an evidently, stochastic motion in deterministic nonlinear systems that present a bounded unstable dynamic behavior. Chaos has been extensively investigated since Lorenz reported a sensitive dependence on initial conditions in an atmosphere prediction model and includes infinite unstable periodic motion. Therefore, attract the attention of research community in all the branches dealing with evolutionary processes: chemistry, biology, medicine, genetics, economics, sociology and electronic systems [1–7]. One of the most popular nonlinear electronic systems is Chua's circuit which is a classical example of bifurcation and chaos in nonlinear circuits in many studies. Invented in 1983, Chua's circuit has been extensively considered research subject to analyze chaotic phenomena. On the other side, random

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motion of a system in a chaotic situation was considered to be unfavorable in engineering fields. Therefore, many efforts were given to eliminate or control chaos in the systems, which led to launching the work on chaos control in 1990 such as the OGY (Ott, Gerbogi and York) control method [8], linear feedback control [9], [10], time delay feedback control [4], [11], [12] and some others were reported: the control of chaos such as sliding mode control [13–17], fuzzy control[18–22], polynomial approach [23] high order sliding mode control [24] and harmonic approach [25], [26], etc. Many researchers have been addressed the control of Chua's circuit, in several control methodologies. In [21] the authors present an H∞ tracking performance design scheme via fuzzy adaptive observer-based control for chaotic Chua's systems with output time delay. In [27], [28], the adaptive technique and high-gain methods were proposed respectively to achieve bounded synchronization in the presence of a norm-bounded perturbations. In [29], j. Yan et al. proposed an adaptive synchronization of modified Chua's circuit, this technique based on adaptive switching surface in order to guarantee the occurrence sliding motion. In [30], the authors present a new technique for chaos synchronization based on quasi-sliding mode control for Rikitake chaotic system. Global anti-synchronization of chaotic modified Chua's circuits via linear feedback control is investigated in [31]. The investigations in [32] unveiled a novel robust chaotic controller for stabilizing uncertain time delay chaotic systems with input non-linearity. In [33], Dadras et al. propose a sliding mode controller for new chaotic dynamical system. In [34], In this study, authors focused more on the fractional order and adaptive finite-time sliding mode control in the financial risk chaotic system. However, despite the advantage of the controller, the chattering phenomenon associated with the classical sliding mode controller occurs and clear.

Accordingly, this paper proposes a new and simple chaos control strategy designed to achieve the chaos synchronization or chaos suppression for Chua's circuit. Therefore, we shall debate how to design the super twisting-based on the sliding mode technique for Chua's circuit under parameter uncertainties. The super twisting sliding mode control stability of the closed loop system is proved by using the Lyapunov theory. Moreover, to validate our proposal we develop a test bench based on the dSpace 1104, for more detail see Fig.5.

The rest of the paper is arranged as follows: the Chua's circuit and its characteristics are given in section 2, section 3 presents the mathematical development of the proposed controller, experimental results are reported in section 4. Finally, some concluding remarks are discussed in section 5.

2. Problem Statement and Preliminaries

2.1. Chua's circuit

The chaotic Chua's circuit, as shown in Fig.1, is a simple electronic circuit that consists of one inductor I_L, two capacitors C_1; C_2, one linear resistor R, and a nonlinear resistor NLR [35]. The Chua's circuit can be described by a third-order nonlinear differential equation, according to the electronics theory, the mathematical model of Chua's circuit is given by:

$$\begin{cases} C_1 \dfrac{d\upsilon_1(t)}{dt} = \dfrac{1}{R}\left(\upsilon_2(t)-\upsilon_1(t)\right) - g\left(\upsilon_1(t)\right) \\ C_2 \dfrac{d\upsilon_2(t)}{dt} = \dfrac{1}{R}\left(\upsilon_1(t)-\upsilon_2(t)\right) + i_L(t) \\ L\dfrac{di_L(t)}{dt} = -\upsilon_2(t) \end{cases} \tag{1}$$

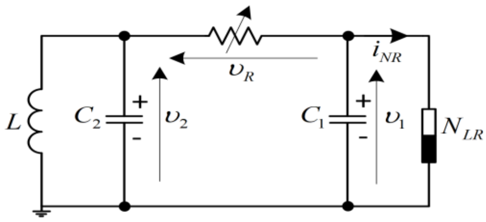

Fig. 1 Chua's circuit

Where V_1, V_2 respectively are the voltages across capacitors C_1 and C_2; i_L is the current through inductor L; stands for the current through the nonlinear resistor NLR and can be expressed by a piecewise-linear function.

$$i_{NR} = g(\upsilon_1) = G_b\upsilon_1 + 0.5(G_a - G_b) - \| \upsilon_1 + 1 \| - \| \upsilon_1 - 1 \| \tag{2}$$

For simplicity, a sole circuit system is described as, $\dfrac{dx}{dt} = f(x(t),t)$,

Where, $x(t) = \left[\upsilon_1(t),\upsilon_1(t),i_L(t)\right]^T$, $f(x(t),t) = Ax(t) - \left[\alpha g(\upsilon_1(t)),0,0\right]^T$

$$\alpha = \frac{1}{C_1R_1},\ \beta = \frac{1}{C_1},\ \gamma = \frac{1}{C_2R_1}, \zeta = \frac{1}{C_2}, \delta = \frac{1}{L},\ A = \begin{bmatrix} -\alpha & \alpha & 0 \\ \gamma & -\gamma & \zeta \\ 0 & -\delta & 0 \end{bmatrix}.$$

Table.1 represent the parameters adopted for Chua's circuit. However, our objective after this simulation is to validate the proposed parameters and to build a prototype (PCB), for more detail see Fig. 2.

Table 1 Parameters adopted for Chua's circuit

Parameters	Values	Unite
R1 R2	220	Ω
R3, R4, R6	2200	Ω
R5	3300	Ω
Amplificator	TL084	/
Variable resistor	2200	Ω
C1	10	nF
C2	10	nF
Indictor	9	mH

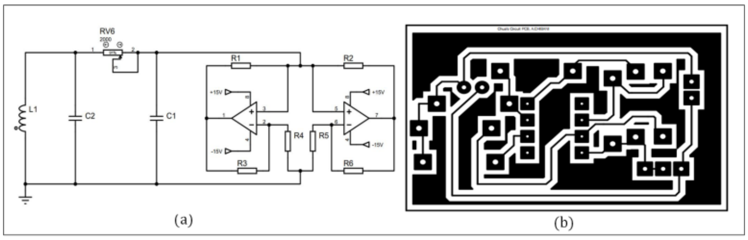

Fig. 2 Chua's circuit prototype: (a) schematic under Proteus, (b) PCB design

Fig. 2a presents the electronic circuit under the proteus platform. however, this phase we need to validate the functioning of Chua's circuit. Fig. 2b presents the PCB prototype of the circuit.

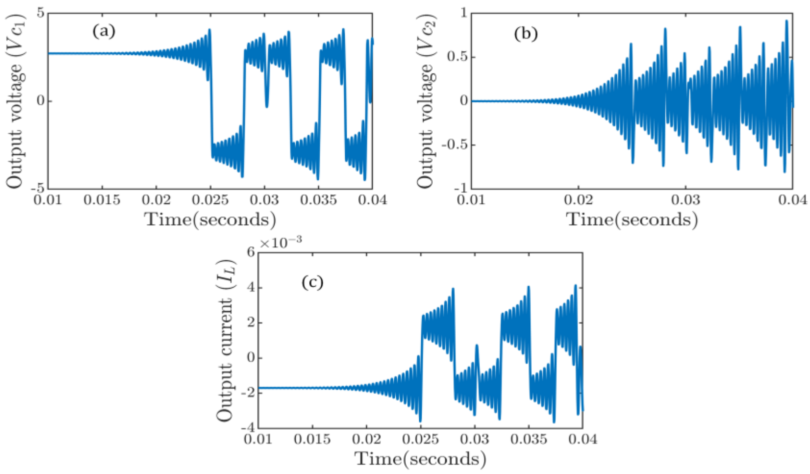

Fig. 3 Simulation results in open loop using proteus platform: (a) voltage capacitor Vc_1, (b) voltage capacitor Vc_2, (c) current Inductor I_L

Fig. 3 focuses on three components: Fig. 3a the voltage across a capacitor Vc_1, Fig. 3b the voltage across another capacitor Vc_2, and Fig. 3c the current through an inductor I_L. The simulation results show that the behavior of these components presents a chaotic phenomenon, meaning they exhibit unpredictable and seemingly random behavior over time.

2.2. Objectives

The main objectives of this study are as follows:

- Construct chaos control strategy $u(t)$ based on the sliding mode technique moreover, guarantee the synchronization stability under the healthy condition or in the case of perturbations.
- Performing the proposed control scheme physically, so that the closed-loop Chua's circuit can be implemented by circuits (TL084) and the dSpace 1104 card.

3. SUPER TWISTING ALGORITHM

The sliding mode control is one of the most accurate and robust control techniques. The typical first-order sliding mode control causes undesirable high-frequency chattering problem. The chattering phenomena can be eliminated by using the second order sliding mode control. However, Different second order sliding mode topology such as: the super twisting algorithm, drift algorithm, sub-optimal algorithm, and prescribed convergence algorithm are discussed in literature [16], [36]–[38]. Therefore, The Super-twisting algorithm is a second order sliding mode controller is more suitable for the system with relative degree one. the main advantage of this algorithm: first, it does not require the time derivative information of the sliding variables. While, measurement of derivative of sliding surface is required which may increase noise in the system. Second, reduce the charting phenomena.

The super twisting strategy present the control law as a combination between two functions: the continuous sliding variable function and the integral of a discontinuous sliding variable function. Furthermore, we have chosen the super-twisting algorithm since the relative degree of our system and we seek for the finite time convergence which is one of its features. In this section, we present the synthesis of super-twisting approach in order to control the Chua's circuit.

We consider the nonlinear system with the following dynamics:

$$\frac{dx}{dt} = f(x) + b(x)u(t) \tag{3}$$

Where $x \in R, f(x) \in R, b \in R$ *and* $b^{-1} \neq 0 \in R$

The main objective is to lead the state vectors to track their references vector. Therefore, the error vector $e_i(t) = 0$ tends to zero vector. The block in diagram Fig. 4 represents the general methodology for our application.

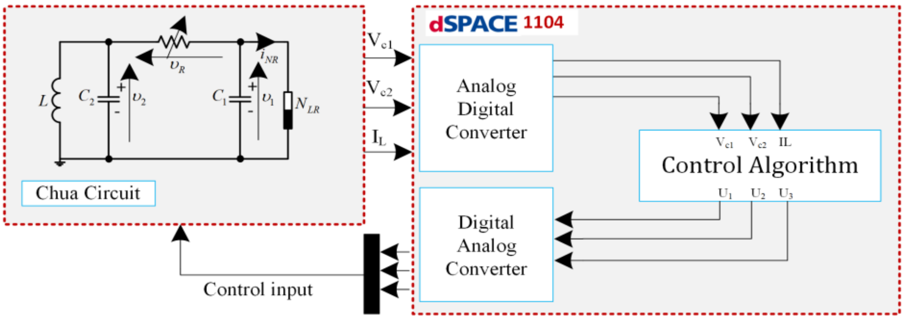

Fig. 4 Block diagram of the controller scheme

The control law $u = [u_1 u_2 u_3]^T$ is designed to drive the system Eq. (1) to the desired surface $s = [s_1 s_2 s_3]^T$

The sliding surface is selected as

$$s=\begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix}=\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix}=\begin{bmatrix} \upsilon_1-\upsilon_1^{ref} \\ \upsilon_2-\upsilon_2^{ref} \\ i_L-i_L^{ref} \end{bmatrix} \tag{4}$$

Where S is the synchronization error and the sliding surface respectively.

Proposition 1

Consider system Eq. (1) and the sliding surface S defined in Eq. (4). Let introduce the super twisting algorithm.

$$\begin{cases} u=\gamma_i \left\| s_n \right\|^{\frac{1}{p}} sign(s_n)+\psi \\ \psi=\lambda_i \int sign(s_n)dt \end{cases} \tag{5}$$

Where γ_i and λ_i are a positive constant number.

Proposition 2

Consider the system Eq. (1), the sliding surface present in Eq. (4) and the super-twisting proposition 1 in Eq. (5), let's the control input in closed-loop system describe by

$$u=u_{eq}+u_{sw} \tag{6}$$

With,

$$u=\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}=\begin{bmatrix} u_1^{eq}+u_1^{sw} \\ u_2^{eq}+u_2^{sw} \\ u_3^{eq}+u_3^{sw} \end{bmatrix} \tag{7}$$

Where,

u_i^{sw} : is the switching control Function. The switching control function drives the system in any initial state to reach the sliding manifold in finite time, which are calculated through the application of the super-twisting algorithm, see system Eq. (5).

u_i^{eq} : is the equivalent control function. The equivalent control function drive the system to move over the sliding manifold under ideal conditions. One of its features, can speed-up the response of the system and reduce the steady state errors [39]. The equivalent control function is calculated by setting the derivative of the sliding surface tend to 0, $\frac{ds_i}{dt}=0$.

$$\frac{ds}{dt}=\frac{d}{dt}\begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix}=\frac{d}{dt}\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix}=\frac{d}{dt}\begin{bmatrix} \upsilon_1-\upsilon_1^{ref} \\ \upsilon_2-\upsilon_2^{ref} \\ i_L-i_L^{ref} \end{bmatrix}=\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{8}$$

$$u_i^{eq}=\begin{bmatrix}u_1^{eq}\\u_2^{eq}\\u_3^{eq}\end{bmatrix}=\begin{bmatrix}\dfrac{d\upsilon_1^{ref}}{dt}-\left(\alpha(\upsilon_2(t)-\upsilon_1(t))-\beta g(\upsilon_1(t))\right)\\\dfrac{d\upsilon_2^{ref}}{dt}-\left(\gamma(\upsilon_1(t)-\upsilon_2(t))+\zeta i_L(t)\right)\\\dfrac{di_L^{ref}}{dt}-\left(-\delta\upsilon_2(t)\right)\end{bmatrix}\tag{9}$$

Based on the equations Eq. (1), (5), (6), (7) and Eq. (8) the super-twisting controller is given by

$$u_i=\begin{bmatrix}u_1\\u_2\\u_3\end{bmatrix}=\begin{bmatrix}\dfrac{dx_1^{ref}}{dt}-\left(\alpha(\upsilon_2(t)-\upsilon_1(t))-\beta g(\upsilon_1(t))\right)+\Psi_1\\\dfrac{dx_2^{ref}}{dt}-\left(\gamma(\upsilon_1(t)-\upsilon_2(t))+\zeta i_L(t)\right)+\Psi_2\\\dfrac{dx_3^{ref}}{dt}-(-\delta\upsilon_2(t))+\Psi_3\end{bmatrix}\tag{10}$$

Where,

$\Psi_1=k_{11}\|s_1\|^p\,sign(s_1)+k_{12}\int sign(s_1)dt,\ \Psi_2=k_{21}\|s_2\|^p\,sign(s_2)+k_{22}\int sign(s_2)dt$

$\Psi_3=k_{32}\|s_3\|^p\int sign(s_3)dt$

3.1. Stability proof

Consider the super-twisting controller given by Eq. (6), the tracking errors $e_i=[e_i]==[x_{ref}^i-x^i]$ are globally asymptotically stable.

Let's using $u=u_{eq}+u_{sw}$, In this case, the matter of the stability condition is expressed as:

$$s=0\quad and\quad \frac{ds}{dt}=0\tag{11}$$

The dynamics of the system Eq. (2) is subjected to the following:

$$\frac{ds}{dt}=\frac{\partial s}{\partial x}\frac{dx}{dt}\tag{12}$$

Since

$$\frac{dx}{dt}=f(x)+b(x)u(t)\tag{13}$$

By using Eq. (6) and Eq. (13) we have

$$\frac{ds}{dt}=\frac{\partial s}{\partial x}\left[f(x)+b(x)u(t)\right]\tag{14}$$

$$\frac{ds}{dt} = \frac{\partial s}{\partial x}[f(x) + b(x)u_{eq}] + \frac{\partial s}{\partial x}[b(x)u_{sw}] \tag{15}$$

By setting $\frac{ds}{dt} = 0$ ds dt = 0 and $u_{sw} = 0$ we get

$$u_{eq} = -\frac{\frac{\partial s}{\partial x}[f(x)]}{\frac{\partial s}{\partial x}[b(x)]} \tag{16}$$

Using Eq. (15) and Eq. (16) we get

$$\frac{ds}{dt} = \frac{\partial s}{\partial x} b(x)u_{sw} \tag{17}$$

We consider the Lyapunov candidate function

$$V = \frac{1}{2}S^2 \tag{18}$$

The derivative of along the trajectories of the system is given by:

$$\frac{dV}{dt} = S\frac{dS}{dt} = s_1\frac{ds_1}{dt} + s_2\frac{ds_2}{dt} + s_3\frac{ds_3}{dt} \tag{19}$$

To ensure the condition of global asymptotic stability, we have two issues: Firstly, we must verify the decrease of the Lyapunov function to zero. Secondly, it's needful to ensure the derivative of Lyapunov function is negative. For our purpose its sufficient to verify that its derivative is negative.

$$\frac{dV}{dt} < 0 \Rightarrow S\frac{dS}{dt} < 0 \tag{20}$$

$$S\frac{dS}{dt} = S\frac{\partial s}{\partial x} b(x)u_{sw} \tag{21}$$

$$S\frac{dS}{dt} = S_1\frac{\partial s_1}{\partial x} b(x)u_{SW}^1 + S_2\frac{\partial s_2}{\partial x} b(x)u_{SW}^2 + S_3\frac{\partial s_3}{\partial x} b(x)u_{SW}^3 < 0 \tag{22}$$

From Eq. (10) we have

$$u_{sw}^i = \begin{bmatrix} u_{sw}^1 \\ u_{sw}^2 \\ u_{sw}^3 \end{bmatrix} = \begin{bmatrix} k_{11}\|s_1\|^p sign(s_1) + k_{12}\int sign(s_1)dt \\ k_{21}\|s_2\|^p sign(s_2) + k_{22}\int sign(s_2)dt \\ k_{31}\|s_3\|^p sign(s_3) + k_{32}\int sign(s_3)dt \end{bmatrix} \tag{23}$$

By replacing Eq. (23) in Eq. (22) we obtain

$$\begin{aligned} S\frac{dS}{dt} &= S_1\frac{\partial s_1}{\partial x}b(x)\Big[k_{11}\|s_1\|^p\,sign(s_1)+k_{12}\int sign(s_1)dt\Big] \\ &+S_2\frac{\partial s_2}{\partial x}b(x)\Big[k_{21}\|s_2\|^p\,sign(s_2)+k_{22}\int sign(s_2)dt\Big] \\ &+S_3\frac{\partial s_3}{\partial x}b(x)\Big[k_{31}\|s_3\|^p\,sign(s_3)+k_{32}\int sign(s_3)dt\Big]<0 \end{aligned} \tag{24}$$

Let's introduce the nonlinear term as

$$s_i\,sign(s_i)=\|s_i\| \tag{25}$$

$$\begin{aligned} S\frac{dS}{dt} &= \frac{\partial s_1}{\partial x}b(x)\Big[k_{11}\|s_1\|^p\|s_1\|+k_{12}\int sign(s_1)dt\Big] \\ &+\frac{\partial s_2}{\partial x}b(x)\Big[k_{21}\|s_2\|^p\|s_2\|+k_{22}\int sign(s_2)dt\Big] \\ &+\frac{\partial s_3}{\partial x}b(x)\Big[k_{31}\|s_3\|^p\|s_3\|+k_{32}\int sign(s_3)dt\Big]<0 \end{aligned} \tag{26}$$

$$\frac{dV}{dt}=\begin{bmatrix} s_1\dfrac{ds_1}{dt} \\ s_2\dfrac{ds_2}{dt} \\ s_3\dfrac{ds_3}{dt} \end{bmatrix}=\begin{bmatrix} \dfrac{\partial s_1}{\partial x}b(x)\Big[k_{11}\|s_1\|^p\|s_1\|+k_{12}\int sign(s_1)dt\Big]<0 \\ \dfrac{\partial s_2}{\partial x}b(x)\Big[k_{21}\|s_2\|^p\|s_2\|+k_{22}\int sign(s_2)dt\Big]<0 \\ \dfrac{\partial s_3}{\partial x}b(x)\Big[k_{31}\|s_3\|^p\|s_3\|+k_{32}\int sign(s_3)dt\Big]<0 \end{bmatrix} \tag{27}$$

Where $k_{11}, k_{12}, k_{21}, k_{22}, k_{31}, k_{32}$ are a constant number.

To sum up, the term $\frac{\partial s_i}{\partial x}b(x)$ is positive according to the system under consideration, where as the gains k_{ij} must be selected negative in order to satisfy the condition stability shown below. In the end, the requirement of global asymptotic stability is achieved.

4. EXPERIMENTAL RESULTS

A Chua's circuit is developed to validate the analysis described above. Table.1 contains the details of Chua's circuit parameters. A suitable test setup built around the dSpace 1104 serves to implement the mathematical model which was established with closed-loop control. The experimental set-up for this work is depicted in Fig. 5. The following constitutes the test setup:

- The Chua's chaotic system.
- A DC power supply is to deliver DC voltage (5V, +15V, -15v) from an AC network.
- An interface Controller Board dSpace (model Ds 1104) with a power Pc 603e at 400 MHz and a fixed-point digital signal processor DSP TMS320F240.

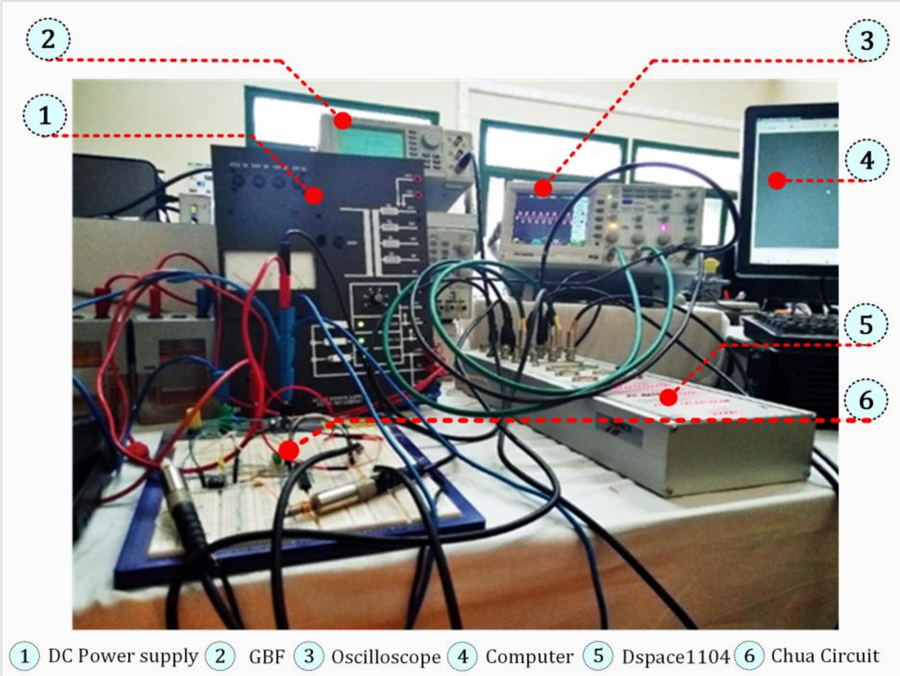

Fig. 5 Experimental setup

Fig. 5, presents a test setup depicted for Chua's chaotic system, The setup is designed to operate with a DC power supply that converts AC voltage from the network into a stable DC voltage of 5V, +15V, and -15V. The system also includes an interface controller board, referred to the dSpace model Ds1104. The dSpace board is equipped with a PowerPC 603e processor running at a clock frequency of 400 MHz. This is designed to handle real-time digital signal processing tasks and is an important component in the overall control and monitoring of Chua's chaotic system and validate our proposed control scheme.

Fig. 6 presents the experimental results in open-loop of the Chua's circuit. As shown in Fig. 6a, the time response of voltage capacitor Vc_1 is depicted, in Fig. 6b the variation of Vc_2 is illustrated, and in Fig. 6c the time response of the Il is presented. From these figures, it can be observed that the Chua's circuit generates chaotic phenomena, which is a characteristic behavior of the Chua's circuit. The chaotic oscillations of Vc_1 and Vc_2 are clearly visible in Fig. 6a and Fig. 6b, respectively. Furthermore, the time response of Il in Fig. 6c.

Fig. 7 demonstrates the experimental behavior of Chua's circuit under the application of the proposed super twisting control scheme. As shown in Fig. 7a and Fig. 7b, the evolution of capacitor voltage Vc_1 and Vc_2 are closely follows their references, which indicates that the synchronization design is guaranteed and effectively realized. Fig. 7c illustrates the experimental behavior of the static error, which confirms that the proposed scheme is both effective and convincing. To further investigate the performance of the super twisting sliding mode algorithm, we evaluated the proposed scheme under various conditions, including both fixed point and periodic orbit scenarios. As illustrated in Fig. 8.a and Fig. 8.b, the effectiveness of our proposed scheme is clearly demonstrated in closed-loop. Additionally, to evaluate the robustness of the proposed method, we also tested its performance in the presence of disturbances and system parameter variations. The results show that our proposed method is effective in ensuring the control, synchronization and stability of the Chua's circuit system.

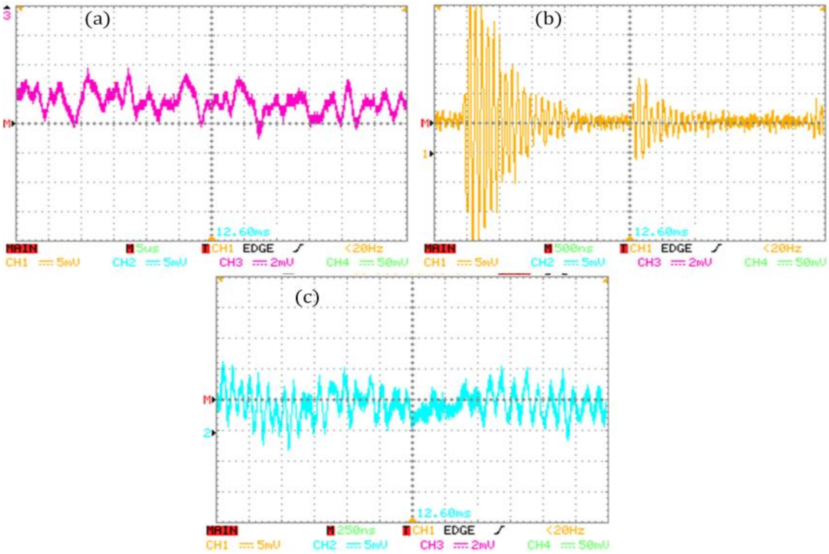

Fig. 6 Experimental results in open loop: (a) current Inductor I_L (b) voltage capacitor Vc_1 (c) voltage capacitor Vc_2

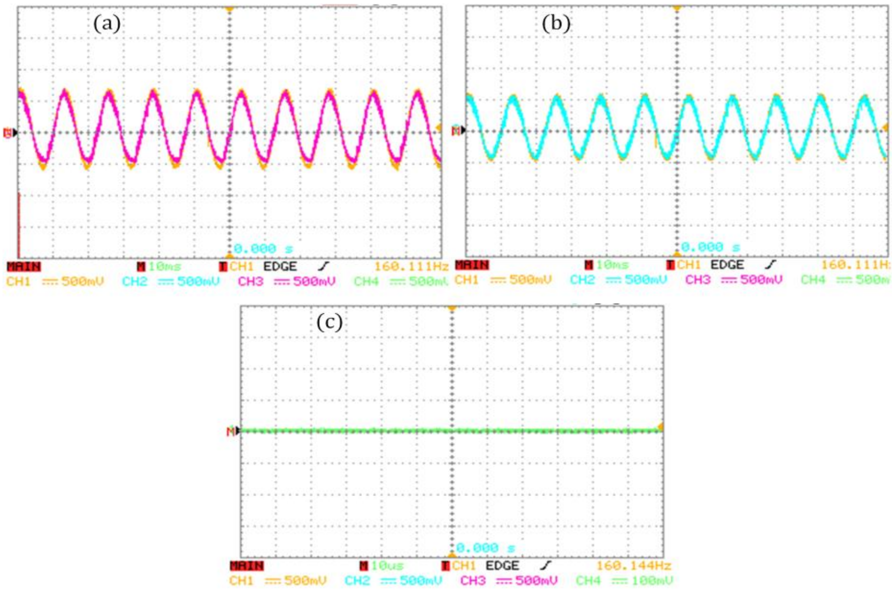

Fig. 7 Experimental time response of the state variables in closed loop with: (a) voltage capacitor Vc_1, (b) voltage capacitor Vc_2, (c)Time responses of the tracking errors

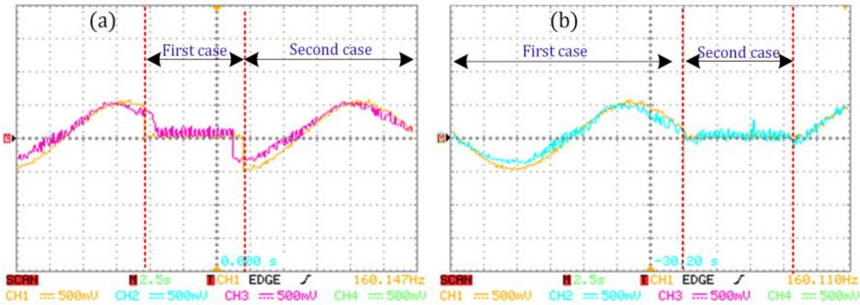

Fig. 8 Time response of the state's variable with different reference (a) capacitor voltage Vc_1, (b) capacitor voltage Vc_2

5. CONCLUSION

In this paper, we presented a chaos controller algorithm for Chua's chaotic system. A new application for super twisting sliding mode controller was proposed. The controller scheme aims to making the states of Chua's circuit to track their desired states; therefore, we tested the ability of the proposed approach under different situations. However, synchronization results of the closed-loop Chua's circuit have been achieved based on Lyapunov stability theory. Moreover, an experimental test setup is presented to demonstrate the effectiveness of the proposed method.

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