Study of Memristive Elements Networks

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Abstract. The existence of the fourth fundamental circuit element, the memristor, was first postulated over 30 years ago by Leon Chua. The implementation of the first “modern” memristor prototype by Hewlett Packard Laboratories in 2008 initiated a great scientific interest for these unique nano-electronic devices and currently, there is a growing variety of systems that exhibit memristive behavior. However, most of the research has focused on the properties of the single devices, therefore very little is known about their response when these devices are organized into networks. In this work, the composite characteristics of memristive elements connected in network configurations are studied and the relationships among the single devices are investigated. We finally show how the threshold-dependent nonlinear memristive behavior could be elaborated to make possible the development of novel and sophisticated digital/analog memristive nano-systems.

Introduction

There had been experimental clues to the memristor’s existence all along the last two centuries. Scientists have been publishing in the literature experimental results with “strange” voltage characteristics, where one sees clearly memristance (memory-resistance), though such a material property had always been shadowed by other effects that were of primary interest \[1\]. In 1971, Leon Chua predicted that there should be a fourth element: the memristor (concatenation of “memory resistor”), joining the resistor, the capacitor, and the inductor \[2\]. Such a device would provide a relationship between magnetic flux and charge, likewise a resistor gives between voltage and current, exhibiting its unique properties primarily at the nanoscale. The reason why memristors are substantially different from the other fundamental circuit elements is that, when you turn off the power supply of the circuit, they still remember how much voltage was applied before and for how long; thus presenting a memory of their past. That’s an effect that can’t be duplicated by any circuit combination of resistors, capacitors, and inductors, which qualifies the memristor as a fundamental circuit element.

Since the realization of the first modern prototype of Chua’s memristor by Hewlett Packard Laboratories (HP Labs) \[3\], multiple applications for the device have been proposed \[4-7\]. Currently, there is a growing variety of systems that exhibit memristive behavior, as academia and industry keep on with their research and prototyping \[8\], with HP’s version of the titanium dioxide (TiO\textsubscript{2}) \[9\] substrate memristor being the most generally recognized memristor type. However, while most of the research has focused on the properties of these single nano-electronic devices \[6, 8\], very little is known about their response when they are organized into networks. When multiple memristors are connected to each other, the overall behavior of the devices becomes complicated and is difficult to predict.

In this work, we study the voltage threshold-dependent composite characteristics of memristive elements connected in regular parallel and serial configurations. Using a nonlinear memristor model \[7\] developed by the present authors, we carry out simulations and analyze the characteristics of complex memristor circuits and investigate the relationships among the single devices. Depending on their orientation (polarity), their initial condition and their internal properties, which are summarized in the actual values of the parameters of the model, their overall response turns up
totally nontrivial. We also show how composite memristive systems can be efficiently built out of individual memristive devices, presenting different electrical characteristics from their structural elements. Finally, we discuss how the threshold-dependent nonlinear memristive behavior could be elaborated and, through the proposed network implementations, make possible the development of novel digital/analog nano-circuits. The presented analysis provides intuition into the response of complex memristive networks and motivates for further elaboration of their composite dynamics for the creation of sophisticated memristive systems.

Threshold-Based Modeling of Memristive Devices

Memristive device modeling is a necessary step towards better understanding and exploitation of their unique properties. In experimentally realizable systems, memristive devices with threshold voltages seem to be the norm rather than the exception, and electronic conduction is in most cases dominated by an effective tunneling barrier-width that varies with the applied voltage [10]. In a previous work [7] we presented a memristor device model which explains the device’s memristive behavior by investigating the occurrence of quantum tunneling as the primary electronic transport mechanism. More specifically, it is a threshold-type switching model of a two-terminal voltage-controlled electrical device that exhibits memristive behavior, whose general definition is given by the following relations:

\[ I(t) = G(L, t)V_M(t) \]  
\[ L = f(V_M, t). \]  

We define as \( L \) the tunnel barrier width and also the single state variable of the system, indicating the internal memristor state. \( G \) is the device’s conductance and parameters \( I \) and \( V_M \) represent current and applied voltage, respectively. This model is based on the assumption that the switching rate of \( L \) is small/fast below/above a threshold voltage (\( V_{SET} \) or \( V_{RESET} \)), which is viewed as the minimum energy required to impose a change on the physical structure of the device. The option for assuming asymmetric threshold voltages to be applied to the SET and RESET operations, i.e. \( |V_{th,SET}| \neq |V_{th,RESET}| \), is also supported by the model. This implies the existence of different tunneling distance change rates, which can actually be attributed to the interaction of the external applied field, the internal field of the concentrated defects (e.g. charge traps, mobile ions, vacancies, etc.), and the diffusion, all acting in the same or in the opposite directions according to the applied voltage bias [3, 10]. The time derivative of the state variable in Eq. 2 is interpreted as the speed of movement of the tunnel barrier due to the applied voltage, and function \( f \) captures the highly nonlinear response of the memristor as function of the applied voltage. Although the switching behavior is definitely complex, it has been showed that it is well represented in our model. Compared to other published models [3, 10-11], our modeling approach provides intuition into these strongly nonlinear dynamical systems, comprising simple and well understood equations and avoiding the use of restrictive material-specific parameters [3, 10]. Different value-sets for all fitting parameters make possible the simulation of memristive devices with different physical properties. In the present work, the memristor device model, briefly summarized above, is used for all conducted simulations of both single memristors and of networks comprising multiple memristive elements.

Dynamics of Memristors in Regular Network Connections

The composite behavior of circuits comprising memristors connected in a serial or a parallel manner is analyzed in this section. Being associated with the totally nonlinear behavior of individual memristive elements, circuits of multiple memristors may work in very complicated way, quite difficult to predict, due to the polarity dependent nonlinear variation in the memristance of individual memristors. Here we explore the dynamics of regular network geometries containing
only memristive devices. We particularly focus on one-dimensional memristive networks with all the devices connected in series or in parallel. Depending on their internal state, their polarity and the device-specific properties represented by the model’s parameter values, even such simple compositions of memristors can prove to respond in a much unexpected manner. We employ the model summarized in the previous section and conduct our circuit simulations using the MATLAB environment. Fig. 1 illustrates the response of a single memristor under applied ac voltage according to our model. Model parameter values \([7]\) are used as given in \(\{a, b, c, m, f_0, L_0, V_{th}\} = \{5 \times 10^3, 0, 0.1, 82, 310, 5, 1\text{V}\}\) and the resulting resistance ratio is \(R_{OFF}/R_{ON} \approx 10^2\) with \(R_{OFF} \approx 200\text{K}$$ and \(R_{ON} \approx 2\text{K}$$ . We note here that, the equations of the model \([7]\) are written in such a way that when \(\{a, b\} > 0\) then a positive/negative voltage applied to the top terminal with respect to the bottom terminal, denoted by the black thick line (see inset of Fig. 1b for the corresponding schematic), always tends to increase/decrease the memristance. The characteristics demonstrated in Fig. 1 will serve as a reference when studying the composite behavior of multiple devices in the rest of this paper, under similar applied voltages of the same frequency.

Fig. 1 Simulation results from the response of the memristor model \([7]\) to a triangular ac applied voltage, showed in (a). The hysteric current-voltage \((I-V)\) characteristic is demonstrated in (b) and the corresponding change of the resistance (memristance) with time and with the applied voltage is shown in (c) and (d), respectively.

**In-Series Connection of Memristors.** Considering a single memristive device as a structural element, we here analyze the behavior of circuit branches with more than one device connected in series. For all initial state configurations we study the following characteristics: current-voltage \((I_m-V_m)\), total resistance-voltage \((R_{TOTAL}-V_m)\), current-time \((I_m-t)\), and total resistance-time \((R_{TOTAL}, t)\), where total resistance (i.e. memristance) is the sum of the individual memristances in the considered circuit branch. Starting from the smallest configuration which consists of two devices, Fig. 2 presents the set of three different polarities which a pair of serially connected memristors will likely have, as well as the simulation results for their composite response during a single period of an ac triangular applied voltage of the same frequency but with higher amplitude, compared to that of Fig. 1a. Three possible polarities are examined, namely the case when both devices are forward or reversely polarized, and the case when they are connected in a forward-reverse in-series configuration, hereinafter defined as “anti-serial” connection. Hereinafter we will refer to forward/reversely polarized memristors as FPMs/RPMs and their initial state combinations are given in the text using the following notation to define the placement of the devices as UPPER/LOWER. From the first two simulation cases illustrated in Fig. 2, one can understand that, when employing devices with identical properties (i.e. equal memristance ratios, switching rates and threshold voltages), if they are placed with the same individual polarity (here both forward or reversely polarized), then their overall behavior resembles that of a single memristor with the same.
polarity, whose properties combine the properties of the individual elements. In each one of the presented situations, the connected elements form a voltage divider circuit; thus in the case of having two FPMs initialized as OFF/OFF, since the devices are absolutely identical, the corresponding voltage drop at each device during the simulation is equal and hence both elements switch from OFF to ON simultaneously when the corresponding voltage at their terminals exceeds their threshold value. Therefore, the resulting threshold of the composite device is the sum of the individual thresholds, and the composite memristance ranges in the interval $[2 \times R_{\text{ON}}, 2 \times R_{\text{OFF}}]$; both devices are toggled from OFF to ON and vice versa when the total applied voltage exceeds $|2V|$ and the lobes of the composite hysteretic current-voltage ($I$-$V$) result smaller, mostly because of the doubled $R_{\text{ON}}$ value. The same applies for the second presented example where the circuit comprises two RPMs initialized as ON/ON. This instance evidently constitutes the opposite case of the first example of Fig. 2; thus the overall behavior is that of a composite but reversely polarized memristor. The third case of Fig. 2 summarizes the simulation results for two memristors connected in series while having opposite polarities. We will note that opposite polarities along with different initial states cause highly nontrivial composite responses to the applied voltages.

![Fig. 2 Simulation results from the composite response of two forward polarized (FPMs), reversely polarized (RPMs) or anti-serially connected memristors, during a single period of a triangular ac applied voltage. All FPMs/RPMs are initially set to the OFF/ON state.](image)

From the content of the previously presented cases it was figured out that, single memristors with opposite polarities present a flipped $I$-$V$ characteristic, and generally demonstrate reversed behavior to the applied signals; in brief, a positive applied voltage tends to switch an FPM/RPM device from OFF to ON/from ON to OFF. Therefore, during a single period of the applied ac voltage, the complementary devices will be likely changing their states in a reciprocal way. In particular, the first feature that appears from the simulation is a perfectly symmetric $I$-$V$ curve out of an asymmetric memristor $I$-$V$ curve. Here, first a positive voltage is applied creating the necessary conditions to either change the state of the RPM to OFF or to change the state of the FPM to ON. As it can be seen in the corresponding graph, when voltage reaches a particular point, the state of the FPM changes first and the current rises to very high values until the RPM finally switches to the OFF state. At this point, the initial state configuration OFF/ON of this complementary switch has been flipped to ON/OFF. Next, the circuit exhibits an ohmic behavior until the voltage reaches a specific negative value, when the RPM first changes to the ON state. As the negative voltage sweep continues, the FPM is also flipped and the circuit continues exhibiting again ohmic behavior until
the end of the voltage sweep. An important observation regarding the resulting I-V characteristic of the anti-serially connected memristors is that the current is linear with the applied voltage except in two finite voltage intervals.

Fig. 3 Simulation results from the composite response of a series of ten memristors under application of consecutive ac voltage periods. Presented examples involve: (a) half FPMs and half RPMs, (b) less FPMs and more RPMs or (c) more FPMs and less RPMs, during three voltage periods when all devices have symmetric threshold voltages. The rest of the examples refer to: half FPMs and half RPMs with (d) \((V_{\text{RESET}}, V_{\text{SET}}) = (-1V, 0.5V)\) and (e) \((V_{\text{RESET}}, V_{\text{SET}}) = (-0.5V, 1V)\) during five voltage periods. The continuously diminishing current amplitude in (e) is given within the \(I_{m-t}\) graph.

Up to this point we have thoroughly examined the dynamic behavior of circuit branches comprising at most two devices in serial or anti-serial configurations. However, appropriate functionality of memristive elements when they are combined and/or introduced to larger circuits during multiple periods of the applied voltage, proves quite intriguing and it has been also explored here. In Fig. 3 we employ a large enough number of serially connected devices, namely ten, while we appropriately adjust the applied voltage amplitude to make sure that it will cause several switching events, to finally examine their overall response in time under various conditions, during a sufficient number of consecutive ac voltage periods, namely three (a-c) or five (d-e). More
specifically, in Fig. 3a we have half of the devices being FPMs and set to the OFF state, whereas the rest of them are RPMs initially found in the ON state. The response of such circuit resembles absolutely that of the last case of Fig. 2, with the only difference that the two high-conduction intervals are dragged horizontally in the V-axis; i.e. here the transition begins when the applied voltage exceeds the resulting accumulated threshold value of the devices with the same polarity. Also, since the total $R_{ON}$ of the branch is here five times larger, the highest measured current is smaller but this difference is infinitesimal and can hardly be detected in the provided graphs because of the high enough $R_{OFF}/R_{ON}$ ratio. This is a good example showing how groups of individual devices can be effectively combined to deliver composite structures that produce combinatorial complex behavior.

Moreover, in Fig. 3b/Fig. 3c we have the same total number of devices but this time we have included less FPMs/RPMs and more RPMs/FPMs. Therefore, it can be seen that when the RPMs/FPMs outnumber the FPMs/RPMs, we can selectively widen and shorten the specific high-conduction current lobes and dominate their duration at will, maintaining the same operation. In specific, in Fig. 3b/Fig. 3c using more RPMs/FPMs has as a consequence a wider current pulse during the positive/negative sweep and a shorter current pulse during the negative/positive part of the sweep. It is worth noticing that the total resistance, after the voltage sweep is completed, always returns to its initial state, thus the examined device combinations guarantee stable function. Furthermore, Fig. 3d and Fig. 3e involve the use of asymmetric voltage thresholds (i.e. $V_{SET} \neq V_{RESET}$) for the individual devices. Particularly, in Fig. 3d we reduce the $V_{SET}$ voltage value from 1V to 0.5V, to finally have the following set of threshold voltages for all memristive components: $(V_{RESET}, V_{SET}) = (-0.5V, 0.5V)$. Although symmetric threshold voltages are recommended for better composite behavior of complementary memristors, we note here that when employing equal number of FPMs and RPMs in the circuit, smaller $V_{SET}$ delivers wider high-conduction intervals simultaneously for both the positive and the negative part of the voltage sweep. Hence, the higher the difference between $V_{RESET}$ and $V_{SET}$ is, when $|V_{RESET}| > |V_{SET}|$, the higher the duration of the conducting intervals will be. However, this does not apply to the case of having $|V_{RESET}| < |V_{SET}|$. As shown in Fig. 3e, after adjusting the respective threshold voltages to the following set of values $(V_{RESET}, V_{SET}) = (-0.5V, 1V)$, the complementary resistive behavior of the circuit was totally ruined. We deliberately run the simulation again for five consecutive periods of the applied voltage, to note that the duration of the high-conducting current lobes significantly shrinks and the maximum measured currents dramatically reduce with time. In particular, in this example they range between 244μA and 6μA as demonstrated within the $I_m$-$t$ graph of Fig. 3e, to finally find an equilibrium state after the three first sweeps. Nevertheless, no high-conduction can be then distinguished since the final effective memristance ratio significantly falls to very small values. This behavior is caused by the fact that the RESET operation, according to the used model, is completed faster due to the exponential relation between the memristance and the state variable [7] (see Fig. 1). Therefore, the devices that first change during each part of the voltage sweep are those who tend to flip their states from ON to OFF. However, the closer these devices get to the OFF state, the greater the voltage drop that corresponds to them will be (consequence of the voltage divider circuit); hence the remaining voltage that drops over the rest of the devices which should flip from OFF to ON is never sufficient (or never applied for sufficient time) and thus the switching process in never fully completed.

In the same context, we have examined the stability of the complementary switching operation for circuits comprising equal number of FPMs and RPMs, when the individual devices are arbitrarily initialized, according to the uniform distribution, to any possible intermediate memristance within the interval $[R_{ON}, R_{OFF}]$. In Fig. 4a we demonstrate the simulation results for a series of ten devices under three consecutive ac applied voltage periods. The value of the total memristance at the end of each voltage sweep cannot be foreseen and can take any intermediate value between $n \times R_{ON}$ and $n \times R_{OFF}$, where $n$ is the number of employed elements (here $n = 10$). Furthermore, after conducting multiple similar simulations, we noted that the resulting $I$-$V$ is always very similar to the presented one, where the current graph can hardly deviate significantly,
presenting always a predominating gradient. One of the first things to note is that, although the initial values of the employed devices are not given, quite surprisingly the circuit very quickly reaches a notably stable overall function. However, the circuit behavior resembles more the behavior which was presented in Fig. 2b and Fig. 2c where one of the high-current lobes is found larger than the other. Nevertheless, the same does not apply if we select to restrict the range of available initial memristance values for the individual elements to a much shorter range around the mean value, i.e. \((R_{ON}+R_{OFF})/2\). It can be seen that the circuit from the beginning operates stably and the high-current lobes are better distinguished, with the overall function notably resembling that of Fig. 2a and Fig. 2d. Hence, we conclude that in such circuits, except for the distribution of FPMs and RPMs, initialization of the individual memristive elements plays a significant role as well in the programming procedure towards a specific desired complementary operation.

In-Parallel Connection of Memristors. Once again, considering a single memristive device as a structural element, we analyze the behavior of circuit branches with more than one device connected, this time in parallel. Starting from the smallest configuration, which consists of two devices, Fig. 5 presents the set of three different examined polarities which the memristors will likely have. More specifically, we are interested in the composite response of a pair of parallel memristors with the same polarity, i.e. either being FPMs or RPMs, or in anti-parallel configuration, under ac triangular applied voltage. In this case, since the same voltage is simultaneously applied to all memristors, we do not expect to notice any shift in the threshold voltages that dominate the composite behavior of the memristive combinations, compared to the response of the individual elements. However, unlike the series connection, in the parallel connection the lower resistance values \(R_{ON}\) will dominate the total resistance of each branch.

In Fig. 5a and in Fig. 5b, both FPMs/RPMs switch simultaneously from the OFF to the ON/OFF state and vice versa, and the resulting I-V resembles that of the single memristor of Fig. 1, only that this time the maximum current is doubled because the total memristance when both devices are found at the ON state is \(R_{ON}/2\) \((R_{ON}||R_{ON})\). The only difference between employing FPMs or RPMs is that the composite device functions in the opposite way. Therefore, it can be concluded that by connecting identical memristors with the same polarity in parallel, we reproduce the individual memristive behavior and achieve higher total current values. Of course, the higher achieved value for the composite memristance is also lower, but the difference in the current can be hardly noticed because of the high enough selected memristance ratio. In the last presented case
shown in Fig. 5c, the simulation results of a pair of anti-parallel memristors are shown. Compared to the previously described cases, we notice a significant difference in the overall composite memristance switching; the memristance is kept at low values except for certain intervals which are denoted by spike-like transitions. This is because, as we have concluded before, devices with opposite polarities have opposite switching characteristics; each time a voltage is applied, one of the devices tends to switch to the OFF state and the other to the ON state, respectively. Hence, there will almost always be a device at the ON state, dominating this way the total memristance. The resulting $I-V$ characteristic looks like a truncated Ohm’s law; the current is linear with the voltage exclusive of two finite intervals, where both devices are at the OFF state. The OFF/OFF state combination is found only as an intermediate state during the state transitions of the circuit components. Of course, proper selection of the threshold voltages will either broaden or shorten the period of duration of the OFF/OFF combination, as we will see in the rest of this subsection. This behavior is opposite to the $I-V$ characteristic of the in-series complementary configuration of Fig. 2.

![Fig. 5](image)

**Fig. 5** Simulation results from the composite response of (a) two forward polarized (FPMs), (b) two reversely polarized (RPMs) or (c) two anti-parallel connected memristors, during a single period of a triangular ac applied voltage. All FPMs/RPMs are initially set again to the OFF/ON state.

Having already noticed that identical memristors/group of memristors with opposite polarities can deliver symmetric individual/network behaviors, it is of great interest to explore their composite response when such devices are connected together. Although only a pair of memristor devices was used to illustrate functionality of anti-parallel memristors, the same principles apply for more than two simultaneously connected devices. The only practical difference lies in the magnitude of the total current observed, which depends on the instant combination of the memristances. Likewise in the in-series connection, we again employ ten elements and examine their composite behavior during a sufficient number (here three) of consecutive ac voltage periods. In specific, in Fig. 6a we use equal number of FPMs and RPMs with identical symmetric threshold voltages, and the simulation results are the same with the last case of Fig. 5, only that this time the measured current results five times larger; this is a consequence of the submultiple limits of the composite memristance values. Therefore we can conclude that, by introducing more devices to the anti-parallel configuration, while maintaining equal the number of FPMs and RPMs, we can reproduce the same function but with higher achieved currents and smaller composite resistance ratios. In Fig. 6b and Fig. 6c we notice how we can create multiple dominating gradients in the $I-V$ characteristic by choosing a different distribution between FPMs and RPMs. It can be seen that the finite voltage intervals, when all devices are found at the OFF state, are maintained. However, the initial and the
The final gradients of the current before and after the aforementioned intervals result different. Particularly, Fig. 6b/Fig. 6c involves less FPMs/RPMs and more RPMs/FPMs. Therefore, with such configurations we can have programmable switches capable of three different conduction levels, i.e., high, medium, or (almost) no conductive, depending on the amplitude of the applied voltage. In Fig. 6d and Fig. 6e we investigate again the use of asymmetric voltage thresholds (i.e., \( V_{\text{SET}} \neq V_{\text{RESET}} \)) for the individual devices, employing equal number of FPMs and RPMs. Particularly, in Fig. 6d/Fig. 6e we have the following set of threshold voltages for all memristive components: \( V_{\text{RESET}} = -1.5\text{V} \) and \( V_{\text{SET}} = 0.5\text{V} \), \( V_{\text{RESET}} = -0.5\text{V} \) and \( V_{\text{SET}} = 1.0\text{V} \). Surprisingly, we note that with \(|V_{\text{RESET}}| > |V_{\text{SET}}|\) the function of anti-parallel devices is transformed to that of anti-serial elements (see Fig. 3a and Fig. 3d).

![Graphs showing simulation results](image)

**Fig. 6** Simulation results from the composite response of ten anti-parallel memristors under application of three consecutive ac voltage periods. Presented examples involve: (a) Half FPMs and half RPMs, (b) less FPMs and more RPMs or (c) more FPMs and less RPMs, when all devices have symmetric threshold voltages. The rest of the examples refer to: Half FPMs and half RPMs with (d) \((V_{\text{RESET}}, V_{\text{SET}}) = (-1.5\text{V}, 0.5\text{V})\) and (e) \((V_{\text{RESET}}, V_{\text{SET}}) = (-0.5\text{V}, 1\text{V})\).
Nevertheless, in this case the measured currents are much lower compared to those of anti-serial memristors due to the lower effective memristance ratio. Finally, in Fig. 6e we adjust the threshold voltages accordingly to values where $|V_{\text{RESET}}| < |V_{\text{SET}}|$. This particular practice results in broader low-conduction intervals in the $I$-$V$ characteristic. Therefore, unlike the anti-serial configurations, where symmetric threshold voltages are recommended, here it seems that asymmetric thresholds facilitate better distinction of the low-conduction periods, compared to the case shown in Fig. 6a. Furthermore, likewise in the anti-serially connected devices, we have examined the stability of the anti-parallel switches when the individual devices are arbitrarily initialized to any possible intermediate memristance within the interval $[R_{\text{ON}}, R_{\text{OFF}}]$. However, this device combination always renders stable operation from the beginning, regardless of the initialization of single devices.

Conclusions

In this work we explored the complex characteristics of nano-electronic memristive behavior that arise in networks of memristive elements. Series and parallel configurations of multiple elements were examined and intriguing responses were discovered, proving that such device combinations of single structural elements could be accordingly elaborated to render unique and stable combinatorial responses under certain ac applied signals. The presented analysis will serve scientists and academics from various research areas who wish to exploit the proposed combinational properties of memristive configurations for the development of novel analog/digital programmable circuits and systems.

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References

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