DOI: 10.5604/01.3001.0010.8544

INVESTIGATION OF THE MEMRISTOR NONLINEAR PROPERTIES

Sviatoslav Khrapko, Volodymyr Rusyn, Leonid Politansky
Yuriy Fedkovych Chernivtsi National University, Department of Radio Engineering and Information

Abstract. *The study of nonlinear systems is an important research topic for scientists and researchers. Memristor, for a long time, it remained just as a theoretical element and rarely appeared in the literature because of having no simple and practical realization. In this paper, we reviewed the theoretical substantiation of the memristor and conducted a practical study of its nonlinear properties using the memristor company KNOWM of series BS-AF-W 16DIP. We also investigated the characteristics of the memristor via the LabView environment.*

Keywords: memristor, hysteresis, nonlinear system, KNOWM

BADANIE NIELINIOWYCH WŁAŚCIWOŚCI MEMRYSTORA

Streszczenie. *Badanie systemów nieliniowych jest ważnym tematem dla badaczy i naukowców. Memrystor przez długi czas pozostawał elementem teoretycznym i rzadko pojawiał się w literaturze z powodu braku prostej i praktycznej realizacji. W tym artykule zostały przedstawione teoretyczne uzasadnienie memrystora i badania jego właściwości nieliniowych na przykładzie memrystora firmy KNOWM serii BS-AF-W 16DIP. Zostały przeprowadzone badania charakterystyk memrystora w środowisku LabView.*

Słowa kluczowe: memrystor, histereza, nieliniowość, KNOWM

Introduction

In 2008 scientists were able to open a new component of electroschemes for the first time since Faraday's days and the beginning of experiments with electricity in the early 19th century. This component is called the memristor, this term was formed as a result of the fusion of words «memory» and "resistor" (electrical resistance). By this term is meant a two-pole device, the electrical resistance of which varies depending on the amount of charge flowing through it. American physicist Leon A. Chua in 1971 made an assumption about the existence of another basic element of the electrochemical system, which implements the relationship between magnetic flux and charge. It is impossible to simulate it from other passive elements, but even then it could be considered as a combination of active elements of the scheme; namely the resistor, the capacitor and the inductor [3, 6]. For example, operational amplifiers can be regarded as active elements. In this name, one of the characteristics of the element is expressed, the so-called "memory effect", that the previously applied force changes its properties, namely, the value of the resistance of the element varies depending on the amount of charge passed through it. This allows the memristor to be used as a memory cell. The resistance of the memristor was called the memresistance (*M*), which is defined as the ratio of the change in the magnitude of the magnetic field flux to the charge change, and its value depends on how long the electrical current flows through the memristor, that is, the amount of charge passed through it. Memristor is different from most types of modern semiconductor memory elements because its properties are not stored as charge. This is its main advantage, because it is not afraid of the leakage of charge, which is the main disaster, which everyone aspires to get rid of when it is transitioning to "nano chips". Another advantage of the memristor is its energy independence. These properties provide storage for memristor same time as exist materials used in its manufacturing. The same flash memory after a year of storage without connecting it to an electric current starts to lose recorded data.

Unlike the theoretical model, the memristor does not accumulate a charge like a capacitor, and does not support magnetic flux as a coil of inductance. The work of the device is provided by chemical transformations in a thin two-layer tape of titanium dioxide. One of the layers of the film is slightly depleted with oxygen, and oxygen vacancies migrate between layers under the action of the electric voltage applied to the memristor. This memristor's implementation should be attributed to the class of nanionic devices. The phenomenon of hysteresis, which we can observe in the memristor, allows us to use it as a memory cell [11].

The design of the memristors is much simpler than the flash memory. These elements represent a two-layer thin 50 nm tape placed between two 5 nm platinum electrodes. One of the layers is oxygen-depleted and the other is an insulating titanium dioxide. Under the influence of the voltage, that is applied to the electrodes, the structure of the titanium dioxide crystals begins to change – oxygen diffusion results in an increase in its electrical resistance by 1000 times. These changes in the cell do not disappear after the current is turned off. By changing the polarity of the supplied voltage, you can switch the state of the cell, and the number of these switching, according to the inventors, is not limited [10].

Another remarkable property of the memristor is that it can accept not two positions of memory: 0 and 1, as ordinary chips, but any other in the gap between zero and one, so the switch can work in the analogue, and in digital mode [12].

It is normal that memristors can be applied and give new extra highlights to simple circuits. Different simple and chaotic applications of memristor to analog, chaotic and synaptic circuits are studied in the literature [7].

1. The theoretical substantiation of the memristor

Chua came from the fact that there should be relations that connect all four main variables of electric circuits: current I, voltage *V*, charge *Q* and magnetic flux *Φ*. Total of such ratios can be six. Five of them are well known. Charge is an integral over time from the current. The connection between the voltage and the magnetic flux is determined by the law of electromagnetic Faraday's induction. Voltage and current are connected through resistance *R*, charge and voltage – through capacity C, and magnetic flux and current – through the inductance *L*. There is no the sixth ratio, which connects the flow and charge. Chua suggested that these values are connected through the "missing" element – memristor, which has "memresistance ". This statement is reflected in the formula (1) [1].

$$M(q) = \frac{d\Phi_m}{dq}, \tag{1}$$

where Φ_m is a flow coupling, generalized with current characteristics of the inductance, due to the absence of a magnetic field as such that can be regarded as an integral of voltage over time;

M(q) is a memresistance, an indicator characterized by any memristor, it relates the rate of change in flow and charge; in general, it depends on q, that is, the charge. If we consider the flow coupling as a temporary voltage integral, and the charge as a time integral of the current, then the following formula is obtained (2):

$$M(q(t)) = \frac{d\Phi_m / dt}{dq / dt} = \frac{V(t)}{I(t)} \quad (2)$$

We see that in the case of $M = const$, the memresistance is a normal resistance, and formula (2) turns into Ohm's law for the area of circle. This equation also shows that the memresistance determines the linear relationship between current and voltage, while M does not change with charge.

Zero current means a variable over time charge. An alternating current can detect a linear dependence in the circuit if the measuring voltage is induced without changing the total charge change – until the maximum change q does not cause large changes to M. If $I(t) = 0$, then $V(t) = 0$ and $M(t)$ is constant. This is the essence of the "memory" effect.

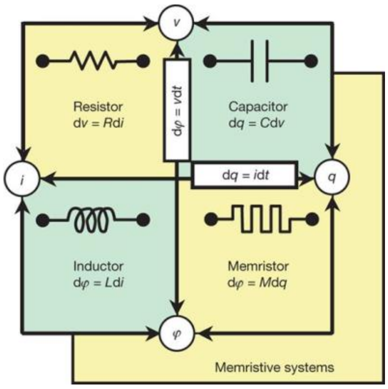

Fig. 1. Connection of the basic elements of the electric circuit

Fig.1. shows this relationship graphically [2, 5]. The voltage- or current-controlled memristor is a fundamental passive two-terminal component with resistance depending on the time history of voltage across or current through it [4].

If a variable sinusoidal voltage of a certain frequency is applied to the memristor, its voltage-ampere characteristic takes the form, which resembles a lissajous figure with center at the beginning of the coordinates: in electronics it corresponds to the assembly of two perpendicular oscillations with multiple frequencies. Normal (resistive) resistance corresponds to the slope of the curve of current dependence on voltage; here we see that at the zero current and voltage intersect such two curves. This means that the resistance may vary depending on the conditions. At the site of the sinusoid (when the voltage drops at the transition through zero) the resistance will be greater than the initial (when it increases). The figure is shown in Figure 2.

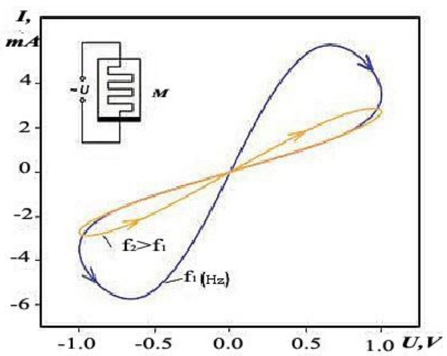

Fig. 2. The phenomenon of hysteresis of the memristor

That is, the memristor, in contrast to the resistor, has a hysteresis. The hysteresis curve turns into a straight line with an increase in the voltage frequency: the memristor is converted into a conventional resistor. This is understandable: since the change in the value of the resistance depends on the amount of charge that has passed, and with the increase in frequency for one period of charge runs less. Therefore, sufficiently short, different polar impulses of current will not affect the state of the memristor, and the magnitude of the current will show us in what state is the memristor. Thus, you can read the information without changing the state of the cell.

Hysteresis characteristics are the essential qualities of memristors [8, 9]. Hysteresis characteristics behave as multi-value mapping and memory features. Many models have been proposed to precisely depict the hysteresis phenomena, for example, Sun et al. [13] proposed a network model using the backslash operator as activation function to model hysteretic operator, Guo and Dang improved the backslash operator [8].

2. Modeling the nonlinear properties of a memristor in a LabView environment

The nonlinear element based on the memristor has a nonlinear hysteresis characteristic, which plays an important role in engineering and, in particular, in electronics. For demonstration was used one of the most advanced LabView software environment, which is a convenient tool for design and simulate various complexity of mathematical models that describe a particular devices. This environment allows creating virtual devices for generating and researching any characteristics.

Figure 3 shows a block diagram that allows generating a hysteresis characteristic.

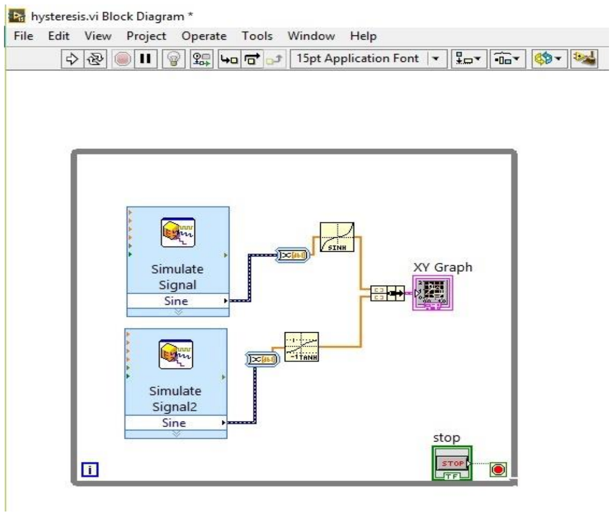

Fig. 3. Block diagram for modeling hysteresis characteristic

As sources of signals, two sources with the following parameters was selected:

1) Frequency 10.2 Hz, amplitude 2.5 V, phase -25 deq.
2) Frequency 10.1 Hz, amplitude 1 V.

Figure 4 shows interface of the program that graphically demonstrates modeling result.

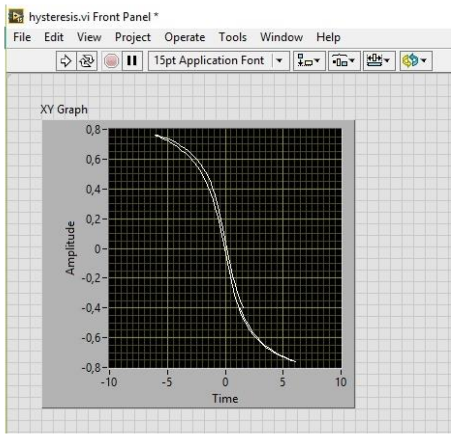

Fig. 4. Program interface that graphically demonstrates modeling hysteresis characteristic

3. Practical research of the nonlinear properties of the memristor

In this study, we use the memristor company KNOWM of series BS-AF-W 16DIP. The topological structure of the used memristor is described in detail in [13].

The memristor devices work mainly through the mechanism of the electric field of forced generation of the movement of metal ions through a multi-layer stack of chalcogenide material. The secondary mechanism of the operation is the phase change, which can be set as the main mode of operation depending on the operating conditions. The stack material is based on the mobile ionic conductivity of the metal through the chalcogenide material. Devices made from a metal layer that is easily oxidized are located near one of the electrodes. When the voltage is applied to a device with a more positive potential on the electrode near this metal layer, the metal is oxidized to form ions.

Figure 5 shows the structure of the layers of materials of the composition of the memristor [13].

After the formation of ions, the movement through the device in the direction of the lower electrode potential, these ions move through a layer of amorphous chalcogenide material (active layer) to reach the lower potential of the electrode while they decrease to their metal form and eventually form a conductive path between the two electrodes, which encompasses layer of the active material, reducing the resistance of the device. Changing the direction of the applied potential leads to the fact that the conductor channel decomposes (dissipates) and the resistance of the device increases. The devices are bipolar, cyclic between the values of high and low resistance when switching the polarity of the applied potential. Resistance is always linked with the amount of metal located within the active layer.

The memristor has two main types of work: ionic conductivity and phase change, and it can be introduced into a state consisting of a combination of two modes. The hysteresis and incremental response will vary depending on the mode in which the memristor is located at a given time.

In this paper we used a method for obtaining volt-ampere traits of the memristor.

The method we used to acquire volt-ampere characteristics is based on using sinusoidal input sign and steady increment of the amplitude of the sine wave for as long as the memristor has the properties required. Resistor *R* is a current-restricting resistor with an estimation of 51 kΩ. A sine wave from 1 to 100 Hz is applied, it is with amplitude of 0.25 V. The voltage is step by step expanded until the point when the hysteresis circle begins to be obvious. For the reason that device is working in ion-conduction mode simplest, the voltage over the load responds via following the enter waveform amid the positive cycle, the load responds and amid the negative-going erase cycle until the eradicate limit makes the gadget resistance increment.

Nonlinear characteristics of the memristor are obtained by the connection circuit presented in Figure 6.

To achieve phase-shift operation, the device is operated under high voltage and under specified conditions. In order to obtain a device from the phase transition mode, pulse, higher return voltage and pulse melting are used. Figure 7 shows the response of the phase change to a higher applied voltages in the abrasion region.

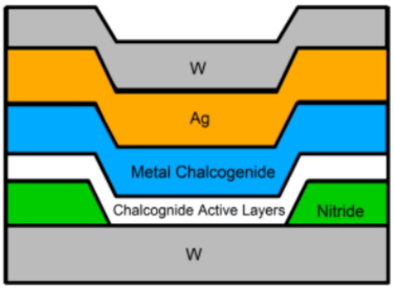

Fig. 5. Structure of the layers of the material of the memristor

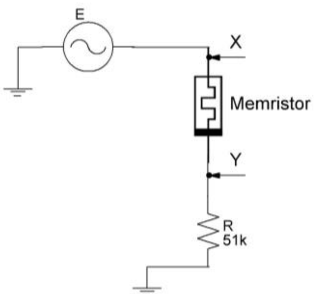

Fig. 6. The circuit of connection of the memristor to obtain I-V characteristics

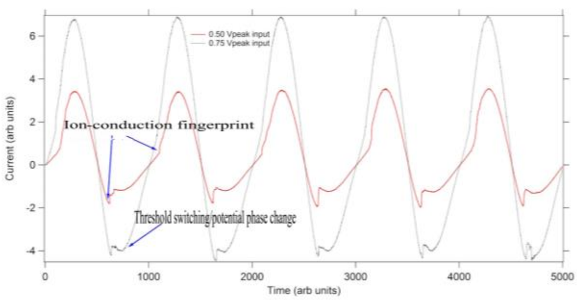

Fig. 7. Reaction of phase change from the value of the applied voltage

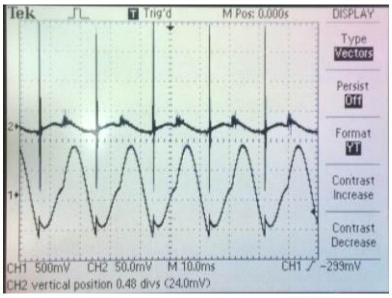

Fig. 8. Experimental phase change of the value of the applied voltage

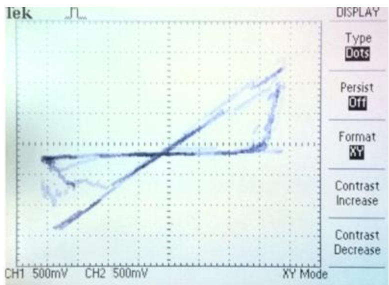

Fig. 9. I-V characteristics of the memristor at a voltage of 1.4 V and a frequency of 30 Hz

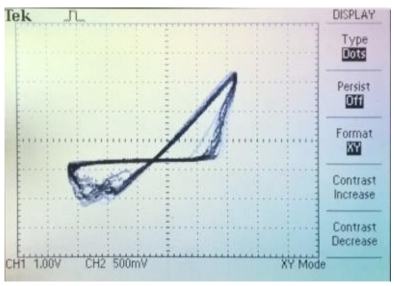

Fig. 10. I-V characteristics of the memristor at a voltage of 2 V and a frequency of 100 Hz

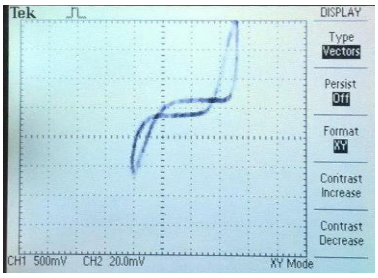

Fig. 11. I-V characteristics of the memristor at a voltage of 0.5 V and a frequency of 15 Hz

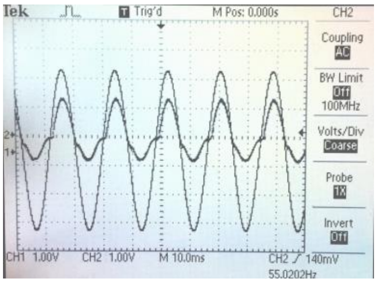

Fig. 12. Time distribution of the signal at a frequency of 50 Hz

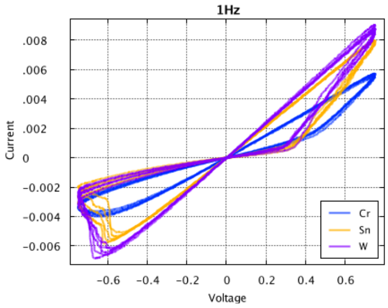

Fig. 13. Theoretical view of I-V characteristics

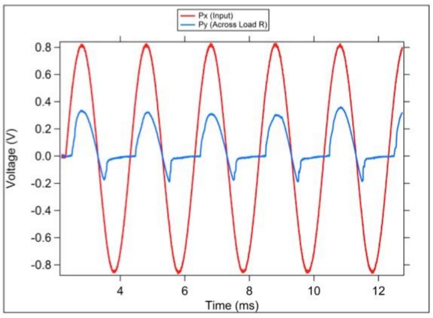

Fig. 14. The theoretical view of the time distribution

Figure 8 shows the experimental result of phase change from the value of the applied voltage.

Practically the following characteristics are obtained, according to the connection circuit shown in Figure 6, the memristor on Figure 9 at the voltage of the source *E* at the level 1.4 V and frequency 30 Hz.

Figure 10 shows the appearance of a hysteresis loop at a voltage of 2 V and a frequency of 100 Hz. Signals for hysteresis loops were removed from the *X* and *Y* points.

Figures 13 and 14 show the theoretical results, which are described in [13].

As can be seen from the above theoretical results coincide with the practical ones. This behavior of the memristor allows it to be used as a bipolar switch.

4. Conclusions

Nonlinear properties of volt-ampere characteristics are investigated, which makes it possible to use nonlinear properties of a memristor for constructing a oscillator of chaotic signals. It is established that in contrast to the transistor, the final state of the memristor in terms of charge does not depend on the bias voltage, that is, to support the resistance of the memristor at a certain value does not require a constant voltage, after power off the memristor retains its condition, while the resistance of the transistor depends from the presence of voltage. This indicates that the memristor can perform both the role of the memory cell and the switch.

Acknowledgments

We express great gratitude to all the staff of the Department of Theoretical Physics of Lodz University, especially to the prof. Krzysztof Kowalski and prof. Jakub Rembieliński for full support.

References

[1] Agafonov O.M.: Memristor – revolucija v mikroelektronikie. X practical-science conference 2015, 2–35.

[2] Bharathwaj M., Pracheta K.: Memristor Based Chaotic Circuits. IETE Technical Review 6/2009, 1–16.

[3] Chua L.O.: Memristor – the missing circuit element. IEEE Trans. Circuit Theory 5/1971, 507–519.

[4] Corinto F., Ascoli A.: Memristor based-element for chaotic circuits. Nonlinear Theory and Its Applications 3/2012, 336–356.

[5] Strukov D.B., Snider G.S, Stewart G.R., Williams R.S.: The Missing Memristor Found. Nature 453/2008, 80–83.

[6] Şuayb Çağrı Yener, Kuntman H.H.: Fully CMOS Memristor Based Chaotic Circuit. Radioengineering 4/2014, 1140–1149.

[7] Şuayb Çağrı Yener: Fully CMOS Memristor Based Chaotic Circuit. Radioengineering 4/2014, 1140–1149.

[8] Zhao Y., Jiang Y., Jiuchao F., Wu L.: Modeling of memristor-based chaotic systems using nonlinear Wiener adaptive filters based on backslash operator. Chaos, Solitons and Fractals 87/2016, 12–16.

[9] Zhen Y., Heng T., Chen G., Chua L.: What are memristor, memcapacitor, and meminductor. IEEE Trans. Circuits Syst-II 62/2015, 402–405.

[10] Nechaj O.: Memristor: "nedostayushchiy element". Komputerra 2011, http://old.computerra.ru/vision/591537/ [1.01.2018].

[11] Memristor, http://dic.academic.ru/dic.nsf/ruwiki/527619#.D0.9C.D0.B0.D1.82.D0.B5.D0.BC.D0.B0.D1.82.D0.B8.D1.87.D0.B5.D1.81.D0.BA.D0.B0.D1.8F_.D0.BC.D0.BE.D0.B4.D0.B5.D0.BB.D1.8C. [1.01.2018].

[12] Nikiriv A.V.: Niemnogo o memristorie, 2014 http://www.trinitas.ru/rus/doc/0023/001a/1052-nik.pdf. [1.01.2018].

[13] Knowm Memristors. Knowm Inc. Santa Fe, New Mexico 2015. http://knowm.org/downloads/Knowm_Memristors.pdf [1.01.2018].

M.Sc. Sviatoslav Khrapko
e-mail: s.khrapko@chnu.edu.ua

Yuriy Fedkovych Chernivtsi National University Department of Radio Engineering and Information Security. Ph.D. student.
Research interests: information technology, intelligent control systems and neural networks.

Ph.D. Volodymyr Rusyn
e-mail: rusyn_v@ukr.net

Yuriy Fedkovych Chernivtsi National University Department of Radio Engineering and Information Security.
Ph.D. (Engineering Sciences) Assistant of Department of Radio Engineering and Information Security.
Research interests: modeling of chaotic generators and control of chaotic oscillations.
Author of nearly 30 publications in this research area.

Prof. Leonid Politansky
e-mail: krtib1989@gmail.com

Head of department of Radio Engineering and Information Security.
Research interests: physical processes in semiconductor devices, radio engineering devices and means of telecommunications. Author of nearly 200 publications.

otrzymano/received: 10.10.2017 *przyjęto do druku/accepted: 15.02.2018*