Realization of a 4-port Generalized Mutator and its Application to Memstor[1] Simulations

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Abstract

In this paper, using one current conveyor and one current follower, a new realization of a 4-port circuit acting like a generalized mutator is being presented. The 4-port, under proper termination of two of the ports, behaves like a mutator and using the resulting 2-port mutator a meminductor and a memristor (memstors[1] in general) are realized by connecting a memristor and a nonlinear resistor respectively to one of the ports. With the memristor model developed by Biolek et al. also included are simulation results that verify the signature of these elements.

1. Introduction

In 1971, Leon Chua, benefiting from the rules of symmetry postulated a new element named "memristor" acronym for "MEMory ResISTOR" [1]. In 2008, 37 years later HP scientists published a paper declaring the physical realization of the memristor as a simple two-terminal device, thus linking memristor theories and applications [2]. With this realization and its mathematical model provided by HP, much research about the applications of the memristor has been done [3-5]. Not being available as an off the shelve device, lot of effort is being made to create simulation models for the memristor [6-11].

A basic approach for these simulations comes from Chua's introductory paper introducing mutators, 2-ports which transform one type of circuit element into another [1]. These mutations are achieved by preserving the original characteristic of the element which is being converted.

As described in [1] there are several types of mutators, two for converting element type X into element type Y, called *X-Y mutator* and each type can be implemented in two ways with various interconnections of controlled sources. The M-R type 1 mutator, introduced in [1], has been the first realization with a circuit consisting of two operational amplifiers, 14 transistors, and a number of passive components.

Many mutator circuits have been proposed since then for realizing memstors, and gyrator circuits for mutating memristors to memiductors or memcapacitors using combinations of several active devices such as operational transconductance amplifiers, operational amplifiers, adders-subtractors, second-generation current conveyors (CCII), with passive elements [12-18].

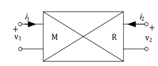
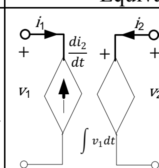
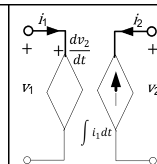
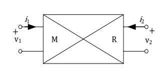
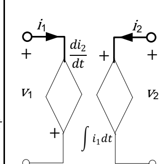
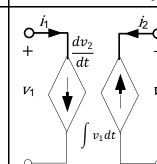
In this paper, a new realization of a 4-Port generalized mutator circuit introduced in [18], which has two important advantages, will be given. In comparison with the other mutator circuits the first advantage of this 4-port is its simple structure and the second one is the ability of transforming many kinds of circuit elements to others by suitable termination of the ports.

[1] A generic name introduced in [18] to cover the family of nonlinear memory elements namely, memristor, memcapacitor, meminductor.

2. M-R Mutators

Two types of M-R mutator realized with dependent sources and extracted from [1], are presented in Table 1.

Table 1. Two types of M-R mutators.

Type	Symbol	Equivalent Circuit	
1	 $v_1 = dv_2/dt$ $i_1 = -di_2/dt$		
2	 $v_1 = -di_2/dt$ $i_1 = dv_2/dt$		

Both type of mutators convert voltage-current characteristic of the resistor at port 2 to that of a memristor with same characteristic at port 1 but with a minor difference: for Type-1 $v_R - i_R$ characteristic is mutated to a $\varphi_M - q_M$ whereas for Type-2 to that of a $q_M - \varphi_M$ characteristic. In the sequel the generalized 4-port is so designed that both types of mutators can be obtained with proper termination of two of the ports.

General definitions of time-invariant nonlinear-resistor and memristor are given as

$$f_R(v_R, i_R) = 0 \tag{1}$$

Where v_R, i_R are the voltage and the current of the resistor and

$$f_M(\varphi_M, q_M) = 0 \tag{2}$$

Where $q_M - \varphi_M$ are the flux and electric charge of the memristor respectively.

The similarity of characteristics (1) and (2) can be observed by linear transformations of the coordinates as in (3)

$$\begin{cases} \varphi_M = K_x i_R \\ q_M = K_y V_R \end{cases} \tag{3}$$

Where K_x and K_y are real constants with values depending on how the mutator is designed.

3. Generalized Mutator 4-Port

The proposed generalized mutator circuit is designed using only one Current Follower (CF) and one second-generation Current Conveyor (CCII) as illustrated in Fig. 1.

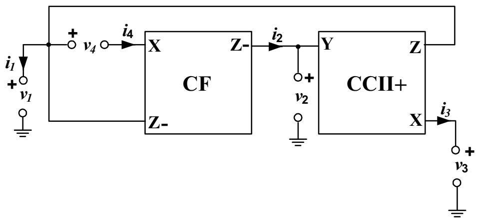


Fig. 1. Generalized 4-port mutator

This circuit was first designed for the purpose of realizing grounded or floating inductors [19]. Here, this circuit is slightly modified for the purpose of realizing a 4-port mutator for transforming basic circuit elements to memstors or mutating the memristor to other circuit elements with nonvolatile memory like meminductors and memcapacitors. As will be shown in the next sections the usage of this circuit can be extended by connecting different circuit elements to some of the ports.

The defining relations of ideal CCII+ and CF elements are given with the matrix representations as depicted in (4) and (5) respectively.

$$\begin{bmatrix} i_y \\ v_x \\ i_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} i_z \\ v_x \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} i_x \\ v_z \end{bmatrix} \quad (5)$$

According to (4) and (5) the relation between port currents and voltages of the circuit in Fig. 1 become:

$$i_1 = i_3 \quad (6)$$

$$i_4 = i_2 \quad (7)$$

$$v_1 = v_4 \quad (8)$$

$$v_2 = v_3 \quad (9)$$

In matrix form (6-10) can be rewritten as:

$$\begin{bmatrix} i_1 \\ i_2 \\ v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_3 \\ i_4 \\ v_2 \\ v_1 \end{bmatrix} \quad (10)$$

The same expression (10) is given in [18] using simple adder subtractor circuits. Two proper terminations of the ports will be considered: the first one is concerned with the realization of a meminductor from memristor (shown in the third section,) and the second one realization of a memristor from a nonlinear resistor (shown in the fourth section.)

4.1. Meminductor Realization with Memristor

As shown in Figure 2., by connecting a resistor to port 4, a capacitor to port 2, and a memristor to port 3, a nonvolatile meminductor is observed at port 1; its circuit is shown in Fig. 2.

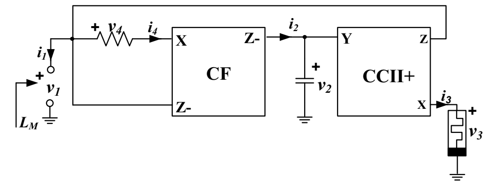


Fig. 2. Meminductor realization with memristor terminated mutator

General definitions of memristor and meminductor are given respectively by (11) and (12):

$$f_M(\varphi, q) = 0 \quad (11)$$

where f_M is the constitutive relation between the flux φ and the charge q of the memristor

$$f_L(\rho, q) = 0 \quad (12)$$

and f_L is the constitutive relation between ρ, the Time Integral of Flux (TIF), and q of the meminductor.

The similarity of characteristics (11) and (12) can be observed by linear transformations of the coordinates as in (13)

$$\begin{cases} \varphi_M = K_x \rho_L \\ q_M = K_y q_L \end{cases} \quad (13)$$

where K_x and K_y are real constants with values depending on how the mutator is designed.

According to (10),

$$i_1 = i_3 \rightarrow q_1 = q_3 \quad (14)$$

Proceeding with the analysis of the meminductor mutator circuit shown in Fig.2, the resistor at port 4 gives:

$$v_4 = R i_4 \quad (15)$$

And the capacitor at port 2 yields:

$$i_2 = C \frac{dv_2}{dt} \quad (16)$$

Using the chain of equalities (10), (16) with (17)

$$v_1 = RC \frac{dv_2}{dt} \quad (17)$$

and taking twice the time integral of both sides of (17) gives:

$$\rho_1 = R_4 C \varphi_2 \quad (18)$$

Finally replacing (18) and (14) in (11) gives:

$$f_M\left(\frac{1}{R_4 C} \rho_1, q_1\right) = 0 \quad (19)$$

By comparing (13) and (19), $K_x = \frac{1}{R_4 C}$ and $K_y = 1$ hold.

The meminductor circuit of Fig. 2 has been simulated by applying a sinusoidal current source with amplitude of 10 mA and frequency of 20 Hz to port 1. The HP memristor model with parameter values μ_v=$10^{-14} cm^2 s^{-1} v^{-1}$, R_{on}=10Ω, R_{off}=20kΩ,

R_{init}=5kΩ, and as window function Joglekar's model [20] $f(x,p) = 1 - (2x - 1)^{2p}$ with p =10 have been used [2]. The resistor and capacitor values are selected as 1kΩ and 1nF, respectively. The results of the SPICE simulation are shown in Fig. 3 confirming the meminductive signature between φ and i.

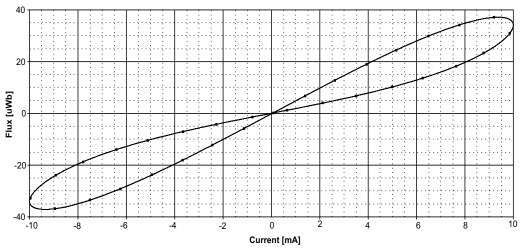


Fig. 3. $\varphi - i$ characteristics of the meminductor.

4.2. Memristor Realization with Nonlinear-Resistor

As shown in Table. 2, by connecting a capacitor to port 1, an inductor to port 2, a nonlinear-resistor to port 4, a memristor will be seen from port 3. The circuit is illustrated in Fig. 3.

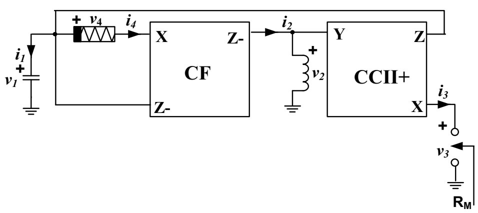


Fig. 4. Memristor realization with resistor terminated mutator

The general definition of a nonlinear-resistor is given as:

$$f_R(v_R\,, i_R) = 0 \qquad (20)$$

where f_R is the algebraic constitutive relation between the voltage v and the current i. Using the port 4 variables shown in the circuit diagram of Fig. 4

$$f_R(v_4\,, i_4) = 0 \qquad (21)$$

is obtained. Replacing v_1 for v_4 and i_2 for i_4 in (21), according to (10), gives

$$f_R(v_1\,, i_2) = 0, \qquad (22)$$

replacing $\frac{1}{C}\int \mathrm{i}_1$ instead of v_1, $\frac{1}{L}\int \mathrm{v}_2$ instead of i_2 in (22) yields

$$f_R\left(\frac{1}{C}\int i_1\,, \frac{1}{L}\int v_2\right) = 0. \qquad (23)$$

Again, replacing i_3 for i_1 and v_3 for v_2 in (23) according to (10), results in:

$$f_R\left(\frac{1}{C}\int i_3\,, \frac{1}{L}\int v_3\right) = 0 \qquad (24)$$

Finally, replacing the integrals in (24) with q_3 and φ_3 (25) is obtained.

$$f_R\left(\frac{1}{C}q_3, \frac{1}{L}\varphi_3\right) = 0 \qquad (25)$$

By comparing (3) and (25), that $K_x = C$ and $K_y = L$ can be verified.

The circuit presented in [17] and shown in Fig. 5 is used for the nonlinear resistor in Fig.4; it was implemented with one Diode (1N 4148) and two resistors. Its characteristic shown in Fig. 6 is obtained by applying a voltage source v_R .

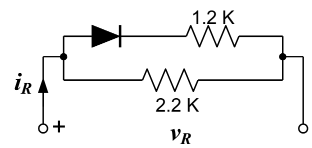


Fig. 5. Implementation on non-linear load of M-R mutators

The mutator circuit in Fig. 4 was simulated by applying a sinusoidal current source with amplitude and frequency of 1 mA and 20 Hz, respectively to port 3. The inductor and capacitor values were selected as 0.01 μH and 20 μF, respectively. Simulation results are shown in Fig. 7. which confirm the memristive relationship between v and i.

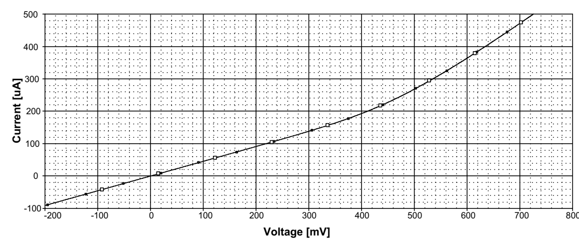


Fig. 6. $i - v$ characteristic of the non-linear resistor

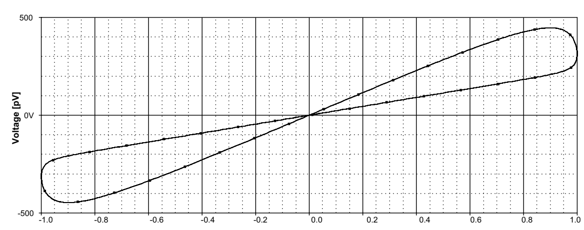


Fig. 7. $v - i$ Characteristic of the memristor mutator.

6. Conclusions

In this paper a simple 4-port circuit structure introduced in [18] for converting one circuit element type to another has been given a new design using one current conveyor and one current follower. In particular this 4-port, acting like a mutator when two of the ports are properly terminated, can be used for converting conventional circuit elements such as capacitors, resistors, inductors, and nonlinear resistors to each other as well as to memristors or transforming memristors to other nonvolatile memory elements like meminductors and memcapacitors.

Using the memristor models developed by Biolek et al. [7] and by Strukov [2], a memristor and a meminductor have been simulated via a nonlinear resistor and a memristor respectively. Results confirmed the characteristics expected of memstors.

Table 2. Different element realizations according to Fig.1 [18]

#	Ports				Output Ports		Element
	1	2	3	4			
1	-	Capacitor	Memristor	Resistor	1	-	MEMINDUCTOR
2	-	Inductor	Resistor	Memristor	1	-	MEMCAPACITOR
3	-	Inductor	Memristor	Resistor	1	-	MEMCAPACITOR
4	-	Resistor	Memristor	Inductor	1	-	MEMINDUCTOR
5	Capacitor	Memristor	-	Resistor	3	-	MEMCAPACITOR
6	Capacitor	-	Resistor	Memristor	2	-	MEMINDUCTOR
7	Inductor	-	Memristor	Resistor	2	-	MEMCAPACITOR
8	Capacitor	Inductor	-	Non Linear Resistor	3	-	MEMRISTOR
9	Inductor	Capacitor	Non Linear-Resistor	-	4	-	MEMRISTOR

7. References

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