Research Article

Synchronization of Neuronal Circuits with Ring Connection on PSpice

Lihua Yuan, Guodong Ren, and Chunni Wang

Department of Physics, Lanzhou University of Technology, Lanzhou 730050, China

Correspondence should be addressed to Chunni Wang; wangcn05@163.com

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The modes of electric activities in neurons and wave propagation between neurons can be changed by using appropriate external forcing or coupling type. Based on the PSpice tool, the coupling synchronization between three Hindmarsh-Rose neurons is investigated. The neuronal circuit is also designed, and the Schmitt trigger circuit is used as peak detector by transmitting the analog signal into digital signal; thus, the rhythm of electric activities of neurons can be analyzed. By selecting different initial states (spiking or bursting), different synchronization states are found. In the case of spiking state, appropriate coupling intensity is effective in realizing rhythm synchronization and then homogenous state is observed by further increasing the coupling intensity. In the case of bursting state, rhythm synchronization is enhanced under appropriate coupling intensity while desynchronization occurs by further increasing the coupling intensity.

1. Introduction

Neuron is the basic unit in neuronal system, and the electric activity can be described by some neuron modes [1–3]. In fact, signals can be transmitted among neurons of networks composed of a large number of neurons under multifarious types of coupling. Neuronal networks with different types of topologies can be proposed to detect the signal or wave propagation and the transition of collective electric activities in network of neurons. Based on the proposed neuron models, the dynamical properties of single neuron, collective behaviors of neurons, and transition of neuronal electric activities have been investigated extensively [4–7]. For example, synchronization between electric activities of neurons [8–10], phase synchronization [11, 12], coherence resonance [13–18], transition of electric modes in neurons [19–24], and the development and transition of spatial pattern in neuronal networks [25–29] have been discussed in numerical studies. In a biological experimental way, isolated neurons can be immersed into certain ionic liquid to detect the effect of external forcing from potassium, sodium, and even the leakage current [30–32]. On the other hand, it becomes interesting to design artificial neuronal circuit with low power

consumption [33–36], and thus neuronal activity can be reproduced from the intelligent neuronal circuits. Furthermore, the development and transition of collective electric activities of neurons can be detected within the coupled neuronal circuits, and it can give some useful guidance to discern the collective electric activities in large scale network of neurons.

In a general way, the scheme of numerical studies could be feasible to study dynamical behaviors of mode transition of neuronal activities based on some theoretical models. However, it shows a reliable way to judge the effectiveness of control schemes based on neuronal circuit composed of analog elements by using some commercial circuit elements. There is some diversity between neurons in realistic neuronal systems, and different responses occur when identical or nonidentical external forcing is imposed on the neuron. As a result, it is more important to study the synchronization and desynchronization between rhythms of electric activities than the topic of complete synchronization. In the case of signal detection from neuronal circuit, signal converter is often used to transmit analog signal to digital signal; thus, the rhythm of signal can be exactly detected, particularly for the case of bursting state. The connection between neurons

in realistic neuronal system is much complex, and a coupling with electric type is more effective in changing electric mode of neurons than the chemical coupling type. It is believed that neurons should be connected with small-world type connection in detecting the collective electric activities of neurons. In fact, the nearest neighbor connection is also effective in describing the coupling action between adjacent neurons when the size of network is small; for example, finite neurons are connected to design a neuronal network. In this paper, firstly, a feasible circuit is designed for Hindmarsh-Rose neuron mode [2], then three neuronal circuits are used to design a coupled neuronal network, and the rhythm synchronization of electric activity of coupled neuronal network will be investigated under mutual coupling and unidirectional coupling, respectively. Based on the PSpice tool [37], the gain in coupling controller is carefully adjusted to detect the modulation and transition of synchronization of network, it is found that synchronization can be reached between the coupled neurons, and it can offer some reliable information and tools to study the synchronization of coupled neuronal circuits.

2. Circuits Implementation of Single Neuron and Coupled Neurons

The Hindmarsh-Rose neuron [2, 38] can describe the main properties of neuronal activities, and the mathematical model is feasible for bifurcation analysis, and thus different electric modes can be observed. The dynamical equations can be described by

$$\begin{aligned}\dot{x} &= y - ax^3 + bx^2 - z + I_{\text{ext}} \\ \dot{y} &= c - dx^2 - y \\ \dot{z} &= r [s(x + 1.6) - z],\end{aligned}\quad (1)$$

where $\dot{x}$, $\dot{y}$, $\dot{z}$ define the membrane potential, recovery variable associated with the fast current (Na^+ or K^+), and a slow adaptation current probably linked to Ca^{2+} , respectively. I_{ext} denotes the external forcing current, parameters are often selected as $a = 1$, $b = 3$, $c = 1$, $d = 5$, $r = 0.006$, and $s = 4$, and the dynamical mode can create different electric modes by adjusting the external forcing carefully. Based on the PSpice tool, a practical neuronal circuit is designed in Figure 1.

To discern the rhythm of electric activity of neuron, the output voltage X_A in Figure 1 is converted into digital signal by using Schmitt trigger circuit so that the peak could be detected, which is shown in Figure 2.

According to Figure 1, different external forcing currents are imposed on the neuronal circuit and the output digital signals are plotted in Figure 3.

It is found in Figure 3 that analog signal from the single neuronal circuit can be converted into digital signal by passing through Schmitt trigger circuit, and the outputs show spiking, bursting state under appropriate external forcing. Furthermore, the collective activities of coupled neuronal circuits under nonreversing (or unidirectional) coupling will be investigated by connecting three neuronal circuits in ring type, and realistic circuit is shown in Figure 4.

Within the coupled neuronal network with three neurons being included, the local kinetics of each node is described by Hindmarsh-Rose neurons, and the dynamical equations for the coupled network are described by

$$\begin{aligned}\dot{x}_1 &= y_1 - ax_1^3 + bx_1^2 - z_1 + I_{\text{ext},1} + D_1(x_3 - x_1) \\ \dot{y}_1 &= c - dx_1^2 - y_1 \\ \dot{z}_1 &= r [s(x_1 + 1.6) - z_1] \\ \dot{x}_2 &= y_2 - ax_2^3 + bx_2^2 - z_2 + I_{\text{ext},2} + D_2(x_1 - x_2) \\ \dot{y}_2 &= c - dx_2^2 - y_2 \\ \dot{z}_2 &= r [s(x_2 + 1.6) - z_2] \\ \dot{x}_3 &= y_3 - ax_3^3 + bx_3^2 - z_3 + I_{\text{ext},3} + D_3(x_2 - x_3) \\ \dot{y}_3 &= c - dx_3^2 - y_3 \\ \dot{z}_3 &= r [s(x_3 + 1.6) - z_3],\end{aligned}\quad (2)$$

where the variables and parameters are defined as mentioned above [34, 37], the subscript i represents the node position, $I_{\text{ext},i}$ is the external forcing current on neuron connected to node i , and D_1 , D_2 , and D_3 are coupling intensity between neurons; for simplicity, $D_1 = D_2 = D_3$ will be used. The synchronization problem in (2) could be investigated in detail by changing the coupling intensity and controllable parameters in numerical studies. Take Figure 4 as an example by analyzing the coupling between neurons N3 and N1 with nonreversing (or unidirectional) type, an effective subtracting circuit can be designed by using the resistances RY43, RY44, RY47, and RY49 and Operational Amplifier U13A; thus, the error of membrane potentials between two coupled neurons can be generated. The resistances RY45 and RY48 decrease the error of membrane potentials with a gain about 0.17, the seesaw amplifier is composed of the resistance RY46, RICOUP2, and Operational Amplifier U13B, and gain for Operational Amplifier is described by RICOUP2/RY46; as a result, the coupling intensity is $0.17 \times \text{RICOUP2/RY46}$. For simplicity, the same coupling intensity and external forcing currents are used for each neuron. In the case of nonreversing (or unidirectional) coupling, the external forcing current $I_{\text{ext}} = 120 \mu\text{A}$, the coupling intensity is selected within 0.17~1, the circuit simulation based on PSpice shows that neuronal circuit will keep quiescent state, and then the external forcing current is increased to $I_{\text{ext}} = 130 \mu\text{A}$, and coupling intensity is selected by 0.17 in Figure 5; the case for coupling intensity 0.34 is shown in Figure 6.

The results in Figures 5 and 6 confirm that each neuronal circuit creates spiking state with higher external forcing current, and stronger coupling intensity is effective in enhancing rhythm synchronization of electric activities. Indeed, further increasing the coupling intensity, all neurons step into quiescent state after transient synchronization period, and the results are shown in Figure 7.

The results in Figure 7 show that the network of coupled neuronal circuits can reach synchronization by increasing

FIGURE 1: The artificial circuit for single Hindmarsh-Rose is illustrated by imposing external forcing, X_A is the output voltage, and I_{ext} denotes the external forcing current.

FIGURE 2: Schmitt trigger circuit: X_A is input analog signal and X_D is output digital signal.

the coupling intensity; furthermore, it develops into homogeneous state after a transient period. The potential mechanism is that each neuron is driven to step into quiescent state due to negative feedback. It is also interesting to investigate the bursting case, by selecting external forcing current $I_{ext} = 150 \mu A$, and the experimental results are shown in Figures 8 and 9.

It is found in Figure 8 that coupled neuronal circuits can still reach rhythm synchronization in the case of bursting state under appropriate coupling intensity.

It is found in Figure 9 that bursting synchronization can be stabilized under appropriate coupling intensity. However, transition from bursting synchronization to desynchronization can be observed by further increasing the coupling intensity, and the experimental results are shown in Figures 10 and 11.

It is found that transition from synchronization to desynchronization is induced by selecting stronger coupling intensity in the case of bursting state; the potential mechanism could be that each neuron undergoes coupling feedback with diversity in the case of directional coupling. In a word, appropriate coupling enhances rhythm synchronization while stronger coupling intensity accounts for homogeneous state after transient spiking synchronization, and desynchronization occurs after bursting synchronization. In realistic neuronal system, bidirectional coupling could emerge between neurons, the dynamical equations are described by (2), and

FIGURE 3: The output digital signal: the external forcing current imposed on the circuits is selected as 130 and 150 μA (a, b).

FIGURE 4: The coupled neuronal circuits for three neurons under nonreversing (or unidirectional) coupling type: X1_D, X2_D, and X3_D are the output digital signals from three different neuronal circuits and I31, I12, and I23 describe the coupling feedback term on the first, second, and third neurons, respectively.

realistic circuits between three coupled neurons based on PSpice are shown in Figure 12:

$$\dot{x}_1 = y_1 - ax_1^3 + bx_1^2 - z_1 + I_{\text{ext},1} + D_1(x_3 + x_2 - 2x_1)$$

$$\dot{y}_1 = c - dx_1^2 - y_1$$

$$\dot{z}_1 = r[s(x_1 + 1.6) - z_1]$$

$$\dot{x}_2 = y_2 - ax_2^3 + bx_2^2 - z_2 + I_{\text{ext},2} + D_2(x_3 + x_1 - 2x_2)$$

$$\dot{y}_2 = c - dx_2^2 - y_2$$

$$\dot{z}_2 = r[s(x_2 + 1.6) - z_2]$$

$$\dot{x}_3 = y_3 - ax_3^3 + bx_3^2 - z_3 + I_{\text{ext},3} + D_3(x_2 + x_1 - 2x_3)$$

$$\dot{y}_3 = c - dx_3^2 - y_3$$

$$\dot{z}_3 = r[s(x_3 + 1.6) - z_3],$$

(3)

where the variables and parameters are selected as the case for nonreversing (or unidirectional) coupling; D_1 , D_2 , and D_3 are coupling intensity between neurons; for simplicity, $D_1 = D_2 = D_3$ will be used. The outputs for potentials

FIGURE 5: The digital outputs for three circuits via Schmitt trigger circuit: $I_{\text{ext}} = 130 \mu\text{A}$ and coupling intensity is set as 0.17.

FIGURE 8: The digital outputs for three coupled circuits via Schmitt trigger circuit: $I_{\text{ext}} = 150 \mu\text{A}$ and coupling intensity is set as 0.17.

FIGURE 6: The digital outputs for three circuits via Schmitt trigger circuit: $I_{\text{ext}} = 130 \mu\text{A}$ and coupling intensity is set as 0.34.

FIGURE 9: Digital outputs for three circuits via Schmitt trigger circuit: $I_{\text{ext}} = 150 \mu\text{A}$ and coupling intensity is set as 0.5.

FIGURE 7: The digital outputs for three circuits via Schmitt trigger circuit: $I_{\text{ext}} = 130 \mu\text{A}$ and coupling intensity is set as 0.42.

FIGURE 10: Digital outputs for three circuits via Schmitt trigger circuit: $I_{\text{ext}} = 150 \mu\text{A}$ and coupling intensity 1.0.

FIGURE 11: Digital outputs for three circuits via Schmitt trigger circuit: $I_{\text{ext}} = 150 \mu\text{A}$ and coupling intensity is set as 1.01.

(voltage) are converted into digital signals via Schmitt trigger circuit, and different coupling intensities and external forcing currents are used to judge the effectiveness of the coupled neuronal circuits network. In the case of small external forcing current, for example, $I_{\text{ext}} = 120 \mu\text{A}$, quiescent state is observed and network shows homogeneous state. By increasing the external forcing current, neuronal circuit can produce spiking or bursting state. To observe the transition of synchronization, different coupling intensities are used to observe the outputs from the coupled neuronal circuits. At first, $I_{\text{ext}} = 130 \mu\text{A}$, the case for spiking synchronization is investigated, and the results are plotted in Figure 13.

In Figures 13 and 14 it is found that appropriate coupling intensity is effective in realizing rhythm synchronization under bidirectional coupling type when each neuronal circuit is in spiking state; furthermore, the network of coupled neuronal circuits creates homogeneous state when each neuronal circuit of the network is decreased into quiescent state due to bidirectional coupling, and the results are similar to the case under nonreversing (or unidirectional) coupling type. However, the transition of synchronization of coupled neuronal circuits shows complexity and diversity; the output digital signals are shown in Figures 15, 16, and 17 under different forcing currents and coupling intensities.

The results in Figures 15, 16, and 17 confirm that bursting synchronization is observed under appropriate coupling intensity, while transition from synchronization to desynchronization occurs by further increasing the coupling intensity; interestingly, bursting synchronization emerges by greatly increasing the coupling intensity. That is to say, the bursting synchronization has no nothing with regular relation with the selection of coupling intensity in the case of bursting state for each neuronal circuit.

Extensive experimental results are practiced in the PSpice and the developed states of coupled neuronal circuits are detected to discern the transition of coupled neuronal circuits, and some results could be presented as follows. When

each neuron is driven by external forcing current $I_{\text{ext}} = 120 \mu\text{A}$, each neuron keeps quiescent state and quiescent synchronization is realized under coupling intensity $D = 0.17, 1.02$ no matter whether nonreversing (or unidirectional) or bidirectional coupling being used. Spiking state is generated at $I_{\text{ext}} = 130 \mu\text{A}$, and spiking synchronization is realized by nonreversing (or unidirectional) coupling at coupling intensity $D = 0.17, 0.34$, while quiescent synchronization is realized by nonreversing (or unidirectional) coupling at coupling intensity $D = 0.42, 0.51, 0.68, 0.85, 1.02$, and 1.1 , where the potential mechanism could be that electrical activities of neurons are suppressed by stronger coupling. Spiking synchronization also makes bidirectional coupling at coupling intensity $D = 0.17, 0.34$, and 0.42 , and quiescent synchronization emerges at coupling intensity $D = 0.51, 0.68, 0.85, 1.02$, and 1.1 . By further increasing the external forcing current as $I_{\text{ext}} = 150 \mu\text{A}$, thus bursting state and synchronization could be observed, and it is found that bursting synchronization occurs under nonreversing (or unidirectional) coupling at coupling intensity $D = 0.17, 0.34, 0.51, 0.68$, and 0.85 , while desynchronization begins to be observed at $D = 1.02, 1.1$. In the case of bidirectional coupling, bursting synchronization occurs at $D = 0.17, 0.34$, and 1.1 , while desynchronization emerges at $D = 0.51, 0.68, 0.85$, and 1.02 . These results indicate that the final collective behavior (synchronization or desynchronization) could depend on the external forcing, coupling type, and also the coupling intensity as well, particularly when the neuron is in bursting state.

Above all, the evolution of coupled neuronal circuits is investigated by using PSpice tool, and it is found that the designed circuits are effective in detecting the development and transition of collective electric activities of neuronal network; indeed, the experimental results are much consistent with previous numerical studies and bifurcation analysis of neuronal activities. As a result, the designed neuronal circuit can be used as basic unit to study collective behavior of neuronal network with larger size and other potential applications. To be mentioned finally, it is thought that analog circuit by using commercial elements [39] or CMOL [40] and simulation program with integrated circuit emphasis (SPice) [41, 42] could be reliable to design intelligent circuit for signal process and analysis, and the synchronization between circuits could be useful for further study about collective behaviors of a large number of neuronal circuits. Indeed, these results based on simulation tools should be further improved in realistic experiments, similar to the mentioned experimental investigations [43–45] by generating multi-scroll attractors or multiwings in chaotic circuit, FPGA, and integrated circuit with lower power consumption should be considered.

3. Conclusions

By using PSpice tool, a reliable and feasible neuronal circuit is designed, and the output analog signals for membrane potential are converted into digital signals via Schmitt trigger circuit; thus, the rhythm of output series could be detected, and the coupling feedback is realized by using subtracting

FIGURE 12: The coupled neuronal circuits for three neurons under bidirectional coupling type: X1.D, X2.D, and X3.D are the output digital signals from three different neuronal circuits; I31, I12, and I23 describe the coupling feedback on the first, second, and third neurons, respectively.

FIGURE 13: The digital outputs for three circuits via Schmitt trigger circuit: $I_{\text{ext}} = 130 \mu\text{A}$ and coupling intensity 0.17 is selected for bidirectional coupled neuronal circuit.

FIGURE 14: The digital outputs for three circuits via Schmitt trigger circuit: $I_{\text{ext}} = 130 \mu\text{A}$ and coupling intensity 0.5 is selected for bidirectional coupled neuronal circuit.

FIGURE 15: The digital outputs for three circuits via Schmitt trigger circuit: $I_{\text{ext}} = 150 \mu\text{A}$ and coupling intensity 0.34 is selected for bidirectional coupled neuronal circuit.

FIGURE 16: The digital outputs for three circuits via Schmitt trigger circuit: $I_{\text{ext}} = 150 \mu\text{A}$ and coupling intensity 0.5 is selected for bidirectional coupled neuronal circuit.

FIGURE 17: The digital outputs for three circuits via Schmitt trigger circuit: $I_{\text{ext}} = 150 \mu\text{A}$ and coupling intensity 1.01 is selected for bidirectional coupled neuronal circuit.

circuit based on Operational Amplifier TL08X. Furthermore, three neuronal circuits are connected to construct a network of coupled neuronal circuits; appropriate external forcing currents are applied to induce spiking, bursting, and quiescent state, respectively. The network is connected under nonreversing (or unidirectional) and bidirectional coupling type. It is found that appropriate coupling intensity enhances spiking synchronization while larger coupling intensity induces homogeneous state after spiking synchronization of the coupled neuronal circuits. In the case of bursting synchronization, transition from rhythm synchronization to desynchronization occurs alternatively by increasing the coupling intensity carefully. Both the nonreversing (or unidirectional) and bidirectional coupling connections between neuronal circuits can reproduce collective electric activities of neuronal network which can be adjusted by changing the external forcing current on neuronal circuit. And the designed network of coupled neuronal circuits is helpful to

detect the transition of synchronization induced by other bifurcation parameters of the network.

Competing Interests

The authors declare that they have no competing interests.

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