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Research Article

Complexity Analysis of a Mixed Memristive Chaotic Circuit

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In this paper, we design a chaotic circuit with memristors, which consists of two flux-controlled memristors and a charge-controlled memristor, and the dimensionless mathematical model of the circuit was established. Using the conventional dynamic analysis methods, the equilibrium point set and stability of the chaotic system were analyzed, and the distribution of stable and unstable regions corresponding to the memristor initial states was determined. Then, we analyze the dynamical behaviors with the initial states of the memristors and the circuit parameter of the circuit system, respectively. By using spectral entropy (SE) and C_0 complexity algorithms, the dynamic characteristics of the system were analyzed. In particular, the 2D and 3D complexity characteristics with multiple varying parameters were analyzed. Some peculiar physical phenomenon such as coexisting attractors was observed. Theoretical analysis and simulation results show that the chaotic circuit has rich dynamical behaviors. The complicated physical phenomenon in the new chaotic circuit enriches the related content of chaotic circuit with memristors.

1. Introduction

According to the principle of completeness with variable combination, Professor Chua predicted the existence of memristor in 1971 [1]. In 1976, he expounded the characteristic of memristor, composition principle and applications [2]. For a long time, the element which satisfied the characteristic of memristor was not discovered, so the study of memristor did not rise to the attention of scientific community and engineering circles. In 2008, the HP laboratory reported the realization of memristor for the first time [3, 4], and since then, memristor has attracted much attention all over the world.

Memristors are often divided into charge-controlled memristor and flux-controlled memristor. Both of them are typical nonlinear elements, and it is easy to generate a chaotic vibration signal by employing this element. So researchers pay more attention to the design and realization of memristive chaotic circuit [5–13]. Corinto et al. analyzed the dynamical behaviors of a memristive oscillator by using the conventional dynamic analysis methods [5]. Teng et al. designed a fractional-order memristor based on the simplest chaotic circuit [6]. Kim et al. constructed a memristor emulator by using the analog multiplier [7]. Itoh and Chua used a memristor with a piecewise linearity to replace Chua's diode [14] in Chua's oscillator and got a chaotic oscillation circuit [8]. Muthuswamy and Chua used a memristive circuit with a source and a discontinuous piecewise linearity flux-memristive character to replace Chua's diode, and they derived some new chaotic circuits [9]. The memristors used in the literature [5–9] are nonsmooth discontinuous piecewise memristors, but it is difficult to realize in practice. After that, the relatively simple mathematical model and the circuit model of physically realizable became a research hotspot in the academia. Muthuswamy put forward a flux-controlled memristor, which has a cubic nonlinear characteristic curve, and used the available devices to build the equivalent circuit [10, 11]. Bao et al. applied the smooth memristor to construct some new circuits and found some special phenomena in the new circuits [12, 13, 15, 16]. In particular, the memristive chaotic systems are also widely applied to related chaotic fields. Zhang and Deng studied the double-compound synchronization of six memristor-based Lorenz systems [17]. In the literature [5–13, 15, 16], only one memristor was applied in an independent circuit. So, it is worth studying whether multiple memristors can coexist in one circuit. When Bao et al. applied two flux-controlled memristors in a single circuit [18], they found that memristors would affect each other, and the dynamical behaviors of the circuit with more than one memristor become more complex. In this paper, based on the circuit model in [18], we design a new mixed memristive chaotic circuit with three memristors. Relative to [18], the higher dimensional circuit system was set up, and the ranges of steady state were different; the new phenomena such as coexisting attractors was observed. In particular, the complexity characteristics with the varying chaotic sequences were analyzed.

In this paper, we focus on the mixed memristive chaotic circuit which has two smooth passive flux-controlled memristors and a charge-controlled memristor. It is organized as follows. The circuit model was designed and its dimensionless mathematical equation was deduced in Section 2. In Section 3, we analyzed the dynamical behaviors of this circuit, including the stability of the equilibrium set, influence of the system initial states, the relationship between the circuit parameter, and the system dynamical behaviors. Particularly, some special dynamic phenomena including coexisting attractors were found; the 2D and 3D complexity characteristics were analyzed. Finally, we summarize the results and indicate future directions.

2. Mixed Chaotic Circuit Based on Memristors

2.1. Model of the Memristors. According to the mathematical model of flux-controlled memristor which was put forward in [19, 20], we can obtain that memristor can be defined as a two-terminal element. For a smooth passive flux-controlled memristor, the magnetic flux ξ between the terminals is a function of the electric charge q that passes through the device, and its state variable are

$$q(\xi) = a_\xi \xi + b_\xi \xi^3,$$
$$W(\xi) = \frac{dq(\xi)}{d\xi} = a_\xi + 3b_\xi \xi^2, \tag{1}$$

where W is the memductance. a_ξ and b_ξ are real constant, in this article, setting the parameters $a_\xi = 1$ and $b_\xi = 1$.

The volt-ampere characteristic curve of the smooth passive flux-controlled memristor driven by a 2.828 V and 1 Hz sinusoidal signal is shown in Figure 1.

According to the mathematical model of charge-controlled memristor which was proposed in [21], for a charge-controlled memristor, the electric charge q is a function of the magnetic flux ξ, and its state variable is defined as

$$\xi(q) = a_q q - \frac{b_q q^2}{2},$$
$$M(q) = \frac{d\xi(q)}{dq} = a_q - b_q q, \tag{2}$$

where W is the memristance. a_q and b_q are real constant.

When setting the parameters $a_q = 1$ and $b_q = 1$, we get the volt-ampere characteristic curve of the charge-controlled memristor driven by 2.828 A and 1 Hz sinusoidal signal as shown in Figure 2.

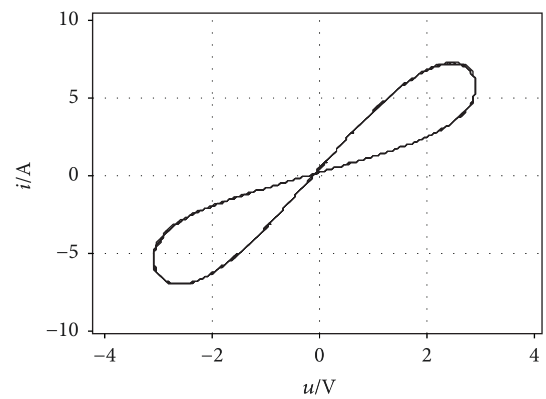


Figure 1: Volt-ampere characteristic curve of the smooth passive flux-controlled memristor.

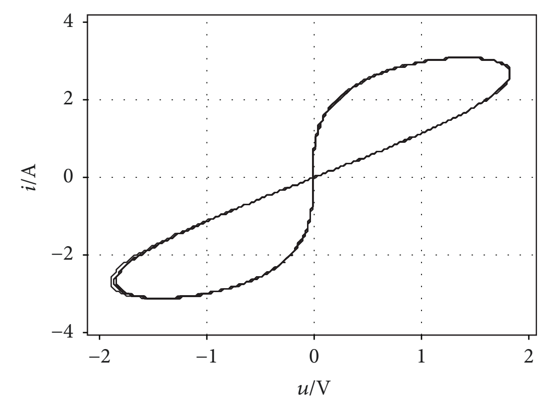


Figure 2: Volt-ampere characteristic curve of the passive charge-controlled memristor.

From Figures 1 and 2, we can see that the volt-ampere characteristic curves of the flux-controlled memristor and charge-controlled memristor are like tilted "8", and they are consistent with that of the HP memristor and Chua's memristor.

2.2. Mixed Chaotic Circuit Based on Memristors. Based on three memristors and the Chua circuit, a nonlinear circuit is designed as shown in Figure 3. In this circuit, W_1 and W_2 are two smooth passive flux-controlled memristors, and M is a charge-controlled memristor. This new memristive chaotic circuit is evolved from Chua's chaotic oscillation circuit. First, Chua's diode is replaced by an active circuit which contains a flux-controlled memristor W_1 and a negative conductance $-1/G$, and then, a flux-controlled memristor is inserted between the LC_1 resonance and the RC_2 nonlinear filter. Finally, a charge-controlled memristor is connected in series with the inductance. So the new circuit consists of six dynamic elements, including two flux-controlled memristors, a charge-controlled memristor, two capacitors, and an inductance. Φ_1, Φ_2, q, V_4, V_5, and i_L are the state variables of those dynamic elements. By the volt-ampere

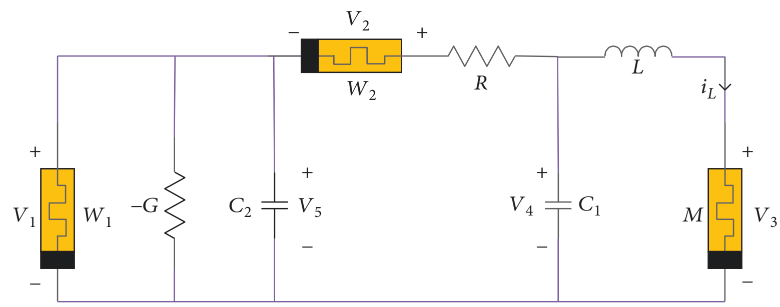


Figure 3: Circuit model based on memristors.

characteristics of each element and Kirchhoff's current and voltage law, we can obtain the differential.

$$\begin{cases} \dfrac{d\phi_1}{dt} = V_5, \\ \dfrac{d\phi_2}{dt} = \dfrac{V_4 - V_5}{RW_2 + 1}, \\ \dfrac{dq}{dt} = i_L, \\ L\dfrac{di_L}{dt} = V_4 - i_L M(q), \\ C_1 \dfrac{dV_4}{dt} = \dfrac{W_2(V_5 - V_4)}{RW_2 + 1} - i_L, \\ C_2 \dfrac{dV_5}{dt} = GV_5 - W_1 V_5 + \dfrac{W_2(V_4 - V_5)}{RW_2 + 1}. \end{cases} \tag{3}$$

Let $x = \Phi_1$, $y = \Phi_2$, $z = q$, $u = i_L$, $v = V_4$, $w = V_5$, $a = R$, $b = 1/L$, $c = 1/C_1$, $d = 1/C_2$, and $e = G$, and by employing the normalized operation, (3) becomes

$$\begin{cases} \dot{x} = w, \\ \dot{y} = (v - w), \\ \dot{z} = u, \\ \dot{u} = b\left(v - u\left(a_q - b_q z\right)\right), \\ \dot{v} = c\left(\left(1 + 3y^2\right)\dfrac{(w - v)}{\left(1 + a\left(1 + 3_y{}^2\right)\right)} - u\right), \\ \dot{w} = d\left(ew - w\left(1 + 3x^2\right) + \left(1 + 3y^2\right)\dfrac{(v - w)}{(1 + a(1 + 3y^2))}\right). \end{cases} \tag{4}$$

Obviously, the new nonlinear memristive chaotic circuit is a six-dimensional circuit system. It can be described by (4). In the following sections, we will use it to complete the theoretical analysis and numerical simulation. Setting the parameters $a_q = -0.01$, $b_q = -0.05$, $a = 0.1$, $b = 10$, $c = 1$, $d = 8$, and $e = 2$, the initial value of the system is $(0,0,0,0,10^{-4},0)$, and the time step is 0.01 s. We can get the chaotic attractors as shown in Figure 4. In this case, the corresponding Lyapunov exponents of the system are $L_1 = 0.2183$, $L_2 = L_3 = L_4 = L_5 = 0$, and $L_6 = -1.8053$. It indicates that the system is in a chaotic state.

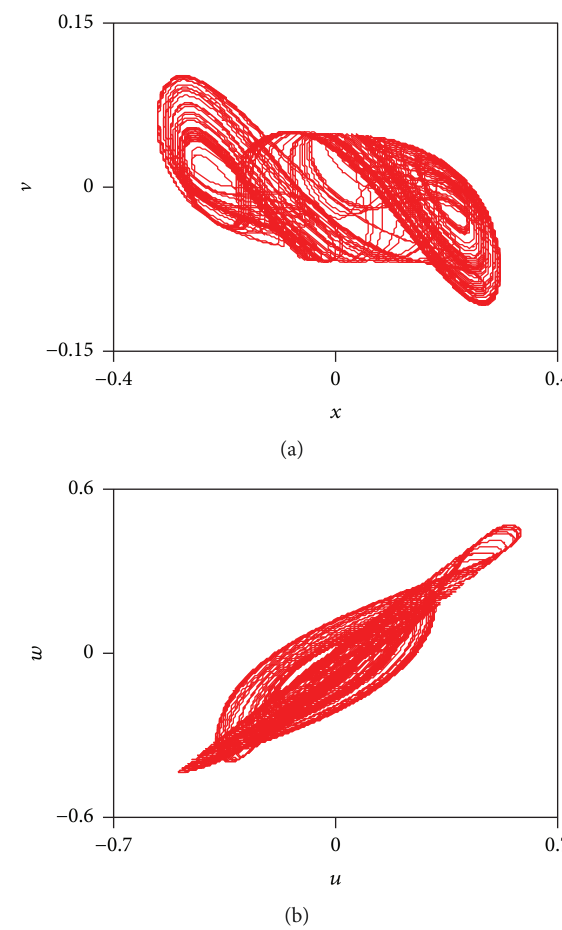
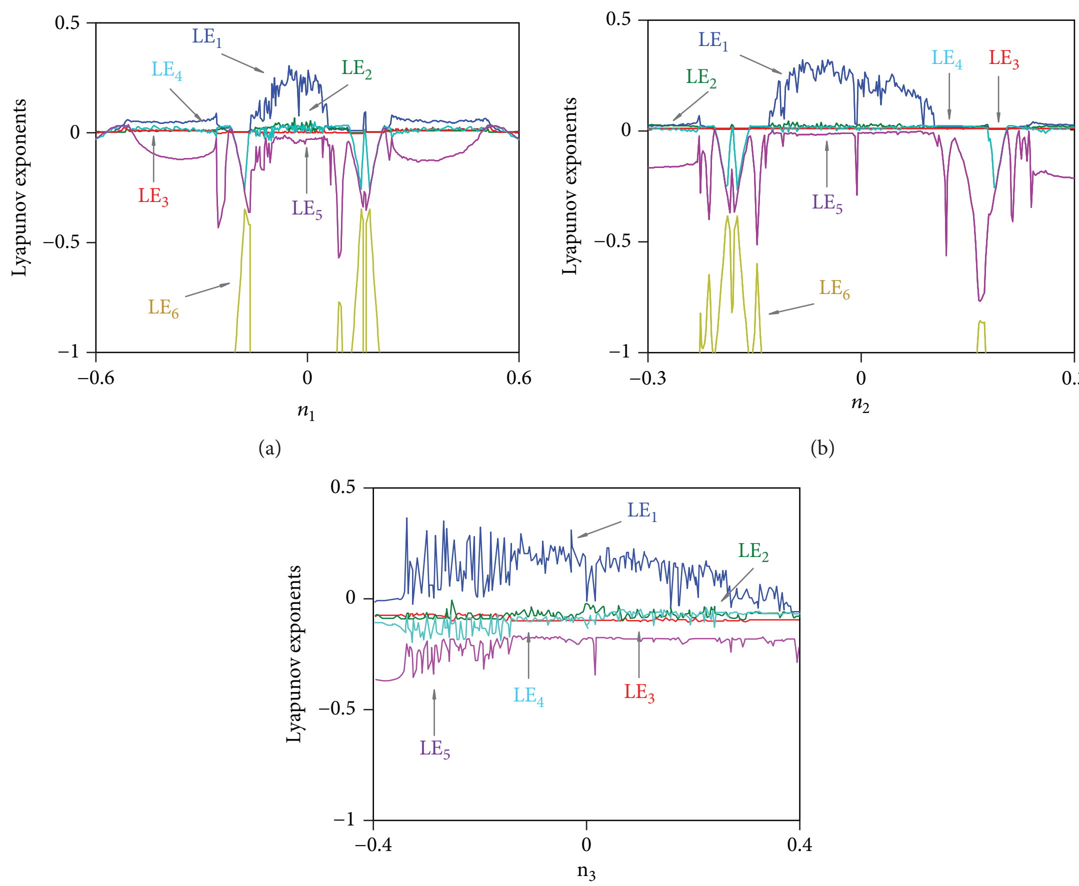


Figure 4: Chaotic attractor of the circuit with three memristors (a) x-v (b) u-w.

3. Dynamical Behaviors of the Circuit

3.1. Equilibrium Point Set and Stability of the Chaotic System. Let $\dot{x} = \dot{y} = \dot{z} = \dot{u} = \dot{v} = \dot{w} = 0$, we get an equilibrium point set $E = \{(x, y, z, u, v, w) \mid u = v = w = 0, x = n_1, y = n_2, z = n_3\}$,



(c)

Figure 5: Lyapunov exponent spectrum with varying initial states n_j $(j = 1,2,3)$. (a) n_1 varying (b) n_2 varying (c) n_3 varying.

where n_1, n_2, and n_3 are real constant. The point set E corresponds to the x-y-z three-dimensional space. That is to say, any points located in the x-y-z three-dimensional space are equilibrium points. If the parameters $a_q = -0.01$, $b_q = -0.05$, $b = 10$, $c = 1$, $d = 8$, $e = 2$, a, n_1, n_2, and n_3 are variable parameters, then the Jacobi matrix J_E in the equilibrium point of the system (4) is

$$J_E = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & \rho & -\rho \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0.1 - 0.5n_3 & 10 & 0 \\ 0 & 0 & 0 & -1 & -\left(1 + 3n_2^2\right)\rho & \left(1 + 3n_2^2\right)\rho \\ 0 & 0 & 0 & 0 & 8\rho\left(1 + 3n_2^2\right) & 8\left(1 - 3n_1^2 - \rho - 3n_2^2\rho\right) \end{bmatrix}, \quad (5)$$

in which, $\rho = 1/(1 + a + 3an_2{}^2)$, and the characteristic equation for the equilibrium point set E is

$$\lambda^3\left(\lambda^3 + a_1\lambda^2 + a_2\lambda + a_3\right) = 0, \quad (6)$$

Table 1: Chaos ranges with different initial states.

$n_1(n_2 = n_3 = 0)$	$n_2(n_1 = n_3 = 0)$	$n_3(n_1 = n_2 = 0)$
−0.099~−0.082	−0.012~−0.019	−0.167~−0.009
−0.084~−0.066	−0.017~−0.013	−0.007~0.119
−0.064~0.044	−0.011~−0.109	0.121~0.143
0.046~0.059	−0.107~−0.009	0.145~0.231
	−0.005~0.087	0.241~0.279
	0.089~0.103	0.293~0.343

where

$$\begin{aligned} a_1 &= 24n_1^2 + 27n_2^2\rho + 0.5n_3 + 9\rho - 8.1, \\ a_2 &= 4.5n_3\rho - 4n_3 - 8.9\rho + 24n_1^2\rho - 26.7n_2^2\rho \\ &\quad + 12n_1^2n_3 - 2.4n_1^2 + 72n_1^2n_2^2\rho + 13.5n_2^2n_3\rho + 10.8, \\ a_3 &= 80.8\rho - 4n_3\rho - 2.4n_1^2\rho + 242.4n_2^2\rho + 240n_1^2 \\ &\quad - 7.2n_1^2n_2^2\rho + 12n_1^2n_3\rho - 12n_2^2n_3\rho + 36n_1^2n_2^2n_3\rho - 80. \end{aligned} \quad (7)$$

It shows that the new memristive system has three zero eigenvalues and three nonzero eigenvalues. All of the cubic

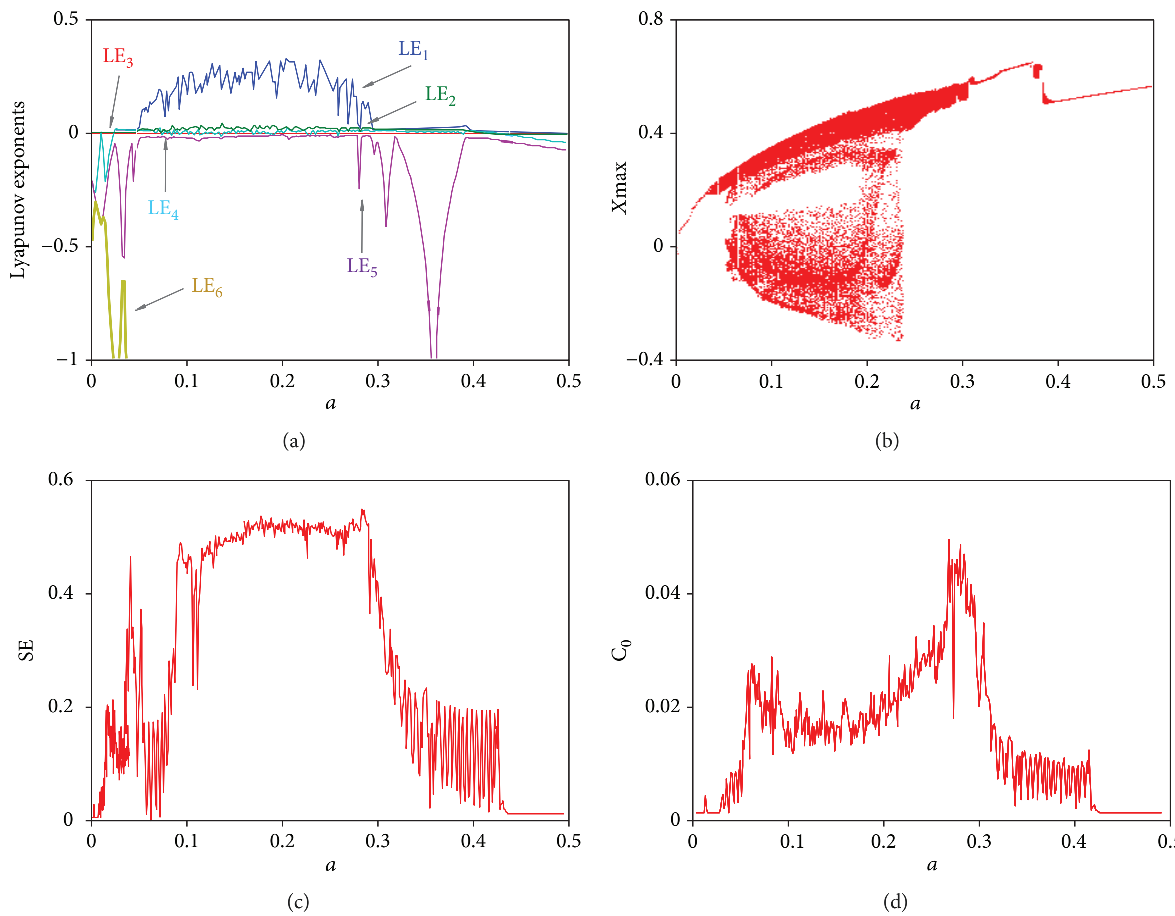


Figure 6: Dynamical analysis with different circuit parameter a. (a) Lyapunov exponent spectrum, (b) bifurcation diagram, (c) SE complexity, and (d) C_0 complexity.

polynomial coefficients of (6) are nonzero real constant. According to the Routh-Hurwitz stability criterion, except for the three zero eigenvalues, the real parts of the roots of (6) are negative. Then, we can get

$$H_j = \begin{vmatrix} a_1 & a_3 & 0 \\ 1 & a_2 & 0 \\ 0 & a_1 & a_3 \end{vmatrix} > 0, \qquad (8)$$

where $j = 1,2,3$, namely $H_1 = a_1 > 0$, $H_2 = a_1 a_2 - a_3 > 0$, and $H_3 = a_3(a_1 a_2 - a_3) > 0$.

If we chose parameter $a = 0.1$, then all the circuit parameters of the system are constant except for the initial states of three memristors. In particular, there are three situations:

(1) If $n_2 = 0$, $n_3 = 0$, then the range of steady state in the n_1 axis is $-0.2122 < n_1 < -0.1659$, $0.1659 < n_1 < 0.2122$, $n_1 < -0.5677$, and $n_1 > 0.5677$

(2) If $n_1 = 0$, $n_3 = 0$, then the range of steady state in the n_2 axis is $-0.2054 < n_2 < -0.1816$ and $0.1816 < n_2 < 0.2054$

(3) If $n_1 = 0$, $n_2 = 0$, then there is no solution for (8). It means that the system (4) has no steady state in this case. No matter where the system (4) starts, the orbit of the system tends to limit cycle, chaotic attractor, or infinity

Table 2: Dynamical behaviors of the system with different a.

a	Dynamical behaviors
0~0.023	Stable sink
0.024~0.04	Limit cycle
0.041~0.0447	Period-2 cycle
0.0448~0.0449	Period-2,-4 bifurcation
0.045~0.059	One-scroll chaotic attractor
0.06~0.246	Two-scroll chaotic attractor
0.247~0.2717	One-scroll chaotic attractor
0.2718~0.2719	Period-4,-2 bifurcation
0.272~0.286	Period-2 cycle
0.287~0.431	Limit cycle
0.432~0.5	Stable sink

As it is well known, Lyapunov exponents measure the exponential rates of divergence and convergence of nearby

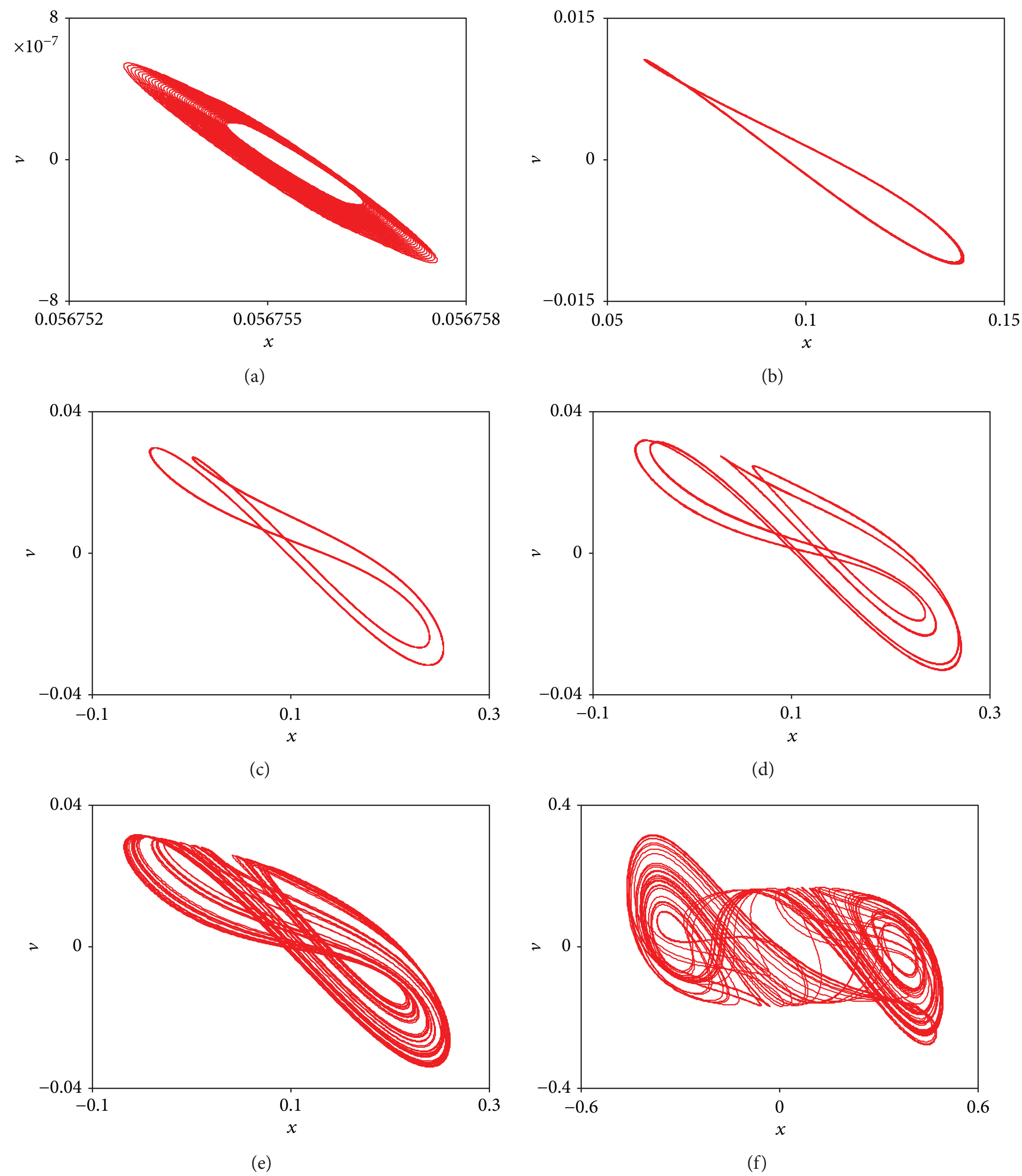


FIGURE 7: Phase portrait with different circuit parameter a. (a) Sink ($a = 0.015$), (b) limit cycle ($a = 0.03$), (c) period-2 cycle ($a = 0.043$), (d) period-4 cycle ($a = 0.04484$), (e) one-scroll chaotic attractor ($a = 0.05$), and (f) two-scroll chaotic attractor ($a = 0.2$).

trajectories in a state space, and the Lyapunov exponent spectrum provides additional useful information for a nonlinear system. Keeping the circuit parameters the same as mentioned above, select the initial states $x(0)$, $y(0)$, and $z(0)$ as the variable parameters. For the sake of clarity, only part of the curve of the sixth Lyapunov exponents is shown in Figure 5. When we select $y(0) = 0$, $z(0) = 0$, the Lyapunov exponent spectrum with the varying initial state $x(0) = n_1$ is shown in Figure 5(a). When $x(0) = 0$, $z(0) = 0$, the Lyapunov exponent spectrum with varying n_2 is shown in Figure 5(b). Similarly, when $x(0) = 0$, $y(0) = 0$, the Lyapunov exponent spectrum with the variation of the initial state n_3 is shown in Figure 5(c).

The Lyapunov exponent spectrum reflects the stability performance of the system. Meanwhile, the three zero eigenvalues of the system are also the important cause. For example, even though all the Lyapunov exponents of the system are less than or equal to zero in some case, the system is not stable point or steady state but a stable sink. All the chaos ranges with different initial values are summarized in Table 1.

3.2. Dynamic Analysis with Different Circuit Parameters. Let $n_1 = n_2 = n_3 = 0$, change the parameter a from 0 to 0.5 and keep other parameters unchanged, we can obtain the Lyapunov exponents and its corresponding bifurcation diagram as

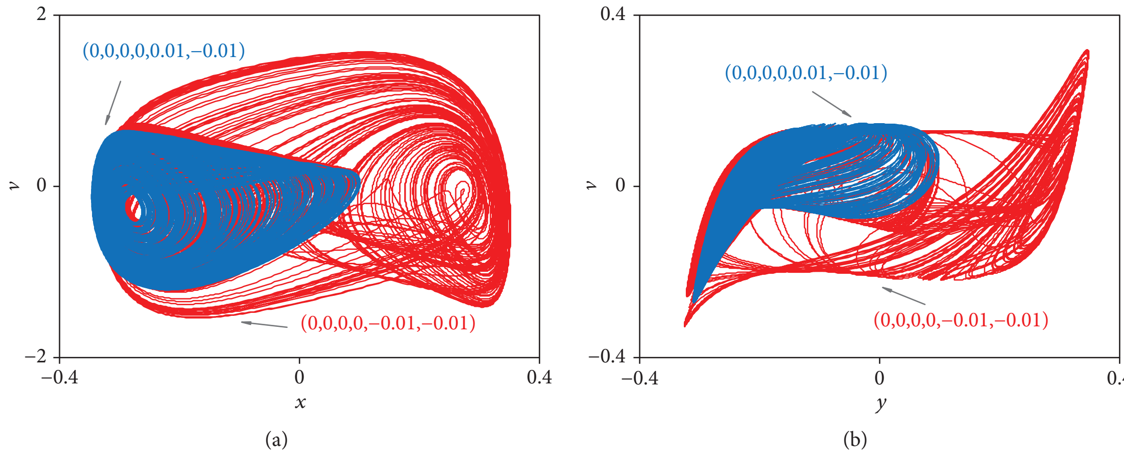


FIGURE 8: Coexisting chaotic attractors with different initial state. (a) Coexisting chaotic attractors on the x-v plane. (b) Coexisting chaotic attractors on the y-v plane.

shown in Figures 6(a) and 6(b). It shows that the Lyapunov exponent spectrum and bifurcation diagram are consistent. SE and C_0 complexity curves are shown in Figures 6(c) and 6(d). As the same to other conventional dynamic analysis methods, they can reflect the complexity of continuous chaotic systems accurately and effectually. In particular, when the system is in a chaotic state, the corresponding complexity value of the system is very high. Oppositely, when the system is in a periodic state, the corresponding complexity value is very low, even to 0. With the circuit parameter a increases, the system transforms into an unstable limit cycle from a sink, and then, the system becomes chaotic through period-doubling bifurcation. Afterwards, the system has a transition from chaotic to limit cycle through reverse period-doubling bifurcation. Finally, the system jumps to sink abruptly. All of the dynamical behaviors of the system with different parameter a are summarized in Table 2. It shows the very rich dynamical behaviors of the new memristive chaotic system.

To further display its dynamic characteristics, x-v phase portraits with different parameter a are presented in Figure 7. We can also observe the route that the system enters chaos by a period-doubling bifurcation. With the increase of the parameter a, the system transforms from a sink to chaos through period-doubling bifurcation, and then, the system transforms from chaos to sink through reverse period-doubling bifurcation.

3.3. Coexisting Attractors. Different initial values can produce different dynamic behaviors, and they can coexist in the same chaotic system. The phenomenon of coexisting attractors is a representation of coexisting oscillation. Select $a_q = -0.01$, $b_q = -0.05$, $a = 0.25$, $b = 10$, $c = 1$, $d = 8$, and $e = 2$, the initial values are (0,0,0,0,0.01,–0.01) and (0,0,0,0,–0.01,–0.01); their corresponding color of attractors is labeled by using blue and red. Then, we can find a pair of coexisting attractors as shown in Figure 8. With the initial state increasing, the system transforms the type of attractor from the one-scroll chaotic attractor to the two-scroll chaotic attractor. The coexisting attractors start from a pair of similar initial values. After the accumulation of multiple cycles, they transformed into a pair of coexisting chaotic attractors. It shows the extreme sensitivity of the chaotic system to the initial state.

3.4. The Analysis of Complexity with Different Circuit Parameters. Complexity characteristic is essentially the reflection of entropy with the chaotic sequence. Generally, the greater the degree of fluctuation in the sequence, the greater the entropy, which means the higher the value of complexity. Figures 9(a) and 9(b) show the complexity characteristic of the system with two varying circuit parameters. We can see that the color of the middle part is darker, that is to say, its complexity value is larger. If the system is applied to the field of chaotic encryption, this part as the range of encryption is the best option, and the antideciphering is also the strongest. Then, in order to better research the complexity characteristics of the chaotic sequence, we use three varying circuit parameters b, d, and e as the object of research. The analysis of 3D complexity can more intuitively reflect the complexity characteristics of the system. Compared to 2D complexity, 3D SE and C_0 complexity has more complex characteristics because a complexity value is determined by three variable parameters. Figures 9(c) and 9(d) show the 3D SE and C_0 complexity with three varying circuit parameters. Due to the integral tolerance problem of the system, the simulation results of 3D SE and C_0 complexity have slight deviation when circuit parameter $e \leq 1$. Although the values of complexity in Figure 9 are different, their changing trends are basically the same because they all reflect the complexity of sequence based on the Fourier transform.

4. Conclusions

In this paper, a new chaotic circuit system was derived from Chua's chaotic oscillators by introducing a charge-controlled memristor and two flux-controlled memristors. It has an equilibrium point set located in the space constructed by the inner state variables of the three memristors, and the

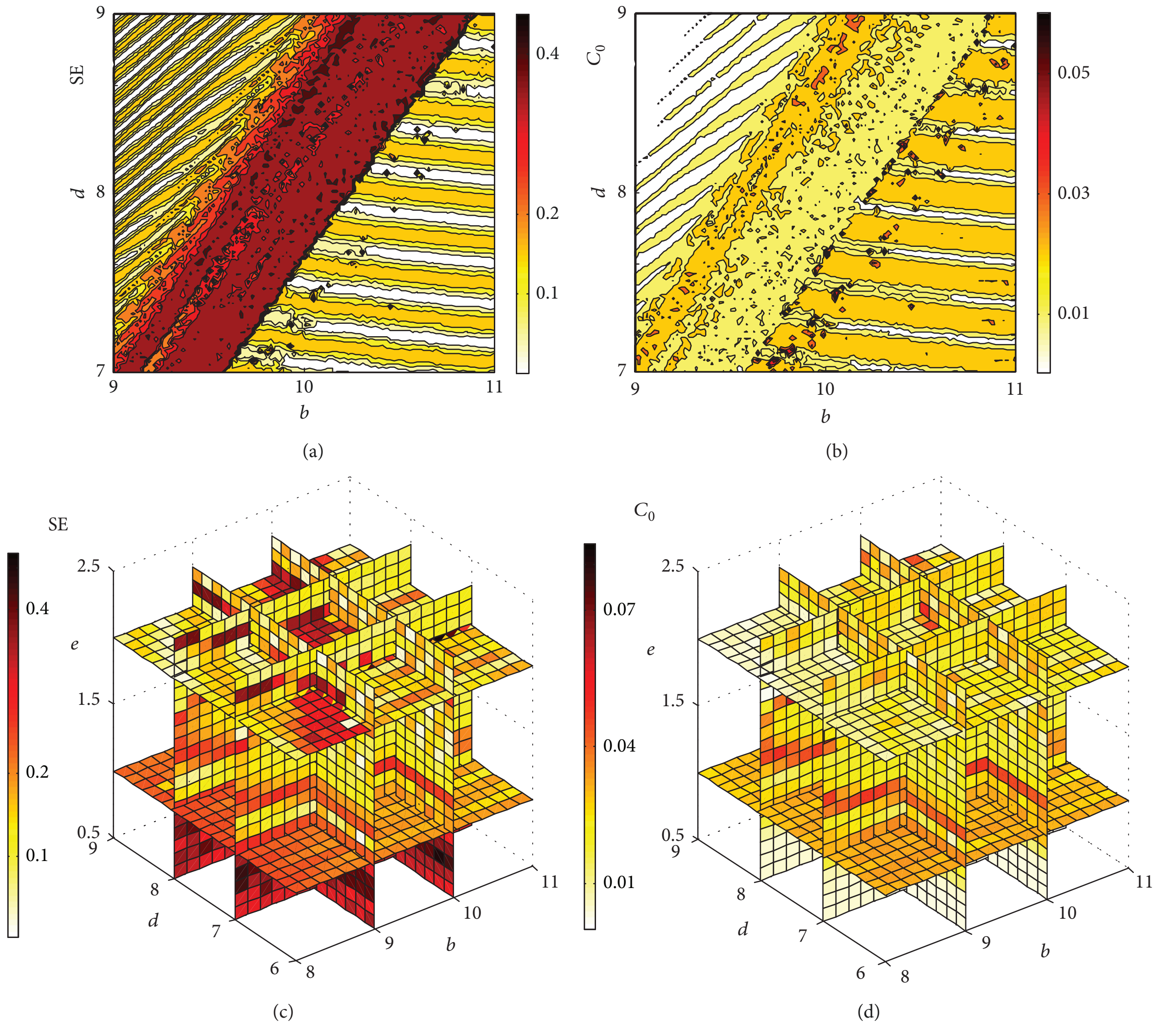


FIGURE 9: Complexity characteristics of the system. (a) 2D SE complexity, (b) 2D C_0 complexity, (c) 3D SE complexity, and (d) 3D C_0 complexity.

stable and unstable regions coexist in the space. By using spectral entropy (SE) and C_0 complexity algorithms, the dynamic characteristics of the system are accurately analyzed. Using the numerical simulation tool, some complex dynamical phenomena such as coexisting attractors were analyzed. Therefore, the new chaotic circuit system is different from the general chaotic system. The dynamical characteristics of the new system accompany with the variation of the circuit parameter and depend on the initial states of the memristors. The new memristive circuit model and the new mathematical model can be widely used in the chaotic-related field. Next, we will try to find more chaotic characteristics in this new memristive chaotic circuit.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no competing interests.

Authors' Contributions

Xiaolin Ye designed and performed experiments, analyzed data, and wrote this manuscript; Jun Mou made a theoretical guidance for this paper; Feifei Yang and Chunfeng Luo designed circuit experiments. All authors reviewed the manuscript; Yinghong Cao made a technical support for this paper.

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