# Dynamical behavior and application in Josephson Junction coupled by memristor 

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## A R T I C L E I N F O

## Key words:

Memristor
Josephson junction
Encryption
Bifurcation


#### Abstract

The memristor has drawn a considerable interest when the nanoscale memristor is regarded as the critical element of novel ultra-high density and low-power non-volatile memories. The nonlinearity of electric circuit is enhanced and the dynamical behavior becomes more complex when memristor is used in circuits because it memductance is dependent on the inputs current. Josephson Junction (JJ) coupled resonator also present complex dynamical behaviors in nonlinear circuit because JJ is used as sensitive inductive component. The Josephson Junction circuit employing memristor is designed in this paper. Firstly, dynamical properties about this model are discussed by numerically calculating phase portraits, Lyapunov exponents and bifurcation diagram. It is found that appropriate parameters setting can induce distinct chaotic and periodical states by analyzing the output series. The dynamical response and potential mechanism for behavior selection is discussed. Interestingly, the chaos encryption based on Josephson junction circuit coupled by memristor is investigated as well.


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## 1. Introduction

With the burst of a Wanna decryptor [1] in the middle of 2017, secure communication within a network [2] has again triggered the considerable attention. Meanwhile, many feasible methods have been proposed to enhance the data security and it is also involved with chaotic encryption, which is one of the important branch of the chaos theory. Come what may, it is necessary to investigate the dynamical system with chaotic features [3-8]. Therefore, these topics are related to the systems with hidden attractor, multi-scroll attractor, attractor without equilibrium points, and infinite equilibrium points [9-20], the main contribution of these topics could be associated with chaos. Interestingly, chaotic behaviors can also be generated in the system mapped from the nonlinear circuit composed of the Josephson Junction [21-23]. The effect of Josephson Junction in superconductors [24-26] has, since its discovery in the 1960s, been the focus of great interest both due to its implications for fundamental questions in physics and electronics, particularly, where it promised significant increase in device speed and sensitivity. The most of the distinct effect of Josephson Junction has been an attempt to develop Josephson Junctions as high-speed (picosecond) switches for digital applications [27]. The emphasis is now shifting to analog applications and devices [28], such as the voltage standard, squid magnetometers, millimeter, submillimeter mixers. It did focus on mathematical techniques for obtaining analytical results by using various models of the Josephson Junction [29].

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Fig. 1. The scheme diagram for memristor-coupled circuit.


Fig. 2. Attractors are calculated by setting different gain $\mathrm{k}_{0}$ at fixed parameters $k_{1}=0.1, k_{2}=0.2, \alpha=0.2, \beta=0.2$, for (a) $k_{0}=-0.3$; (b) $k_{0}=-0.1$; (c) $k_{0}=0.1$; (d) $k_{0}=0.3$.

This approach is nicely supplemented by graphs from computer simulations and circuit approach. The Josephson Junction consists of superconductors on both sides and in the middle of the insulator being supplied. Indeed, Cho [30] presented a review on the development prospect of the high-temperature superconductor in China. Furthermore, the superconductivity at different high-temperature in iron-based X-doped has been reported extensively [31]. As a result, the nonlinear electronic component associated with Josephson Junction formed from the kinds of superconductor can play important role in electricswitch application [32].

Another important nonlinear electronic component is memristor [33] that is proposed by Chua based on symmetry arguments [34]. Generally, the resistor, capacitor and inductor have been used to describe the inter-relation of current-voltage, voltage-charge and current-magnet flux, respectively. Using memristor component, however, is set up a connection between charge and magnet flux. Although this kind of memristor had been found and predicted in theory, it seemed to show no importance to the application in scientific and engineering domains. Researchers began to discern the significance of memristor until the realization of its nano-size electrical device had been reported at HP lab in 2008 [35]. The memristor, with the ability of memory and low-power feature, may make a distinct candidate for the artificial intelligence [36-38], regarded as the synapses [39] in the link with neurons and gliocyte or the electrical element component in the integrated circuit of chaos. In the neurodynamics, improved neuron model coupled by memristor can be built and the different modes of electrical activities can be detected to be consistent with biological experiments [40,41]. For example, Wu et al. [42] imposed phase noise on the improved neuron, and a time-varying electromagnetic field is induced to trigger different modes of electrical activities, and coherence resonance behavior can be observed. It is believed that memristor coupling can describe the effect of memory, and bridge the output voltage and magnetic flux by generating induction current. It could be very


Fig. 3. The time series are plotted by setting different gain $\mathrm{k}_{0}$ at $k_{1}=0.1, k_{2}=0.2, \alpha=0.2, \beta=0.2$, for $(\mathrm{a}) k_{0}=-0.4 ;(\mathrm{b}) k_{0}=-0.1$; (c) $k_{0}=0.1$; (d) $k_{0}=1.5$.
important to describe the memory effect in neurons. Some neurons are connected to autapse, which is a specific synapse to connect the neuron via close loop. Autapse connection can enhance the self-adaption of neurons, for example, it can keep against electromagnetic radiation [43]. Furthermore, Ma et al. [44]. developed new cardiac model by using memristor to explain the mechanism of cardiac breakdown when electromagnetic radiation is considered. On the other hand, the memristor can contribute to build memory circuit about encryption system or chaotic dynamics. Itoh and Chua proposed that the memristor, consisted of the monotonic rising and the piecewise linear curve, can displace the Chua diodes in the Chua chaotic circuit [45]. According to the expression of memristor, the involvement of memristor in dynamical system can be effective to switch between chaotic and periodical states by resetting the initials [46]. In the case of secure communication, the chaotic information involved memristor will enhance better the safety.

Therefore, it is interesting to build a new nonlinear circuit composed both of memristor and Josephson Junction as well. In this paper, memristor is coupled to a resonator connected to Josephson Junction, the dynamical equations are approached in physical view. The dynamical behaviors are numerically approached and discussed, and then the improved system is used for image encryption.

This paper is organized as follows. The second section gave the model setting and approach of dynamical equations. The third section presented standard bifurcation analysis, calculating of largest Lyapunov exponent, phase portrait, image encryption based on this new system. The fourth section gave a simple example about image encryption based on the new chaotic system. The last section gave appropriate conclusions for this topic.

## 2. Model descriptions

The Josephson junction circuit $[47,48]$ coupled with memristor can be illustrated as follow:


Fig. 4. Bifurcation diagram for maximal junction potential vs. the gain $k_{0}$, the parameters are set as $k_{1}=0.1, k_{2}=0.2, \alpha=0.2, \beta=0.2$.

The outputs of above mentioned circuit can be approached by circuit equations by using the Kirchhoff's law, it reads as follows:

$$
\left\{\begin{array}{l}
I_{\text {source }}=C \frac{d V}{d t}+\frac{V}{R_{V}}+I_{C} \sin (\gamma)+I_{L}+I_{M}  \tag{1}\\
V=\frac{h}{2 e} \frac{d \gamma}{d t} \\
V=L \frac{d I}{d t}+I_{L} R \\
\frac{d \varphi}{d t}=V
\end{array}\right.
$$

where $V$ is the potential of Josephson Junctions and, at the same time, total voltage on bias DC power, $I_{c}$ represents the Junction current, $R_{V}$ is equivalent to the nonlinear Junction resistance. $I_{\text {source }}$ is the external bias DC current, $\gamma, h$ represents the phase difference in superconductor and Planck constant, $e$ is elementary charge. $R, L$ denotes the resistor and inductance at circuit branch, respectively. $I_{M}$ calculates the total induction current on Junction. According to the Faraday law of electromagnetic induction, the nonlinear memductance function and induction current for memristor are described by

$$
\begin{equation*}
I_{M}=\frac{d q(\varphi)}{d t}=\frac{d q(\varphi)}{d \varphi} \frac{d \varphi}{d t}=\rho(\varphi) V=k_{0}\left(\alpha+3 \beta \varphi^{2}\right) V \tag{2}
\end{equation*}
$$

where $q(\varphi)$ is the memristor constitutive relation between charge and magnetic flux $\varphi$, the parameters $\alpha, \beta$ are often selected by appropriate values such as $\alpha=0.2, \beta=0.2$. Furthermore, the circuit equations can be mapped into dimensionless dynamical equations after scale transformation by setting $\tau=2 e I_{c} R t / h, x=V /\left(I_{c} R\right), y=V /\left(I_{c} R\right), z=I_{L} / I_{c}, w=\varphi / \varphi_{0}$. For practical approach in realistic circuit, these parameters are often selected as $i=I / I_{C}=1.26, \beta_{C}=2 e I_{C} R^{2} C / h=0.707, \beta_{L}=2 e I_{C} L / h=2.5$, $g=R / R_{V}=0.0478$ so that the memristor-coupled nonlinear circuit can generate chaotic state. When the effect of electromagnetic induction is considered, the dynamical equations for the four-variable Josephson Junction model are described by


Fig. 5. Bifurcation diagram for maximal junction potential vs. the gain (a) $k_{1}, k_{2}=0.2$ or (b) $k_{2}, k_{1}=0.1$, the parameters are set as $k_{0}=-0.1, \alpha=0.2, \beta=0.2$.

$$
\left\{\begin{array}{l}
\frac{d x}{d \tau}=\frac{1}{\beta_{c}}\left[i-g x-\sin (y)-z-k_{0} x\left(\alpha+3 \beta^{2} w\right)\right]  \tag{3}\\
\frac{d y}{d \tau}=x \\
\frac{d z}{d \tau}=\frac{1}{\beta_{l}}(x-z) \\
\frac{d w}{d \tau}=k_{1} x-k_{2} w
\end{array}\right.
$$

The fourth variable $w$ describes the magnetic flux, the $\rho(w)$ is the memductance of a flux-controlled memristor. The parameter $k_{0}, k_{1} k_{2}$ are gains used to calculate the effect of electromagnetic induction on Junction. The term $k_{2} w$ describes a feedback on magnetic flux that contributes the induction current.

## 3. Numerical results and discussions

In the numerical studies, the fourth-order Runge-Kutta algorithm is used with time step $h=0.01$. At first, initial values setting for the Josephson Junction coupled memristor are selected as ( $x_{0}, y_{0}, z_{0}, w_{0}$ ) $=(0.2,0.3,0.3,0.1)$. When the parameters ( $k_{1}, k_{2}$ ) are fixed, relation between the sampled Junction potentials and current of the inductance is detected to generate different phase portraits by selecting appropriate gains for $k_{0}$, and the results are shown in Fig. 2.

It is found in Fig. 2 that the periodical, multi-periodical and chaotic state can be observed by selecting appropriate the gain $k_{0}$. It indicates that the dynamical properties of Junction potential depend on the coupling intensity ( $k_{0}$ ) bridged the voltage and the magnetic flux. According to Eq. (2), the induction current generates negative feedback at $k_{0}>0$ and the excitability, oscillating behaviors could be suppressed. However, negative value setting for $k_{0}$ can generate positive feedback on junction voltage thus chaos could be induced. As a result, the chaotic attractor shown in Fig. 2b, and care suppressed by applying $k_{0}=0.3$, which negative feedback is strong enough to suppress chaos. The sampled time series for outputs voltage are calculated in Fig. 3 by applying different feedback gains.


Fig. 6. The sampled time series and attractors are calculated by setting different gain $k_{1}$ at $k_{0}=-0.1, k_{2}=0.2, \alpha=0.2, \beta=0.2$, for (a) (b) $k_{1}=0.05$;(c) (d) $k_{1}=0.2$.

The sampled time series in Fig. 3 extensively confirmed the chaos and/or periodicity under appropriate feedback gain in induction current. Furthermore, the bifurcation diagram for the maximal junction potential vs. feedback gain $k_{0}$ is calculated in Fig. 4.

The bifurcation diagram in Fig. 4 confirmed that multiple electrical activities can be found in the sampled time series for junction potentials under appropriate feedback gain. The gain can regulate the coupling relation between junction potential and the magnetic flux, which induced the diversification of the junction current. Indeed, chaos emergence is detected by setting appropriate feedback gain $k_{0}$. Furthermore, the feedback parameters $k_{1}$ and $k_{2}$ are comparable to detect the dynamical behaviors under at fixed the coupled gain $k_{0}=-0.1$, thus the bifurcation diagrams are plotted in Fig. 5.

The bifurcation diagram in Fig. 5 confirmed that the transition between multi-periodical and chaotic state can be triggered by increasing the parameter $k_{1}, k_{2}$. As a result, then different electrical activities can respond to the electromagnetic induction described by the memristor and magnetic flux. That is to say, the gain on the magnetic variable is important to detect the abundant dynamical characteristics. It is convenient to observe the electrical activities, and the sampled time series of the junction potential, the phase portraits are calculated by selecting appropriate values based on the bifurcation diagram, the results are plotted in Figs. 6 and 7.

According to Eq.(2), the gain $k_{1}$ calculates the degree of electromagnetic induction, and it bridges the relation between magnetic flux and voltage. Stronger $k_{1}$ enhances the dependence of magnetic flux on voltage, and also transition from chaotic state to periodical behavior is triggered with increase of the feedback gain $k_{1}$. Furthermore, the effect of gain $k_{2}$ is also investigated in Fig. 7.

That is, stronger value setting for gain $k_{2}$ can decrease the magnetic flux and also the induction current, thus the negative feedback on voltage is suppressed, as a result, transition from periodical state to chaotic behaviors is triggered.

Above all, a new Josephson Junction circuit model coupled by a memristor is proposed. The distribution for magnetic flux in the junction plays important role in changing the dynamical properties in electrical activities. It is interesting to find the parameter region for chaos emergence by calculating the largest Lyapunov exponent spectrum. The results are calculated in Fig. 8.

It is found that positive Lyapunov exponent can be approached by setting appropriate parameters. In the next section, the application of chaos on image encryption is discussed.


Fig. 7. The sampled time series and attractors are calculated by setting different gain $k_{2}$ at $k_{0}=-0.1, k_{1}=0.1, \alpha=0.2, \beta=0.2$, for (a) (b) $k_{2}=0.1$;(c) (d) $k_{2}=0.15$.


Fig. 8. The Lyapunov exponent spectrum is calculated by setting appropriate gains. For (a) $k_{0}, k_{1}=0.1, k_{2}=0.2$; (b) $k_{1}, k_{0}=-0.1, k_{2}=0.2$; (c) $k_{2}, k_{0}=-0.1$, $k_{1}=0.1$, the parameters are set as $\alpha=0.2, \beta=0.2$.


Fig. 9. Schematic diagram for encryption processing based on chaotic system.


Fig. 10. Schematic diagram for encryption processing based on simulation, for (a) the original image; (b) the ciphertext image; (c) the recovery image under wrong Key'; (d)the recovery image under right Key'.

## 4. Application example

In this section, processing of the encryption and decryption is described by adding the secure-key stream, which stems from the above designed chaotic system coupled with memristor, to original image. The frame diagram of principle is presented as follow:

The flowchart in Fig. 9 found that the random series $R=\left[r_{1}, r_{2}, r_{3}\right]=[x, y, z]$ can stem from the Generator of key stream under the Key consisted of the intrinsic parameters and part of initial value of variables $\left[i, k_{0}, k_{1}, k_{2}, x_{0}, y_{0}, z_{0}, 1\right]$. Then this key stream is combined with a block of plaintext (pixel set of original image $I(i, j)$ ) to produce the ciphertext $I^{\prime}(i, j)$. Through


Fig. 11. The histogram is plotted for image (a) the original image; (b) the ciphertext image.
a transmission for the dedicated channel, the reception can get the data $I^{\prime}(i, j)$ and combine with the function of decryption to obtain recovery image $I^{\prime}(i, j)$. The function of encryption (4) and decryption (5) is described as follow:

$$
\begin{equation*}
I^{\prime}(i, j)=\left\{\left[r_{1}(i, j) \oplus I(i, j) \oplus r_{2}(i, j)+L-r_{3}(i, j)\right] \bmod L\right\} \bmod 256 \tag{4}
\end{equation*}
$$

$$
\begin{equation*}
I^{\prime \prime}(i, j)=\left\{r_{1}(i, j) \oplus\left[I^{\prime}(i, j)+r_{3}(i, j)\right] \bmod L\right\} \oplus r_{2}(i, j) \bmod 256 \tag{5}
\end{equation*}
$$

where, $L$ described the color depth of a image; mod denotes the modulo operator from mathematics; $\oplus$ can use XOR (exclusive or) to mix signals from the pixel value of original image and chaotic time series. When the decryption key is equal to the encryption key from the generator of key stream induced (Key=Key'), the recovery image $I$ " $(i, j)$ would be decrypted and bring it into correspondence with the original image $I(i, j)$ as $\left[I^{\prime}(i, j)=I(i, j)\right]$. Using above method is simulated to encrypt image by Based on MatlabR2009b platform, the above scheme is used to encrypt image, and results are shown in Fig. 10.

It is successfully demonstrated in Fig. 10 that the chaotic system, with the memristor coupled the Josephson Junction circuit, is effective to apply in the encryption and decryption of an image. Moreover, the histogram based on the original and ciphertext image is described to compare with their performance. The gray scale value of image ( G ) is in accordance with the abscissa, and the distribution of pixel value (D) is the ordinate.

It is observed in Fig. 11 that the ciphertext image is more symmetrical and well-distributed than the original picture. That is to say, based on the Josephson junction circuit coupled with memristor, the key stream of chaos has come into being, which can be effective to cover up the plaintext information completely.

## 5. Conclusions

Based on the law of electromagnetic induction, the Josephson Junction circuit model is improved to consider the effect of electromagnetic induction and radiation by introducing the magnetic flux variable into the model. Memristor is used realize feedback coupling between magnetic flux and Junction potential. The sampled time series, phase portrait, and bifurcation for Junction potentials of circuit in Josephson junction are investigated by using nonlinear analysis. It is found that the dynamical behaviors and electrical modes are much dependent on the magnetic flux. And its application of this model as typical of chaotic encryption was confirmed. It indicates that the chaotic system coupled by memristor can enhance the communication security and rich nonlinear properties are enhanced by adding more bifurcation parameters. As a result, our present model could be further investigated for potential application in networks.

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