Octave Memristor Models' Library and Application for Analysis of Memristors and Memristor-Based Circuits

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Abstract— **Memristors are favorable electronic components with decent switching and memory features. Owing to their low energy usage, nano-scale sizes, and sound compatibility with present CMOS high-density integrated schemes, memristors are potentially applicable in neural nets, memory arrays, and different reconfigurable microelectronic devices. Design and analysis of memristor elements and circuits, based on memristors with electronic simulators is very important task. This paper presents modelling and investigations of single memristors and several humble memristor-based circuits in GNU Octave, applying some analytical and numerical solutions. The suggested work could be valuable for educational and scientific goals. Additional analyses are made in LTSPICE for confirmation the proper action of considered memristor circuits with high efficiency. During the analyses, several modified and standard memristive models are utilized and compared. Design of new electronic circuits based on nano-electronic elements is an important step towards generation of very high-density integrated circuits.**

Keywords — **GNU Octave software, finite differences method, LTSPICE environment, numerical modeling**

I. INTRODUCTION

In the latest years, *memory* and *switching* performance in doped metal-oxide substances, as titanium dioxide, niobium oxide, tantalum oxide and others are under rigorous studies [1], [2]. Such features are linked to processes of diffusion and *accumulation* of electric charges in non-stoichiometric metal oxides at applied voltage or current signals [3], [4]. The *memristor* forecast in 1971 by Leon Chua and realized in Hewlett-Packard labs by Stanley Williams is with similar properties [5]. Memristors have very low power consumption, non-volatile behavior and memorizing features, *high-speed switching*, nano-sizes and a strong compatibility to Complementary Metal Oxide Semiconductor (CMOS) integrated chips [6], [7]. Memristors display high applicability in different areas, as in *memory matrices*, analog and digital *reconfigurable schemes*, *neural nets* and others [8], [9]. Design and manufacturing of electronic devices include synthesis and preliminary investigations by *computer simulators*, commonly utilizing software as MATLAB, SPICE, and other products [10], [11]. Along with other SPICE family products, as OrCAD PSpice, NGSPICE, CADENCE, HSPICE, and many others, LTSPICE [8] is a preferred product for electronic circuits' analysis, having in mind its user-friendly communication, free and open license, and good *convergence* [11]. Along with some commercial products, as MATLAB [10], GNU Octave [12] is a preferred product for engineering and math analyses, because it is *free* and accessible environment with a good functionality [13]. Both LTSPICE [14] and GNU Octave [15] are appropriate and applicable for *educational* and *scientific* aims, especially in some special situations, as in the COVID-19 pandemic [12]. GNU Octave is an *open* source and *high-level* language for programming, designed for *numerical* computations. It is supported on Microsoft Windows, Linux, and Mac OS [12]. It is also suitable for home application by *students* and *educating* staff. This was the main reason these free products to be used in the work.

In scientific references, a lot of specialized memristor *models* are available [16], [17], [18]. Metal oxide memristors are quite different to each other, due to some details of their configuration and operation [16]. Such memristor models are complex, and sometimes universal models of memristors are applied [11], [19]. The *purpose* of this work is to represent a *flexible*, *simple*, and *efficient* GNU Octave model of memristors, applicable for exploration of oxide memristors and humble memristor-based circuits. Related to this aim, several tasks are addressed. The applied GNU Octave memristive model is created on Joglekar [20] and Laiho-Lehtonen models [16], utilizing the Hann window [6]. The presented model is capable to work at high-frequency excitations. The used Hann window function constrains the state measure and solves the electrode state issues [6], [19]. The applied memristor model has some *benefits*, compared to several standard models - *simple equations*, low simulating time, and a respectable *accuracy* [19]. The considered model uses *sensitivity thresholds* and efficiently works in soft-switching and hard-switching states. The memristor model is utilized and investigated in several simple circuits, together with several frequently used models for their comparison in GNU Octave and LTSPICE environment. Tuning the main characteristics of the proposed memristor-based circuits is achieved by voltage pulses. The applied modified memristive model, along with a lot of modified and standard models and some simple memristor devices is incorporated in a free collection and is accessible at the link: https://github.com/StoyanKirilov/Memristor-Modeling.

The article has the next arrangement. The next Section 2 offers a short overview on metal oxide based memristors' structure, functioning and modeling. In Section 3 is

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described the proposed GNU Octave library with memristor models and some examples and the respective analyses. Memristor analyses and potential applications are presented and discussed in Section 4. A brief comparison of some frequently utilized standard and modified memristor models is offered in the following Section 5. The last Section 6 completes the work.

II. MEMRISTORS, NANOSTRUCTURES AND THEIR MODELLING [3], [11]

For justification of memristor *action* and *modeling*, a short summary is primarily offered [3].

A. A description for memristor structure and functioning

Memristor elements are frequently based on *partially* doped metal oxides [3]. A basic nanostructure of oxide memristor is offered in Figure 1 (a). The terminals of memristor are denoted as *cathode* and *anode*. The length of saturated layer is w, and the whole memristor length is D. An important quantity of memory elements is their state variable x. It presents the ratio of saturated layer length w to entire memristor length D: $x = D^{-1}w$. It is in scope among one and zero [4]. *Commutation* and *memorizing* features of memristors are based on accumulation of charges and resistance' retain and alteration at applied voltage impulses [3]. In the suggested schematic the memristor is connected in a forward direction. Memristors' behavior depends on *polarity* of applied voltage [3], [7]. Figure 1 (b) present a simple equivalent circuit of the discussed nanostructure, using two state-dependent and nonlinear resistors. The symbol of memristor in electronic devices is shown in Figure 1 (c) for observation [3].

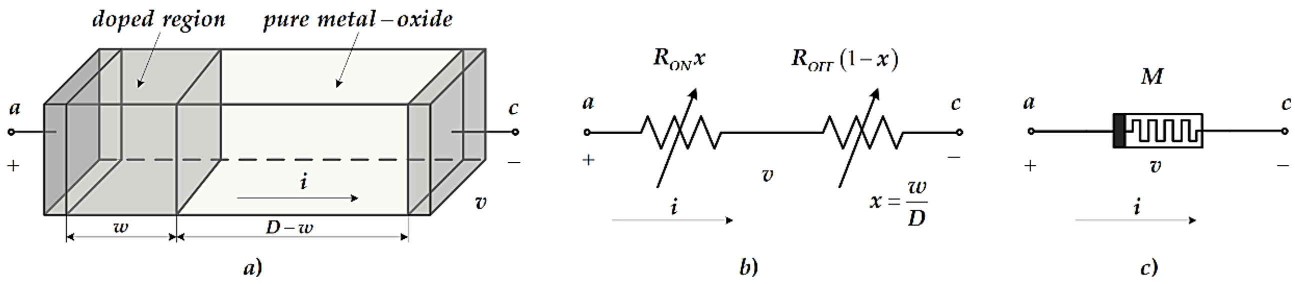

Figure 1 (a) Memristive nanostructure [20]; (b) Corresponding electric scheme [20]; (c) Memristor symbol

A. Math Modelling of Memristor Elements [3], [11]

A model of memristor holds *two equalities* [3], [6]. The first expression connects *voltage and current*, the next one links *time derivative* of state x and *voltage* (or the *current*) [3]. A large assembly of models, as Joglekar, Williams [20], Biolek [2] and many others is expressed by (1):

$$\left| \begin{array}{l} i = \left[R_{OFF} \left(1-x\right) + R_{ON} x \right]^{-1} \cdot v \\ \dot{x} = k \cdot \eta \cdot f\left(x\right) \cdot i\left(v\right); \;\; x\left(t=0\right) = x_0 \end{array} \right. \tag{1}$$

Here, η denotes the element's polarity, it is $\eta = 1$ for a memristor in forward biasing and $\eta = -1$ for reverse direction [3]. The OFF-state and ON-state resistances (also known as *memristances*) are R_{OFF} and R_{ON}, k is a physical constant, and $f(x)$ is a *window* for limiting of x [3]. The quantity x_0 is the primary measure of state quantity. Many of frequently used windows are built on *polynomials* or *trigonometric* functions [8]. Memristor models' equations could be *numerically* solved by appropriate methods [14] and software [12]. Some of the models could be *analytically* solved in closed forms [3].

B. Analytical solution of a memristor model

Here, an analytical solution of Strukov-Williams memristor model [5] is presented. The used *window function* is a simple *polynomial*: $f_{sw}(x) = x - x^2$. Its complete mathematical model is as follows [3], [5]:

$$\left| \begin{array}{l} i = v \cdot \left[R_{OFF} + \left(R_{ON} - R_{OFF} \right) x \right]^{-1}; \;\; x\left(t=0\right) = x_0 \\ \dfrac{dx}{dt} = k \cdot \eta \cdot v \cdot \left[\left(R_{ON} - R_{OFF} \right) x + R_{OFF} \right]^{-1} \cdot \left(x - x^2 \right) \end{array} \right. \tag{2}$$

After separating the variables x and t in the state *differential* equation of system (2) and integrating in limits from x_0 to x, the next equation (3) is obtained:

$$\int_{x_0}^{x} \frac{\left(R_{ON} - R_{OFF} \right) x + R_{OFF}}{x - x^2} dx = k \cdot \int_0^t v \, dt \tag{3}$$

The *analytical* solution of equation (3) is presented by the next formula (4):

$$\begin{array}{l} R_{OFF} \ln x - R_{ON} \left(1-x\right) = \\ = k \cdot \displaystyle\int_0^t v \, dt + R_{OFF} \ln x_0 - R_{ON} \left(1 - x_0\right) \end{array} \tag{4}$$

The solution could be derived in a *closed form* using the following approximation: $R_{ON} << R_{OFF}$ [4]:

$$x = \exp\left\{ R_{OFF}^{-1} \cdot \left[k \cdot \int_0^t v \, dt + R_{OFF} \ln x_0 - R_{ON} \left(1 - x_0\right) \right] \right\} \tag{5}$$

C. Numerical Modelling of Memristors [3], [12], [14]

An example for numerical solution of a system describing a memristor model will be presented, using the same model [5] and the *finite-differences method* [14]. First, time interval between starting time t_{min}=0 and final time t_{max} is sampled, using N numbers of samples [14]. Then, the time step is $\Delta t = (t_{max} - t_{min})/N$. Correspondent to time is the index variable: $n=1:1:N+1$. The *difference equation* correspondent to *differential equation* (2) is [14]:

$$\frac{x(n)-x(n-1)}{\Delta t}=\eta\cdot k\cdot\frac{v(n-1)}{R_{ON}x(n-1)+R_{OFF}\left[1-x(n-1)\right]}\cdot x(n-1)\cdot\left[1-x(n-1)\right];\; x(n=1)=x_0 \quad (6)$$

Equation (6) and the corresponding difference equations of many standard and modified memristor models are resolved in *GNU Octave* environment. The codes are available for use and comparison by the interested readers at https://github.com/StoyanKirilov/Memristor-Modeling .

D. A highly-nonlinear and modified memristor model [19]

Another representation of memristor nanostructure [19], related to the discussed modified model B_{mod} is presented in Figure 2 (a). The central doped layer has a surface, denoted by a_1. The whole structure has an area, denoted by a_2. The state variable is represented as $x = a_1 / a_2$. Figure 2 (b) presents an equivalent circuit, where G_{ON} and G_{OFF} are the ON-state and OFF-state conductances (*memductances*) [3].

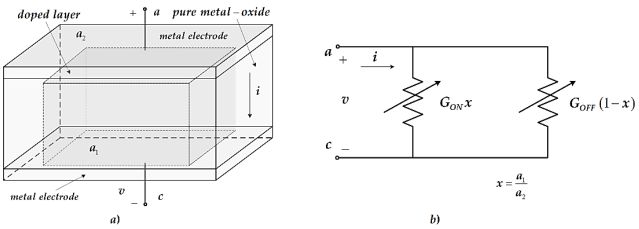

Fig. 2 (a) Memristor nanostructure [3], [19]; (b) Equivalent circuit of memristor [3], [19]

The corresponding system for the discussed *adapted* memristive model is offered by formula (7). It is built on TaO memristive model, Laiho-Lehtonen model [16] and the window function of Hann [6]: $f_H = sin^2(\pi x)$. This model includes an activation threshold - v_{thr} [19].

$$\begin{vmatrix} i = v\cdot\left[G_{OFF}(1-x)+G_{ON}x\right];\; x(t=0)=x_0 \\ \dot{x} = v^m\cdot k\sin^2(\pi x),\; |v|\ge v_{thr};\; \dot{x}=0,\; |v|<v_{thr} \end{vmatrix} \quad (7)$$

Follows a short description of the proposed GitHub library with GNU Octave memristor models.

III. GNU Octave Memristor Modelling

Before testing the proposed models, the readers must previously install GNU Octave from the web-site: https://octave.org/download . Then they could reach the proposed memristor library at the link: https://github.com/StoyanKirilov/Memristor-Modeling . A screenshot of the web-site is presented in Figure 3. It contains several folders: *Basic Circuit Element*, *Memristor Model Comparison*, *Modified Models*, *Simple Memristor Circuits* and *Standard models*. Simply click on button "*Code*" and then on "*Download zip*". After extracting the content, each file could be started by opening with Octave, and clicking on "*Run*" button in the Editor tab in GNU Octave environment.

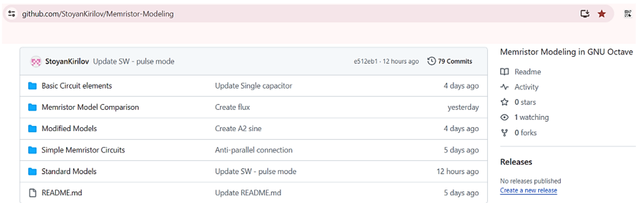

Figure 3 GitHub for GNU Octave Memristor Models Library and Simple Memristor Circuits

Models of the *elementary passive circuit components* – inductor, resistor and capacitor are included for comparison of their behaviour with the considered memory elements. In the folder "Memristor model comparison" memristor models are expressed as functions in Octave. The input signal contains the applied voltage, time and polarity coefficient, and the outputs are the state variable, memristance and current. In the folder "*Modified models*" several improved and *high-quality* memristor models [11] are presented. The frequently used standard memristor models [3] are included in the next folder. Their corresponding LTSPICE memristor models, together with many electronic devices and circuits based on memristors are freely available for utilization and comparison at the web-site: https://github.com/mladenovvaleri/Advanced-Memristor-Modeling-in-LTSpise [11].

IV. Memristor Analysis and Applications [3], [11]

Here are presented and commented the outcomes, derived after analysis of single memristors and several simple memristor-based circuits, using the discussed GNU Octave memristor library.

A. Single memristor analysis at sine-wave and pulse signals

Here, the modified memristor model B_{mod} is discussed [19]. Figure 4 presents the results obtained from the analysis of model B_{mod} [19] – formula (7) at sine mode.

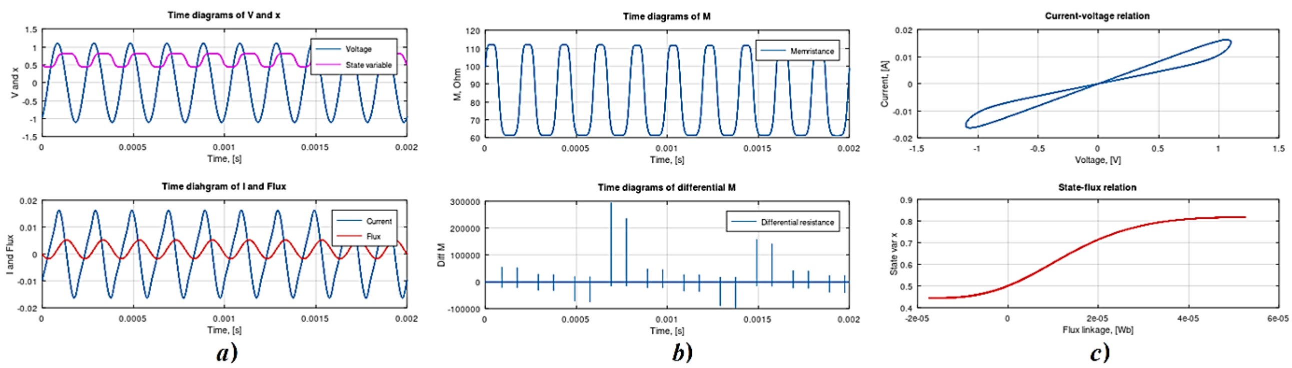

Figure 4 (a) Diagrams of state, voltage, current, flux, f = 5 kHz; (b) Time diagrams of memristance and differential resistance; (c) Voltage-current and flux-state relationships of memristor model Bmod

Time diagrams for *soft-switching mode* of voltage across memristor, state measure, current and flux linkage are presented in Figure 4 (a) for observation of highly-nonlinear properties of analyzed memristor model, operating in a soft-commutation regime [3], [19], [25]. The corresponding change of memristance and differential resistance are depicted in Figure 4 (b), for expressing the *negative differential resistance* of memristors in some regions of their operation in the time domain. The equivalent voltage-current and flux-state diagrams are given in Figure 4 (c). Additional analyses of memristor model B_{mod} express shrinking of its voltage-current pinched hysteresis curve, in accordance to main *fingerprints* of memristors [2], [3]. The obtained state-flux relation is a *single-valued* and continuously growing function, confirming proper action of memristive model in a soft-switching state [3]. Analysis of model B_{mod} (7) at pulse mode is presented in Figure 5. Adjustment of state variable and memristance by positive pulses with a frequency of 20 kHz and amplitude of 1V is presented in Figure 5 (a). The state variable has a starting value of 0.05 and it is tuned to 1 for about 100 µs. The corresponding change of memristance is from 900 Ω to about 60 Ω. Similar tuning process with negative pulses with the same frequency and amplitude is shown in Figure 5 (b). The initial measure of state quantity is 0.95 and is decreased to zero for about 100 µs. The related change of resistance is from 60 Ω to 1300 Ω. The action of model B_{mod} at bipolar impulses with amplitude of 1.5 V is presented in Figure 5 c) for observation of its behaviour at a soft-switching mode. The change of resistance is among 60 Ω and 480 Ω. The derived *switching time* is in a good agreement to analytically calculated values.

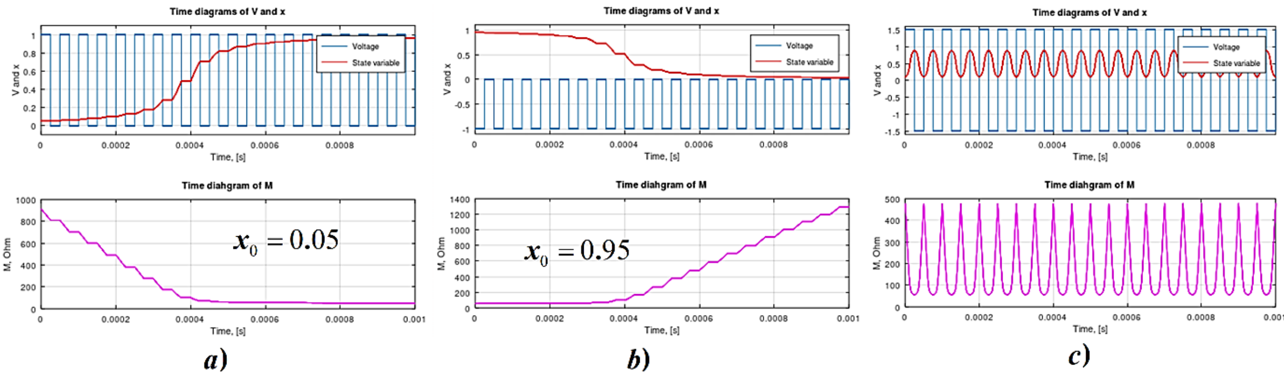

Figure 5 (a) Diagrams of memristance, voltage, and state at positive pulses for model B_{mod}; (b) diagrams of state and memristance at negative voltage pulses; (c) diagrams of x and M for bipolar voltage pulses

A. *Simple memristor-based circuits [21], [22] - analysis*

Here, some simple memristive schemes are analysed in GNU Octave environment. *Anti-series circuit* with two memristors is analyzed at sinusoidal mode, using the considered modified memristor model B_{mod}. The outcomes are presented in Figure 6 for observation and comments. Figure 6 a) presents the time graphs of voltage, the respective voltage drops across the memristors v_1 and v_2, and the variation of the state variables of memory elements x_1 and x_2.

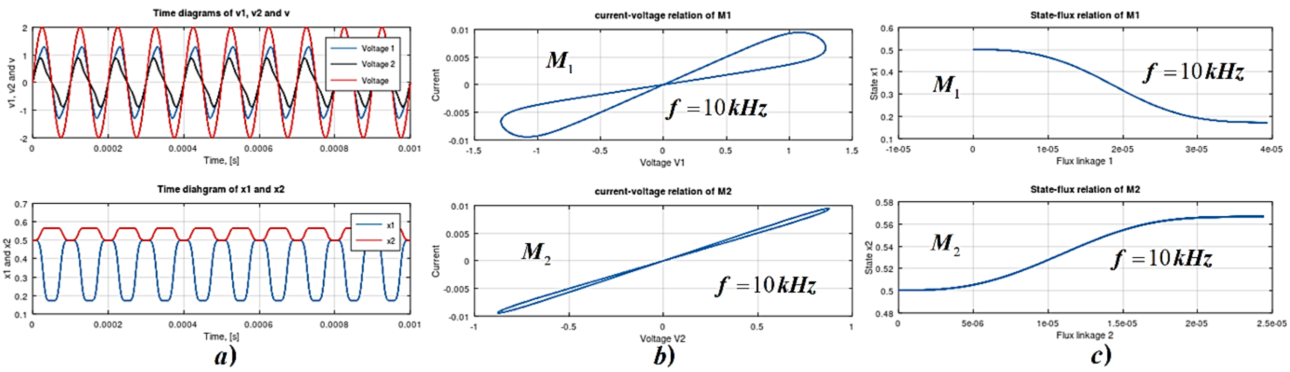

Figure 6 (a) Time graphs of voltages v_1 and v_2 across the memristors and the state variables x_1 and x_2; (b) Current-voltage relations of memristors M_1 and M_2; (c) State-flux relations of memristors M_1 and M_2

While the applied voltage v is a sinusoidal one, the voltages v_1 and v_2 are with *highly distorted form*. Due to the anti-series connections of memristors M_1 and M_2, the first state variable x_1 changes in a broader interval, with respect to the change of x_2. The corresponding current-voltage relations of M_1 and M_2 are presented in Figure 6 (b). The surface of the first hysteresis curve is larger than those of the second current-voltage relation, which is in a good agreement with the variation of the respective state variables. The derived *flux-state characteristics* are depicted in Figure 6 (c). Due to the applied polarities of memristors, the first flux-state function is a monotonically-decreasing and single-valued line, while the second one is an increasing and nonlinear curve. Low-pass and high-pass filters created by memristors are presented in Figure 7 (a) and Figure 7 (b), correspondingly [21], [22]. The input signal has a magnitude of 0.2 V, which is lesser than memristor sensitivity threshold and the memory element operates as a simple resistor [3]. In the considered case, memristor has a resistance of 1 kΩ and capacitor has a value of 1 μF. The frequency changes between 1 Hz and 1 kHz. The *amplitude-frequency responses* are analysed in GNU Octave environment and results are presented in Figure 7 (c). *Adjustment* of characteristics of memristor-based filters are realized by applying *sequences* of positive or negative voltage pulses, which are discussed in Figure 5. A comparison with LTSPICE analyses confirm the proper operation of the proposed Octave models.

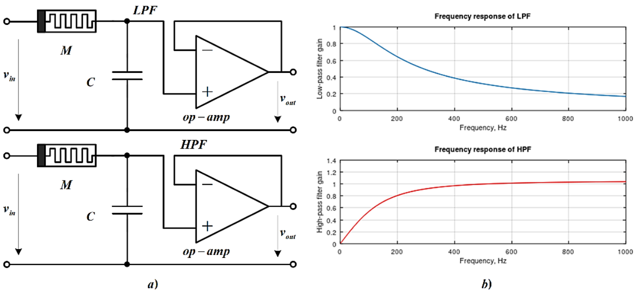

Figure 7 (a) Low-pass memristor filter (LPF) and High-pass memristor filter (HPF); (c) Frequency responses of memristor-based LPF and HPF

Analysis of *discharge of a capacitor* through a memristor is realized in GNU Octave environment and is proposed to readers for scientific and educational purposes [13]. The respective circuit is presented in Figure 8 (a) for visualization of its basic elements – the capacitor *C*, the memristor *M* and the switch '*sw*'. The capacitor has a value of 100 μF and initial voltage of 3 V. The memristor is modelled by the standard Strukov-Williams model K_1. Time graphs of current, voltage, and memristor state measure are shown in Figure 8 (b) for observation of their change with time. Flux and power dissipated in memristor are also shown in Figure 8 (b). The related voltage-current function of memristor is shown in Figure 8 (c), together with the state-flux characteristics. Owing to the change of memristance, the alteration of voltage across the capacitor is a *non-exponential curve*, in contrast to the capacitor discharge through a linear resistor. The considered circuit is analysed in LTSPICE [11] as well and the results are very similar one to another. Follows a short comparison of considered memristive models is represented, using several criteria – *accuracy*, *simulation time*, *complexity*, and *operating frequency*.

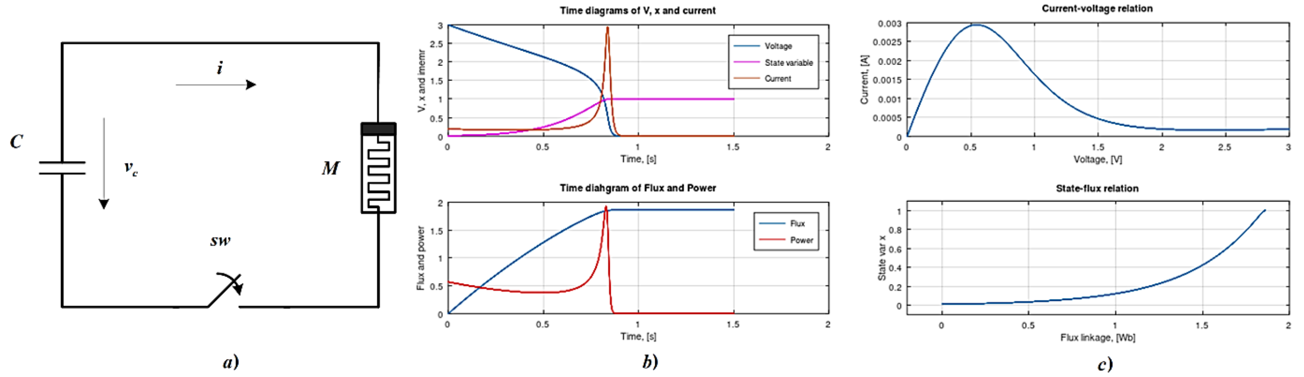

Figure 8 (a) A discharge of capacitor through a memristor; (b) time illustrations of state, voltage, flux, current, and power; (c) corresponding voltage-current relationship and state-flux characteristics

V. A Comparison of Considered Models of Metal-Oxide Memristors [3], [11]

Here, several memristor models – K_1 – K_8 [3], [11], and A_{14mod} [24], B_6 [23], and B_{mod} [19] are analysed and compared, according to the operation in Octave environment. For a brief *comparison* of discussed standard and improved memristive models, some criteria as simulation time, functioning frequency, switching properties and complexity are considered in Table 1.

Table 1. A comparison of considered memristive models – Strukov-Williams, Joglekar, Lehtonen-Laiho, Biolek, A_{14mod}, B_{mod} and B_6

Model of Memristor	Strukov-Williams	Joglekar	Biolek	Laiho-Lehtonen	A_{14mod}	B_6	B_{mod}
Switching features	moderate	moderate	satisfactory	good	good	good	Good
Frequency	small	small	moderate	high	high	high	High
Complexity	small	small	moderate	high	small	small	Small
Simulating time, *[s]*	2.23	2.28	2.32	2.86	2.41	2.33	2.31

After the comparison made among the standard and modified metal-oxide memristor models, it might be concluded that the improved models A_{14mod}, B_6 and B_{mod} are with good *switching properties*, low *complexity*, and high *operating frequency*, comparable to Laiho-Lehtonen memristor model [16]. Related to Strukov-Williams, Joglekar and Biolek memristive models, the enhanced models B_{mod} and B_6 have improved characteristics and properties with slightly stronger complexity and higher time for simulation.

VI. Conclusion

The key purpose of this work - *realization* of *GNU Octave library* with memristor models and simple memristor circuits has been realized. The related *scientific* and *educational* tasks are resolved – the main standard and modified memristive models are analysed in sine-wave and pulse mode; a *comparison* amongst the models is conducted; several humble memristor circuits – anti-series scheme, high-pass and low-pass memristor filters are analysed; a discharge of a capacitor through a memristor is studied. Additional simulations realized in LTSPICE are made and a comparison of the outcomes confirms the correctness of the proposed Octave models of memristors. The possibility for tuning the memristance of the considered models is represented by examples with applying sequences of positive and negative voltage pulses. This work gives an opportunity to readers for exploration of single memristor elements and simple memristor devices, together with the basic circuit elements in user-friendly and free GNU Octave software environment, for scientific and educational purposes. In the future, the proposed Octave library could be enriched with additional models for analysis of electronic circuits and devices.

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