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PAPERS

Memristor-based series voltage regulators

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Series linear voltage regulators are integrated circuits commonly used to make adjustable voltage sources. When used with potentiometers, these regulators are able to give adjustable voltage at the output. Memristor is a new nonlinear circuit element which came out in the last decade. It is able to provide electronically adjustable resistance. If a memristor is fed with a voltage over the threshold and it is not under saturation, its resistance also called memristance is dependent on the integration of its current, also called memristor charge. Memristor shows promise for different types and lots of digital and analog applications. In this paper, memristor-based series voltage regulator topologies are suggested and they are examined using parameters and simulations. Some design criteria have been given for the memristor-based series voltage regulators.

K e y w o r d s: memristor, voltage regulators, analog applications, circuit analysis, thin films phase

1 Introduction

In 1971, Chua has predicted that another circuit element, a charge dependent resistor, should have existed, he went so far to claim it as a fundamental circuit element, and he named it memristor [1]. He later claimed that systems with similar properties to memristors existed and gave examples to them [2]. No ideal memristor has been found yet. In 2008, a TiO_2 thin-film system sandwiched between platinum contacts are shown to behave as if memristors for some part of their operation region [3]. It is actually a memristive system according to the definition given in [2]. Nowadays, non-ideal memristors are also called memristors [4]. Some review papers on memristive systems can be found in [5-7]. The new nonlinear circuit component is currently under research for analog applications such as programmable amplifiers, filters and oscillators [8-25]. It is expected that when the new component is improved enough, it will be available on the market and memristor-based applications will follow after [26,27].

According to news, memristor is about to appear in the market [26-27]. Thats why it is important to find new application areas for the new circuit element. In [1], Chua had claimed that it might be only possible to use a memristor in AC not in DC since its flux which is its voltages integration with respect to time would go to infinity when a DC voltage is applied. The thin-film ionic memristors have a saturation mechanism, *ie* its memristance can only take values from on resistance to off resistance [3]. This saturation mechanism allows DC applications of memristor possible. Yet, they are still limited, mostly memory or logic circuit applications of memristor reported in the literature [6]. A memristor-based timer is examined in [28]. Although the memristors in this applications also operate under DC for a while however to reset them a negative voltage higher than their threshold voltages is applied. In [29], it is reported that a memristor which operates under DC can be used as a temperature sensor.

Linear Voltage Regulators are commonly used integrated circuits to make constant voltage sources, *ie* 7805 is the most famous of them [30]. When used with potentiometers, these regulators are also able to give adjustable voltage at output, *ie* LM317 is one of the most famous ones [30]. To the best of our knowledge, there is no memristor-based series voltage regulator reported in literature. If one of the resistors in the voltage dividers of the linear regulators are to be replaced with a memristor, a memristor-based voltage regulator can be obtained. The memristor would behave as an electronically adjustable resistor. In this study, for the first time in literature, a few memristor-based series voltage regulators are suggested, analyzed using circuit and memristor parameters, and simulated using the Spice model given in [31]. It is possible to electronically tune memristors used in such a memristor-based linear voltage regulator, perhaps with pulses produced with a microcontroller or a microprocessor circuit.

Design criteria are given for how to design them considering memristor and the other circuit elements. Also a spice model of a memristor model given [31] is used to simulate its behavior under and above the threshold voltage. LTspice program is used for circuit simulations. Importance of the threshold voltage is highlighted for a

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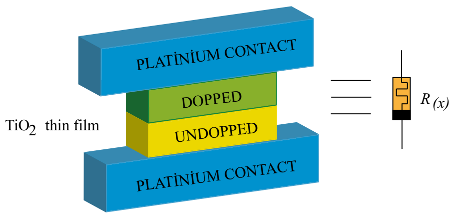

Fig. 1. TiO_2 Memristor topology

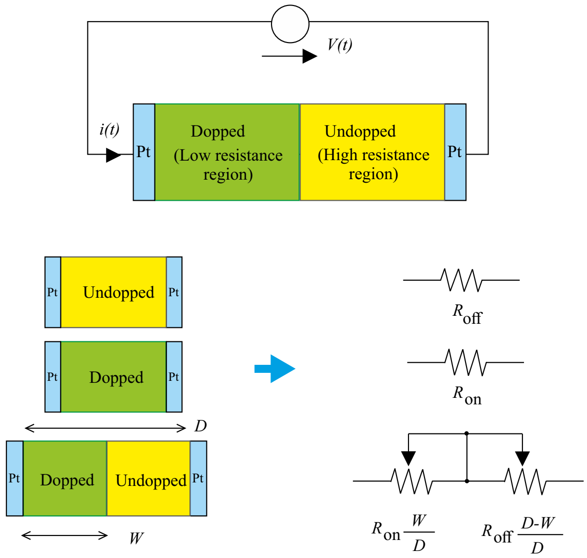

Fig. 2. TiO_2 Memristor and its equivalent circuit [3]

good design and the given criteria is examined using simulations.

2 The TiO_2 memristor nonlinear drift model

The topology of a thin film TiO_2 memristor is shown in Fig. 1. The thin film TiO_2 memristor is made of a titanium dioxide region which is placed between platinum contacts as shown in Fig. 1. The equivalent circuit of a thin film TiO_2 memristor is shown in Fig. 2.

If a current flows through the thin-film TiO_2 memristor in positive direction for a time higher than its resistive switching time [3], the oxygen ions become completely doped in TiO_2 region and its resistance takes its minimum resistance value possible (R_{on}) as shown in Fig. 2. When a current flows through the thin-film TiO_2 memristor in negative direction for a time higher than its resistive switching time, the oxygen ions are not doped at all in TiO_2 region and its resistance takes the maximum resistance value possible (R_{off}) as shown in Fig. 2. If both doped and undoped regions coexist, two potentiometers can be used to model the equivalent circuit of the TiO_2 memristor which is shown in Fig. 2.

There are different types of memristor models given in literature [3], [31-34]. Window functions are used to model memristors [3], [31-33]. Biolek function is superior to some of the models since it prevents sticking at the boundaries by having a current and current polarity dependent switching mechanism [32]. Some memristors are reported to have considerable threshold voltages and there are some memristor models with symmetric and asymmetric thresholds [9], [33-34]. Under threshold voltage, the memristor resistance or resistance can be assumed to stay constant since the boundary of the low and high resistance regions do not move. If a voltage higher than its threshold voltage is applied to a memristor, its memristance changes. A memristor model with threshold and nonlinear dopant drift is given in [33] and it is used for simulations in this paper. Its window function does not only depend on the variable x but also on its current. Memristor's memristance starts varying when its voltage is higher than its threshold voltage.

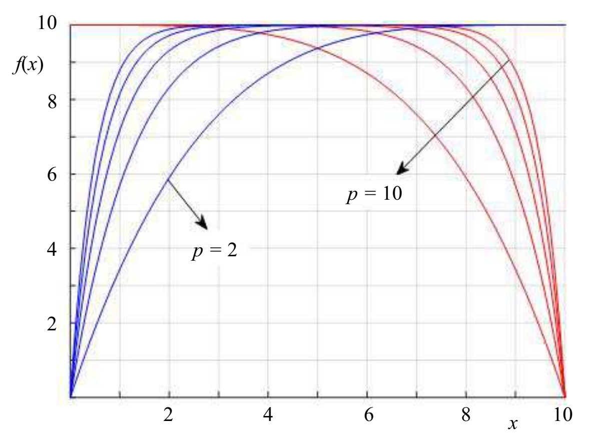

Fig. 3. The window function for 5 different integer p values [31]

The memristor model in [33] is given as,

$$V_{\mathrm{m}}(t) = R(x) i_{\mathrm{m}}(t) \tag{1}$$

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \begin{cases} \dfrac{\mu_v i_{\mathrm{m}}(t) R_{\mathrm{on}}}{D^2} f(x,i), & V_{\mathrm{TH}} \le V \\ 0, & -V_{\mathrm{TH}} \le V < V_{\mathrm{TH}} \\ \dfrac{\mu_v i_{\mathrm{m}}(t) R_{\mathrm{on}}}{D^2} f(x,i), & V < -V_{\mathrm{TH}} \end{cases} \tag{2}$$

where $x = w/D$, and w is the oxidized length of memristor, $R(x)$ is the memristor memristance, D is the physical length of memristor, μ_{v} is the mobility coefficient, $i(t)$ is the memristor current, R_{on} is the minimum resistance value of memristor, V_{TH} is the threshold voltage of memristor, $f(x,i)$ is the window function.

The threshold voltage of the memristor given in [33] is less than 1 V (approximately 0.58 V). In this study, it is assumed that ten of the memristors are connected in series to obtain an equivalent memristor with a threshold of 5.8 Volts.

According to (2), the memristor resistance does not change if the voltage applied is under its threshold voltage.

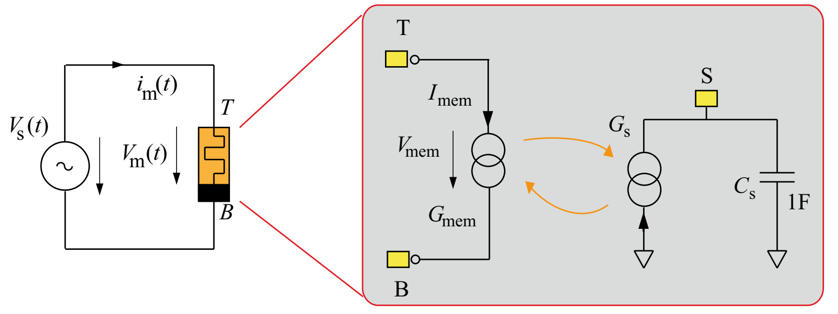

Fig. 4. Memristor excited with a sinusoidal signal

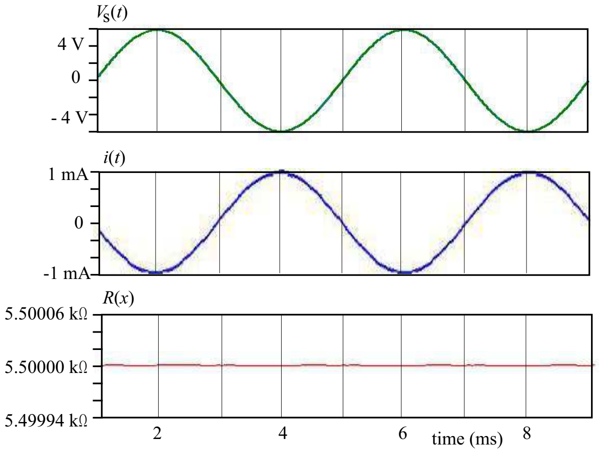

Fig. 5. Voltage, current and memristance curve of memristor under threshold voltage

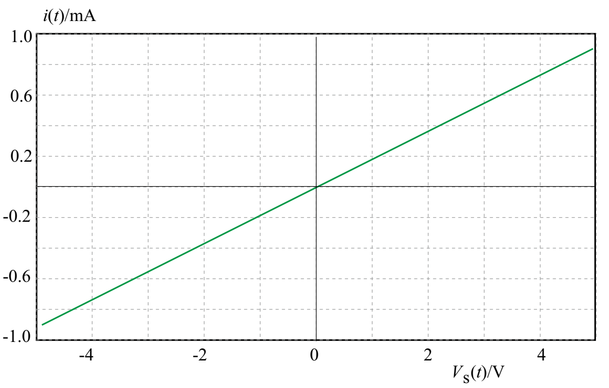

Fig. 6. Voltage-current curve of memristor under threshold voltage

The memristor resistance as a function of x is

$$R(x) = R_{\rm off} - (R_{\rm off} - R_{\rm on})x \tag{3}$$

Window functions explain the nonlinear drift behavior of ions of memristors. The window function $f(x,i)$ in (2) is given as

$$f(x,i) = 1 - \big(x - stp(-i)\big)^{2p} \tag{4}$$

where p is power of window function which is an as integer number, and i is the memristor curren. According to the model in [31], its resistance ranges from $R_{\rm on}$ and $R_{\rm off}$, which is the maximum resistance value of the memristor. In other words,

$$R_{\rm off} \geq R(x) \geq R_{\rm on} \tag{5}$$

The window function given in [31] is drawn in Fig. 3 for 5 different p values. The memristor parameters are given in Tab. 1.

Table 1. Parameters of memristor model

Minimum resistance	$R_{\rm on}$	1 kΩ
Maximum resistance	$R_{\rm off}$	10 kΩ
Window function power	p	10
State variable initial value	x_0	0.5
The dopant mobility	$_{\rm v}$	$0.04\ {\rm m^2/(Vs)}$
Length of element	D	$16\,\mu$m
Threshold voltage	$V_{\rm TH}$	$10 \times 0.58 = 5.8$ V

The memristor was modelled in LTspice. Circuit of the AC excited memristor and its macromodel can be seen in Fig. 4. $G_{\rm mem}$ is representing memristor, G_x and C_x are a current source and a capacitor to calculate state variable.

Its zero-crossing hysteresis loop is shown in Fig. 6 under threshold voltage. Under the threshold voltage, its voltage-current characteristic is a line as shown in Fig. 6 since the memristor memristance does not change.

In the second case, a voltage higher than its threshold voltage, which is equal to $V_{\rm s}(t) = 8\sin(400\pi t)$, is applied to the memristor. Its voltage, current and memristance waveforms are shown in Fig. 7. While the memristor memristance is changing, its current is not sinusoidal as shown in Fig. 7 if memristor is not under saturation, *ie* x is between 0 and 1. Its zero-crossing hysteresis loop is shown in Fig. 8 above the threshold voltage. The memristor model is also to be used in the fourth section for the simulations.

3 Conventional and memristor-based series voltage regulators

In this section, the memristor-based series linear voltage regulator schematics are given. A regulator is an analog circuit which produces an almost constant voltage at

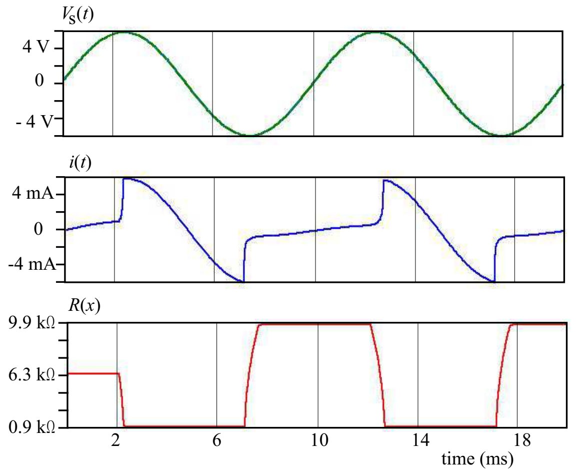

Fig. 7. Voltage, current and memristance curve of memristor above the threshold voltage

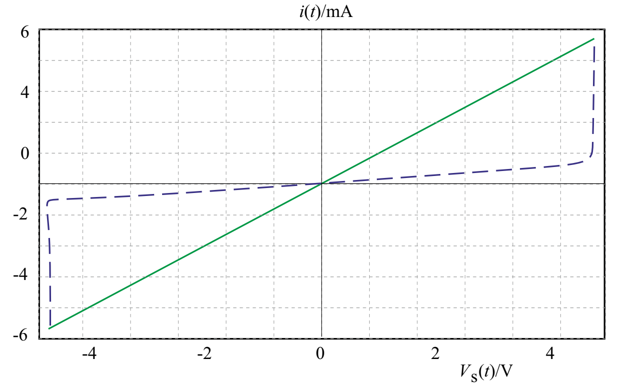

Fig. 8. Current-voltage hysteresis loop of the memristor excited with a voltage higher than its

the output V_o which is always less than the input voltage V_i with a ripple. The simplest voltage regulator made of a transistor, a resistor and a Zener diode is called a series voltage regulator its output voltage

$$V_o = V_z - V_{BE} \tag{6}$$

is shown in Fig. 9(a). Hhere V_{BE} is the diode base-emitter voltage and is around 0.7 V for silicon diodes. This circuit operates in a limited range due to its dependency on Zener current and Zener voltage. More sophisticated voltage regulators have additional circuit components to keep V_{BE} constant for a better voltage regulation and temperature compensation. Using an OpAmp, the Zener dynamics can be isolated from the regulator output. Such a circuit is shown in Fig. 9(b) and, due to having a potentiometer, the output voltage is adjustable now

$$V_o = V_z\big(1 + \frac{R_2}{R_1}\big) \tag{7}$$

By employing a memristor and a resistor instead of using a potentiometer, electronically tunable memristor-based voltage regulators can be done as shown in Fig. s 9(c) and 9(d). If the memristor replaces R_2 in Fig. 9(b), the topology is called memristor-based series voltage regulator A (MBSVG-A) as shown in Fig. 9(c). Its output voltage is given as

$$V_o = V_z\big(1 + \frac{R(x)}{R_1}\big) \tag{8}$$

If the memristor replaces R_1 in Figure 9(b), the topology is called memristor-based series voltage regulator B (MBSVG-B) as shown in Figure 9(d). Its output voltage is given as,

$$V_o = V_z\big(1 + \frac{R_1}{R(x)}\big) \tag{9}$$

Complementary connected memristors or resistive switches with a midpoint, usually used in memory applications [33], can also be used to obtain another type memristor-based series voltage regulator called MBSVG-C as shown in Figure 9. Its output voltage is given as,

$$V_o = V_z\big(1 + \frac{R_2(x)}{R_1(x)}\big) \tag{10}$$

MBSVG-C is more complex than the other topologies to examine due to two state variables. It is not considered more in this paper.

A memristor's memristance can be tuned applying programming pulses which can be either positive or negative [7-14]. A circuit which can produce such pulses to tune MBSVG-B is shown in Fig. 10.

4 Design criteria

In this section, design criteria for all three topologies of the memristor-based voltage regulators introduced in the previous section are given. For all regulators given in Fig. 9, the resistor R_s should be chosen by considering the maximum current of the Zener diode $I_{z,\max}$, the input voltage V_{in} and the Zener voltage V_Z

$$\frac{V_{in} - V_z}{R_S} \le I_{z,\max} \tag{11}$$

$$R_S \ge \frac{V_{in} - V_z}{I_{z,\max}} \tag{12}$$

Also, for normal operation of all the regulators

$$V_{in} \ge V_{out} + V_{sat} \tag{13}$$

where V_{sat} is the maximum saturation voltage of the transistor.

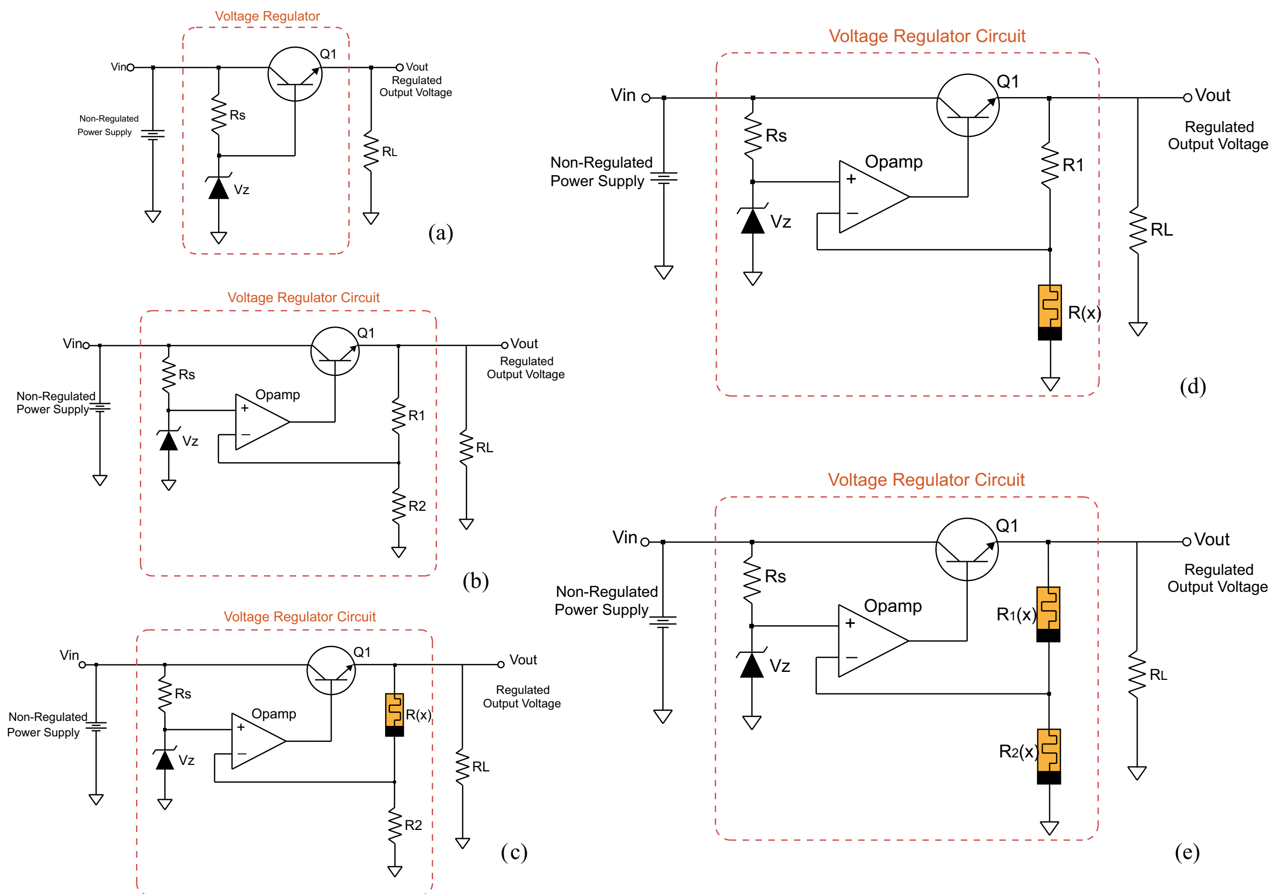

Fig. 9. (a) – Zener diode-based voltage regulator, (b) – Zener diode-based voltage regulator with an OpAmp, (c) – MBSVG-A, (d) – MBSVG-B, (e) – MBSVG-C

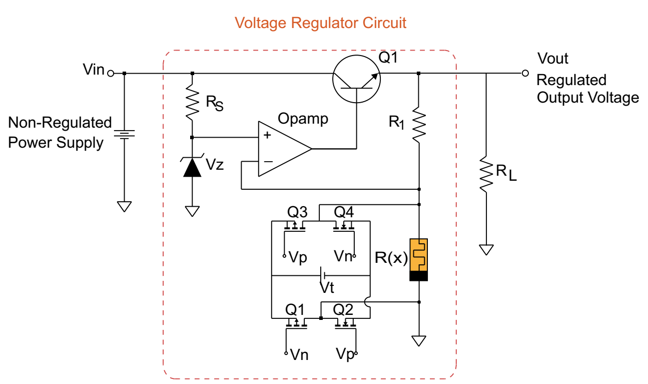

Fig. 10. MBSVG-B with a tuning circuit

4.1 Criteria for MBSVG-A

In MBSVG-A and MBSVG-B circuits, the output or the load voltage is given as,

$$V_{\mathrm{out}} = V_{R1} + V_X \tag{14}$$

Where V_X is the voltage across the memristor used. Due to the opamp, in the MBSVG-A circuit

$$V_{R2} = V_{\mathrm{Z}} \tag{15}$$

Therefore, the output voltage

$$V_{\mathrm{out}} = V_{\mathrm{Z}}\big(1 + \frac{R_X}{R_1}\big) \tag{16}$$

For a good regulation of the output voltage of the MBSVG-A, the voltage across the memristor should be less than its threshold voltage

$$V_X \le V_{\mathrm{TH}} \tag{17}$$

The input voltage must satisfy the following inequality

$$V_{\mathrm{in}} \ge V_{\mathrm{TH}} + V_{\mathrm{z}} + V_{\mathrm{sat}} \tag{18}$$

Therefore, the following must also be true for output voltage except during tuning of memristor resistance:

$$V_{\mathrm{out}} \le V_Z + V_{\mathrm{TH}} \tag{19}$$

$$V_Z\big(1 + \frac{R(x)}{R_1}\big) \le V_Z + V_{\mathrm{TH}} \tag{20}$$

Therefore, inequality is obtained

$$\frac{R(x)}{R_1} V_{\mathrm{z}} \le V_{\mathrm{TH}} \tag{21}$$

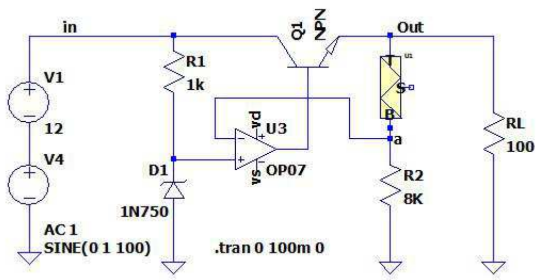

Fig. 11. LTspice schematic of the mbsvg-a voltage regulator

Since the maximum value of $R(x)$ is equal to R_{off}

$$\frac{R_{\text{off}}}{R_1} V_z \leq V_{\text{TH}} \tag{22}$$

The resistor R_1 can be chosen as,

$$\frac{V_Z}{V_{\text{TH}}} R_{\text{off}} \leq R_1 \tag{23}$$

If $R_1 >> R_{\text{on}}$, The minimum output voltage is almost equal to the Zener voltage

$$V_{\text{out}} \cong V_z \tag{24}$$

Therefore, the output voltage range is,

$$V_z \leq V_{\text{out}} \leq V_Z + V_{\text{TH}} \tag{25}$$

4.2 Criteria for MBSVG-B

Under normal operation, in Figure 9(d), the memristor voltage is equal to the Zener voltage

$$V_x = V_z \tag{26}$$

Therefore, the following is also true. The memristor voltage should be less than or equal to the Zener diode

$$V_X \leq V_Z \tag{27}$$

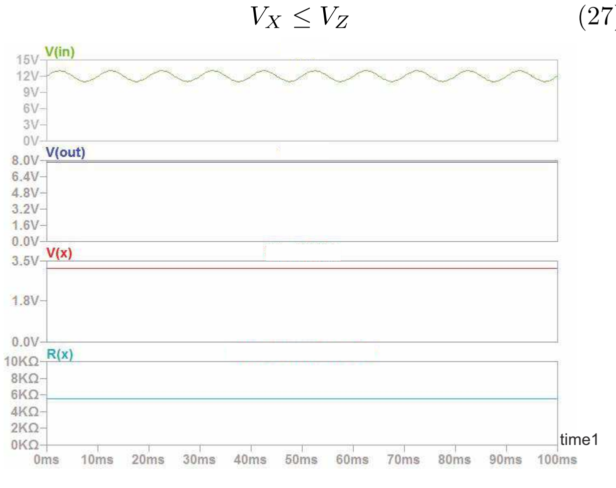

Fig. 12. MBSVG-A waveforms under normal operation mode:(a)– the input voltage,(b)– the output voltage,(c)– the memristor voltage,(d)– the memristor resistance

Considering noises, the condition must be satisfied

$$V_Z < V_{\text{TH}} \tag{28}$$

The output voltage is given as,

$$V_{\text{out}} = V_R 1 + V_X = V_z + V_R 1 \tag{29}$$

Combining (22) and (9)

$$V_{\text{out}} = V_Z \big(1 + \frac{R_1}{R(x)}\big) \tag{30}$$

$$V_{R1} = V_Z \frac{R_1}{R(x)} \tag{31}$$

V_{R1} is inversely proportional to the memristor's memristance value. If its memristance takes the minimum value R_{on}, V_{R1} becomes maximum. If its memristance takes the maximum value R_{off}, V_{R1} becomes minimum.

Therefore, the output voltage range is,

$$V_z \big(1 + \frac{R_1}{R_{\text{off}}}\big) \leq V_{\text{out}} \leq V_Z \big(1 + \frac{R_1}{R_{\text{on}}}\big) \tag{32}$$

When resistance value of R_1 is chosen high, output voltage of circuit becomes high voltage limit of the regulator. When resistance value of R_1 is chosen low, output voltage of circuit becomes low voltage limit of the regulator. If the desired maximum output voltage $V_Z(1+R_1/R_{\text{off}}) \leq V_{\text{out,max}}$ is considered

$$R_1 = R_{\text{on}} \big(\frac{V_{\text{out}}, \max)}{V_z} - 1\big) \tag{33}$$

If memristor's maximum memristance is chosen as $R_1 << R_{\text{off}}$, the output voltage range can be given as

$$V_z \cong V_{\text{out}} \leq V_Z \big(1 + \frac{R_1}{R_{\text{on}}}\big) \tag{34}$$

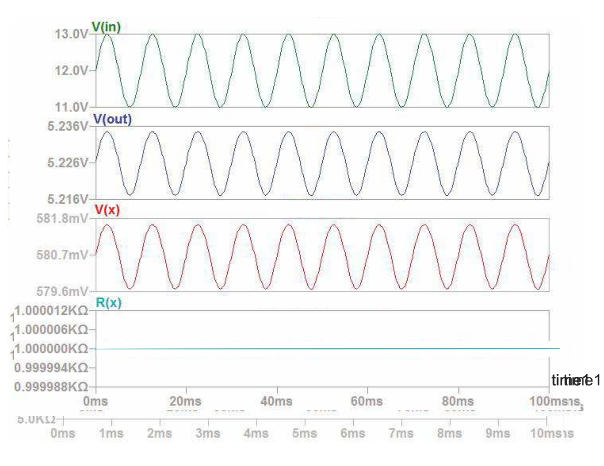

Fig. 13. MBSVG-A zoomed waveforms under normal operation mode:(a)– the input voltage,(b)– the output voltage,(c)– the memristor voltage,(d)– the memristor resistance

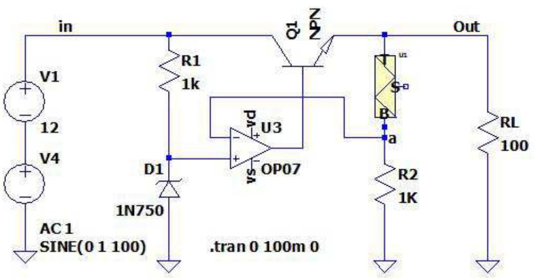

Fig. 14. LTspice schematic of the MBSVG-A voltage regulator for R2 = 1 kΩ

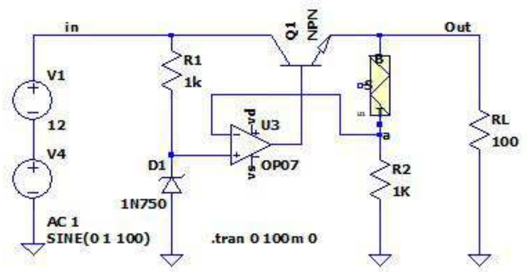

Fig. 16. The MBSVG-A regulator with the reversed memristor

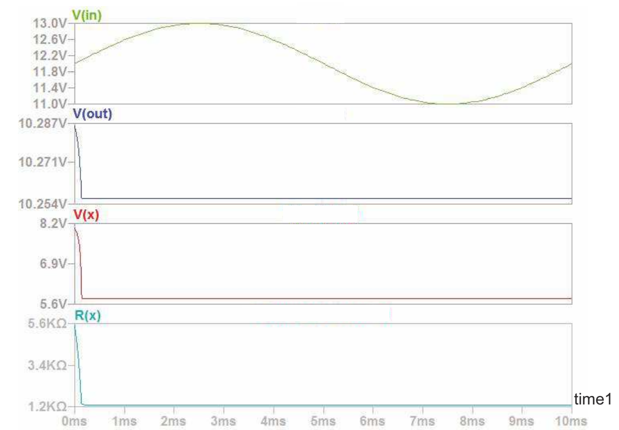

Fig. 15. MBSVG-A waveforms under abnormal or failure operation mode: (a) – the input voltage, (b) – the output voltage, (c) – the memristor voltage, (d) – the memristor resistance

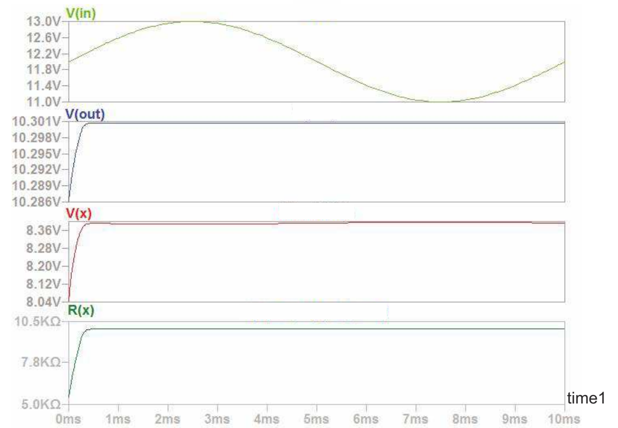

Fig. 17. When the memristor polarity is reversed, MBSVG-A waveforms under abnormal or failure operation mode: (a) – the input voltage, (b) – the output voltage, (c) – the memristor voltage, (d) – the memristor resistance

4.3 Criteria for MBSVG-C

MBSVG-C is more complex than the other topologies to examine due to two state variables. It is not considered more in this paper.

5 Simulations

Due to space considerations, only the MBSVG-A is simulated in this section using LTspice with the memristor model given in the second section. The schematic of the MBSVG-A voltage regulator is shown in Fig. 11.

5.1 The behavior of the MBSVG-A voltage regulator under threshold voltage or normal mode of operation

The input voltage, the output voltage, the memristor voltage, the memristor resistance obtained from the simulations for an input voltage of $V_{\rm in}(t) = 12 + 1\ \sin(200\pi t)$ are shown in Fig. 12. Zoomed waveforms are shown in Fig. 13. The regulator circuit operates properly since the memristor voltage does not reach its threshold voltage as seen in Fig. 12(c) and Fig. 13(c). This is called normal operation mode.

5.2 The behavior of the voltage regulator above threshold voltage or abnormal(failure)mode of operation

Memristor has a memory owing to its memristance value. If memristor has a voltage higher than its threshold voltage, its memristance or its memory is destroyed. If an input voltage which results in a memristor voltage higher than its threshold voltage is applied to the input voltage, which is equal to $V_{\rm in}(t) = 12 + 1\ \sin(200\pi t)$, this results in destruction of the memristor variable $x(t)$ and the circuit does not operate as desired. R_2 is equal to 1 kΩ in this case as shown in Fig. 14. The circuit waveforms for this case is shown in Fig. 15. That is why precautions should be taken not to allow this happening. This is called abnormal or failure mode of operation.

The polarity of memristor is also imperative. It can also result in an abnormal mode of operation. The polarity of the memristor is reversed in the regulator circuit as shown in Fig. 16. The destruction of memristance value is shown in Fig. 17 for an input voltage of $V_{\rm in}(t) = 12 + \sin(200\pi t)$.

6 Conclusions

Memristor is a new nonlinear circuit element whose behavior is not well-known. Its usage in electrical circuits should be exploited as much as possible. In this paper, we have shown that adjustable voltage regulators can be made with a memristor having enough threshold and the required R_{off} to R_{on} ratio. Such voltage regulators could be electronically controlled with a microcontroller and the adjusted voltage value would not be forgotten if the power supply is cut-off.

TiO_2 memristor and its equivalent circuit models are not matured enough yet. In the future, we expect that the memristor as a two-terminal circuit element will emerge in the market for analog applications and when this happens, a user can take the information available to model a TiO_2 memristor or another memristor and use their design criteria given in this paper as a starting point to design such memristor-based voltage regulators. Perhaps, they may be used commonly in the future.

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