Emulation of a memristor element using a programmable microcontroller device

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Best Section Paper Award

***Abstract*—This paper deals with emulation of a memristor, a device that recently has attracted a considerable interest since its fabrication based on transition metal oxides (TiO_{2-x}/TiO_2) as resistance changing materials. The model and the circuit that emulates the behavior of the forth basic element (memristor) is based on the programmable microcontroller device that exploits the pulse width modulation (PWM) to create the response function that is characteristic of this element (the connection between magnetic flux and electric charge at every instance of time). Device has been realized and tested following the fingerprints that characterize the memristor behavior (changing resistance with memory effect, pinched hysteresis loops). The applications of the memristors have been already broad, starting from new types of non-volatile memories till neuromorfic devices.**

***Index Terms*—Memristor; emulation; microcontroller; pulse width modulation.**

I. INTRODUCTION

MEMRISTOR is so called fourth element in circuit analysis. Its main characteristic is that it connects at every instance of time physical quantities of magnetic flux and electric charge. Memristor had been introduced in the theory of circuits design in 1971 by Leon Chua [1] and latter the concept has been widened to cover the whole class of systems [2]. A major breakthrough happened in 2008 when the group in Hewlett Packard reported a design and production of the “missing” element [3] based on transition metal oxides (TiO_{2-x}/TiO_2). Since then the number of publications and reports on memristors and memristive systems increases rapidly. The whole issue of IEEE Magazine [4] was devoted to this topic and there are several recent books that cover various aspects of design, fabrication, simulation, emulation and application of memristors and memristive systems [5-7]. In Europe, a concerted effort has been made by establishing the COST Action (European Co-operation in Science and Technology) under the name “Memristors - Devices, Models, Circuits, Systems and Applications (MemoCiS)”. The Action gathered researchers from 21 countries with different expertise, from electrical engineers specialized in circuits, signals and systems over physicist of material science till engineers in technological development.

II. THE THEORY AND METHOD

The ideal memristor is defined by the relation between magnetic flux linkage $\psi(t)$ and electric charge $q(t)$ at every instance of time t:

$$\psi(t) = f(q(t)) \tag{1}$$

and inversely by:

$$q(t) = g(\psi(t)) = f^{-1}(\psi(t)) \tag{2}$$

By differentiating the equation (1) in time we obtain the following relation:

$$\frac{d\psi(t)}{dt} = \frac{df(q)}{dq} \cdot \frac{dq(t)}{dt} \tag{3}$$

while from the equation (2) it follows:

$$\frac{dq(t)}{dt} = \frac{dg(\psi)}{d\psi} \cdot \frac{d\psi(t)}{dt}. \tag{4}$$

If we define the charge-controlled memresitance $M(q)$ and the flux-controlled memductance respectively $G_m(\psi)$ as:

$$M(q) \equiv \frac{df(q)}{dq} \tag{5}$$

and

$$G_m(\psi) \equiv \frac{dg(\psi)}{d\psi} \tag{6}$$

we obtain the basic relations for the current-actuated memristor’s output voltage:

$$v_m = M(q) \cdot i_m \tag{7}$$

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and the voltage-actuated memristor's output current:

$$i_m = G_m(\psi) \cdot v_m \tag{8}$$

where $i_m = dq/dt$ and $v_m = d\psi/dt$.

A. Memristor Port and State Equations

The memristor could be regarded as a classical electric two-terminal device defined by a port equation that gives the relation between an excitation function $u(t)$ and response $y(t)$:

$$y(t) = F(x) \cdot u(t) \tag{9}$$

and a state equation:

$$\frac{dx}{dt} = u(t). \tag{10}$$

The relationship function $F(x)$ is a nonlinear function of the state variable x whose time derivative is defined by the equation (10). From equation (10) follows that the state variable x is a time-domain integral of the excitation function $u(t)$ and correspondingly, a time integral of the response is the integral of $F(x)$ over state variable.

Thus, we can recognize two types of memristor devices, one is voltage-controlled memristor (VCMR) and the other is current-controlled memristor (CCMR). In the case of the VCMR, the excitation is voltage v_m and the time integral is flux-linkage ψ_m, while the response is current i_m and time integral is charge q_m, so defining function in the port equation is G_m while the constitutive relation is $q(\psi)$. In the case of the CCMR, the excitation is current i_m and the time integral is charge q_m, while the response is voltage v_m and time integral is flux-linkage ψ_m, so defining function in the port equation is M_m while the constitutive relation is $\psi(q)$. These cases are summarized in Table I.

TABLE I
MEMRISTOR TYPES AND THEIR VARIABLE

Memristor type \ Variable	VCMR	CCMR
Excitation $u(t)$	v_m	i_m
Response $y(t)$	i_m	v_m
Time integral of excitation	ψ_m	q_m
Time integral of response	q_m	ψ_m
Defining function	G_m	M_m
Constitutive relation	$q(\psi)$	$\psi(q)$

By differentiating (6) we get the change rate of memductance $\dot{G}_m(\psi)$ which is proportional to the implemented memristor voltage modulated by the function that depends on flux-linkage:

$$\dot{G}_m(\psi) = \frac{d^2 g(\psi)}{d\psi^2} \cdot v_m = c \cdot H(\psi) \cdot v_m \tag{11}$$

where c is a constant, and $H(\psi)$ is the normalized function to unity [8]. In that case the realized memductance could be written as:

$$G_m(\psi) = G_{m,0} + \int_{-\infty}^{t} \{(c \cdot v_m) \cdot H(\psi)\} \cdot dt' \tag{12}$$

while the block diagram of logical scheme is shown in Fig.1 as given in [8] if we assume the $H(\psi)$ to be the unity function.

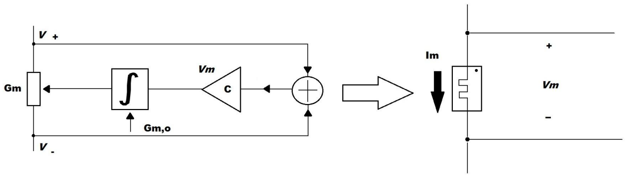

Fig. 1. Block diagram of the realized memconductance according (12) with unity function $H(\psi)$.

B. Memristor Fingerprints

In order that a device could be a memristor it should satisfied a number of fingerprints [9,10]. The main fingerprint is the display of the pinched hysteresis loop when a memristor is subjected to bipolar periodic drive. This hysteresis is shown in the voltage- current plane as a double-valued Lissajous figure that passes through zero point where the loops are pinched. This behavior should be exhibited at all driving frequencies ω and all amplitudes of the sinusoidal excitation signal as well as for any initial condition $x(0)$ of the state variable. Furthermore, the hysteresis lobe areas must decrease with the increase of ω and tend to single-valued function at infinite ω.

In DC regime memristor behaves like a nullor, i.e. when voltage and current are steady input, output is zero voltage and zero current. Under periodic excitation, ideal memristor should go into periodic regime without transients. Owing to these phenomena, memristors are proposed to be used as non-volatile memories or artificial synapse [9].

III. MEMRISTOR EMULATION

In this work we have implemented the design of a memristor by following the basic idea that it represents a device whose (mem)resistance is changing according to (12). The processing of the signal was achieved by microcontroller in which the applied signal was first converted by 10 bit A/D converter and then transferred into pulse width modulated (PWM) signal with the frequency of 40 kHz. The integration of the signal was performed by the microcontroller in order to achieve the (mem)resistance defined in (12).

The memristor emulation circuit is designed and tested. Two different tests were performed: a) Recording the memristance versus potentiometer position at the microcontroller input and DC voltage at the input of the circuit; b) AC voltage at the input of the circuit. Additionally, a simulation using the code in MATLAB was performed according to model [11,12] and the results are presented in Fig. 2.

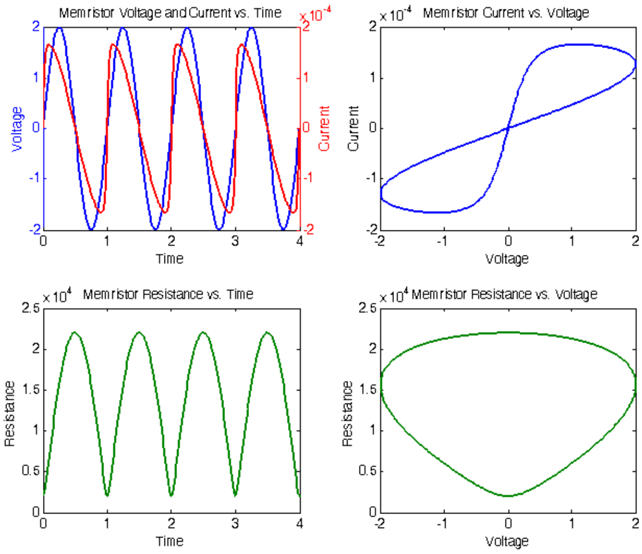

Fig. 2. Simulation of the memristor effect using MATLAB code.

The used output circuits are given in Appendix. We have first used the H11AG1 optocoupler transistors to separate microcontroller unit from the output circuit (Fig. 3) but the use of h11f1 optocoupler FETs turns to give better results due to wider range of achieved resistances and better integration time of the signal.

IV. CONCLUSION

A memristor device was emulated by the use of microcontroller by applying the basic principles of memristor function, i.e. behavior of (mem)resistance according to (12). Still, more work is needed to test the device following the known fingerprints and to define the limits of the emulated circuit.

APPENDIX

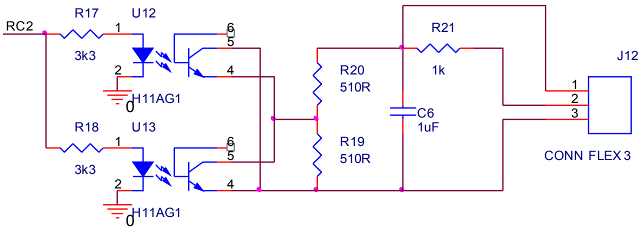

Fig. 3. Schematic circuit of memristor emulation with opto-transistors.

An improved schematic circuit with FET optocouplers used instead of optocoupler transistors is shown in Fig. 4. We used a h11f1 optocoupler in its function as a remote variable resistor.

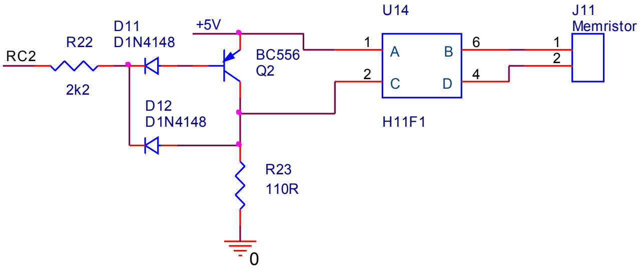

Fig. 4. Schematic circuit of memristor emulation with FET optocoupler h11f1 used as a remote variable resistor.

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REFERENCES

[1] L. O. Chua, “Memristor: The missing circuit element,” *IEEE Trans. Circuit Theory*, vol. 18, no. 5, pp. 507–519, 1971.

[2] L. O. Chua and S-M. Kang, “Memristive devices and systems,” *Proc. IEEE*, vol. 64, no. 2, pp. 209–223, 1976.

[3] D. B. Strukov, G. S. Snider, D. R. Stewart, and S. R. Williams, “The missing memristor found,” *Nature*, vol. 453, no. 7191, pp. 80–83, 2008.

[4] R. Tetzlaff and C. W. Wu, “From the Guest Editors”, *IEEE Circuits and Systems Magazine*, vol. 13, no.2, pp. 4-6, May 2013.

[5] R. Kozma, R. E. Pino, G. E. Pazienza, (Eds.), *Advances in Neuromorphic Memristor Science and Applications*, Berlin, Germany: Springer (Series in Cognitive and Neural Systems), 2012.

[6] R. Tetzlaff, (Ed.), *Memristors and Memristive Systems*, Berlin, Germany: Springer, 2014.

[7] A. Adamatzky, L. O. Chua, (Eds.), *Memristor Networks*, Berlin, Germany: Springer, 2014.

[8] S. Shin, Le Zheng, G. Weickhardt, S. Cho, and S-M. Kang, “Compact Circuit Model and Hardware Emulation for Floating Memristor Devices,” *IEEE Circuits and Systems Magazine*, vol. 13, no.2, pp. 42-55, May 2013.

[9] S. P. Adhikari, M. Pd. Sah, H. Kim, and L. O. Chua, “Three Fingerprints of Memristor”, *IEEE Trans. Cicuits Syst.*, vol. 60, no. 11, pp. 3008-3021, Nov. 2013.

[10] D. Biolek and Z. Biolek, “Fourth Fundamental Circuit Element: SPICE Modeling and Simulation” in *Memristors and Memristive Systems*, Berlin, Germany: Springer, 2014, ch. 4, pp. 105-162.

[11] A. G. Radwan, M. Affan Zidan, and K. N. Salama, “On the mathematical modeling of Memristors,” *22nd Int. Conf. on Microelectronics (ICM 2010)*, pp. 284-287, Egypt, December 2010.

[12] A. G. Radwan, M. Affan Zidan, and K. N. Salama, “HP memristor mathematical model for periodic signals and DC,” *IEEE International Midwest Symposium on Circuits and Systems (MWSCAS)*, pp. 861-864, USA, August 2010.