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Experimental Comparison of Frequency Analysis of Active and Passive Filter Circuits Designed By Using Memristor Instead of Resistor

İshak PARLAR[1*], M. Nuri ALMALI[1], Ali Can ÇABUKER[1]

[1,2]Van Yuzuncu Yıl University, Faculty of Engineering, Electrical and Electronics Engineering Department, 65090,Van, Turkey

Abstract

In this study, the emulator circuit proposed by Mutlu et al., which gives a stable output curve in terms of application was used. The quality factor, cut-off frequencies and bandwidths of the circuit on passive and active filters were evaluated. It was observed that the quality factor of memristor-based filters was higher because the memristor is self-excited at low frequency points (≤ 100Hz). At high frequencies, it was observed that there was no positive effect since the output response of both active and passive filter circuits based on memristor behaved like a linear resistor.

Keywords: Emulator circuit, memristor, quality factor, cut-off frequency, active and passive filters.

Direnç Yerine Memristor Kullanılarak Tasarlanan Aktif ve Pasif Filtre Devrelerinin Frekans Analizlerinin Deneysel Karşılaştırılması

İshak PARLAR[1*], M. Nuri ALMALI[1], Ali Can ÇABUKER[1]

Özet

Bu çalışmada Mutlu ve diğerleri tarafından önerilen ve uygulama açısından kararlı bir çıkış eğrisi veren emülatör devresi kullanılmıştır. Pasif ve aktif filtrelerde devrenin kalite faktörü, kesim frekansları ve bant genişlikleri değerlendirilmiştir. Memristor düşük frekans noktalarında (≤ 100Hz) kendinden uyarılı olduğu için memristor tabanlı filtrelerin kalite faktörünün daha yüksek olduğu gözlemlenmiştir. Yüksek frekanslarda, hem aktif hem de pasif filtre devrelerinin memristör temelli çıkış tepkisi lineer bir direnç gibi davrandığından dolayı pozitif bir etkinin olmadığı gözlemlenmiştir.

Anahtar Kelimeler : Taklit devresi, memristör, kalite faktörü, kesim frekansı, aktif ve pasif filtreler.

1. Introduction

Resistor, known as the most basic circuit elements in electronics; change of voltage according to current, capacitor; variation of voltage with load, coil; It consists of circuit elements that reveal the change of current according to magnetic flux. These circuit elements depend on parameters known as magnetic flux, load, current and voltage. In his studies, Chua found the missing piece with a simple integral calculation based on the relations between these 4 parameters. A total of 6 equations are needed for the binary combination of 4 parameters. But so far, 5 equations have been defined. The missing equation, Leon Chua, Professor of Electricity at the University of Berkeley, in his article titled "Missing Circuit Element-Memristor" in 1971, theoretically proved the incompleteness of the relationship between charge and magnetic flux and named this new circuit element "memristor" [1]. Approximately 40 years after its theoretical study, Williams and his team realized that the new circuit element they found in the Hewlett-Packard (HP) laboratories, after long efforts, exhibited the same behavior as the memristor mentioned by Chua in 1971 [2]. After the physical announcement of this new generation circuit element to the whole world, its popularity rapidly increased. Application areas related to memristor were increasing and constituted a potential area of influence.

Today, many models showing memristor properties have been proposed in simulation programs. These models are mostly designed in programs such as Pspice, Matlab, Simulink, VeriLog. As a result of the researches, it has been revealed that the memristor has a great importance not only in analog circuits but also in the field of nanotechnology. In the literature, it is seen that intensive studies have been carried out on memristor-based filters in recent years. The behavior of memristor-based filters and their effects on it are investigated, and studies continue to examine their time-frequency properties. [3-8] In the literature researches, it is seen that especially a certain filter circuit is studied. This study is important in terms of examining the effects of a simulated circuit proposed in the literature on both active and passive filters in a general context. In this study, the imitation circuit proposed by Mutlu et al. was designed and implemented. Then, low frequency analyzes on active and passive filters were examined and quality factor, Bode diagram and cutoff frequencies were compared.

2. Materials and Methods

We must first begin by identifying the memristor emulator circuit model to be used in both active and passive filter circuits. These points are indicated in the subsections.

2.1.Mathematical Model of the Designed Emulator Circuit

Chua has lots of transistors, op-amp resistors, etc. He had developed a simulated circuit with circuit elements [1]. Since this circuit consists of many elements and takes a long time to implement, Linear Drift Fast TiO_2 memristor emulation circuit, which consists of fewer elements and gives the most stable output response during application, is discussed. In Figure 1, a circuit consisting of a differential amplifier, an integrator circuit and an analog multiplier is shown by Mutlu et al. [8].

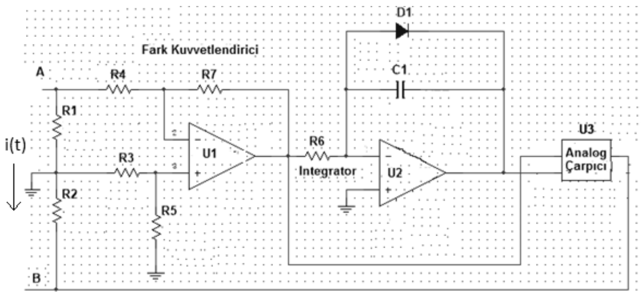

Figure 1. Difference Amplifier and Analog Multiplier in Emulator Circuit

For the TiO_2 Memristor model proposed by Mutlu et al., if an external bias voltage v(t) is applied from outside, it limits the poles between the two regions. The voltage-current relationship for the memristor is given by Eq.(1) [5].

$$v(t) = R_{ON}\frac{w(t)}{D} + R_{OFF}\left(1 - \frac{w(t)}{D}\right)i(t) \quad (1)$$

$w(t) = \mu_V \frac{R_{ON}}{D} q(t), \mu_V$ has the mean shear velocity and cm^2/sV, D is the sum of the doped and undoped areas and has m units, and $q(t)$ corresponds to the total charge passing through the memristor device. If i(t) is accepted as the current flowing from A to B, the load passing through the circuit q(t), It is expressed as in Eq. (2).

$$q(t) = \int_{t=-\infty}^{t} i(t)dt \quad (2)$$

In order to prevent the memristor load from going negative, the diode (D1) in Figure1 or a very high resistance value can be used. In the following formula, the memristor load and current are multiplied by each other. The voltage expression in the analog multiplier is Eq. It is shown as in (3).

$$V_{MULTIPLIER} = V_{U3} = \left(\frac{-R_3R_1}{R_2}\right)^2 \frac{1}{R_6C_1} q(t)i(t) \quad (3)$$

3. Results and Discussion

3.1. Analysis Results

Studies were carried out by examining the 1Vpp sinusoidal input signal and the frequency of 1-200Hz on the active and passive filters of the simulated circuit. Memristor-based passive high-pass filter, passive low-pass filter, active high-pass filter and active low-pass filter circuits are examined, respectively, and their quality factors, Bode diagrams and cut-off frequencies are discussed. Figure 2 shows the linear drift fast TiO_2 memristor emulator circuit proposed by Mutlu et al.

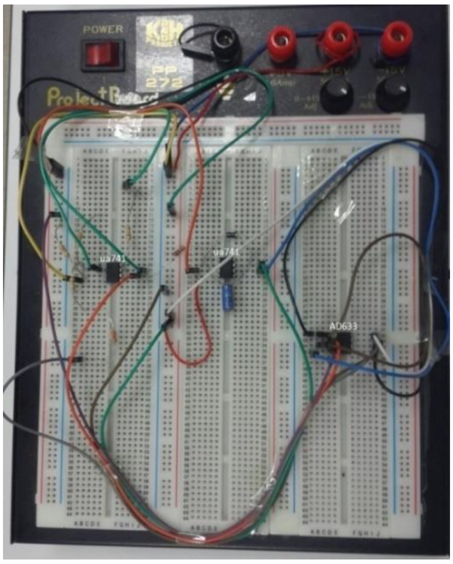

Figure 2. Application of Emulator Circuit Built on An Electronic Workboard

Memristor Based Passive High Pass Filter

In this section, the effects of Linear Drift Fast memristor emulator circuit proposed by Mutlu et al. on active and passive filters are investigated. First, the effects on the memristor-based passive high-pass filter circuit in Figure 3 are discussed.

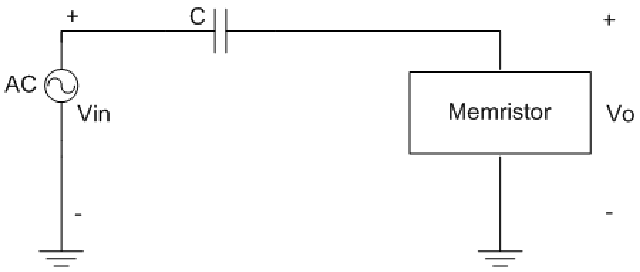

Figure 3. Memristor-Based Passive High-Pass Filter Schematic

The input-output voltage expressions, cut-off frequency and quality factor equations of the system given in Figure 3 are given below, respectively.

$$\frac{V_o}{V_{in}} = \frac{R_M}{R_M + jX_C} \tag{4}$$

The transfer function of the claim can be expressed as:

$$\frac{V_o(s)}{V_{in}(s)} = \frac{s}{s + 1/R_M C} \tag{5}$$

R_M indicates the resistance of the amplitude memristor. Talukdar et al., if a sinusoidal waveform is given as the input voltage, R_M will oscillate along Ravg and give the memristor resistance for the sinusoidal input voltage as in Eq. (6) [12-16];

$$R_M = R_{avg} \pm \Delta R_M \sin(wt + \varphi) \quad (6)$$

In this case, the endpoints of the memristor resistance, cut-off frequency and quality factor equations can be expressed as follows.

$$R_{max,min} = R_{avg} \pm \Delta R_M \quad (7)$$

$$f_{o,M} = \frac{1}{2\pi(R_{avg} \pm \Delta R_M)C} \quad (8)$$

$$Q = \frac{f_{o,M}}{BW} \quad (9)$$

Table 1 shows fixed input voltage and different output voltage values for different frequencies in M-C and R-C passive high-pass filter circuits. It is seen that it gives the output without any weakening in the input voltage at increasing frequencies. When looking at low frequencies, it is seen that this input signal gradually decreases and even approaches zero at lower frequencies. Another important point here is that the initial resistance of the memristor (R_{INITAL}) was measured as approximately $1M\Omega$ in the application studies of the Memristor emulator circuit. The R-C value was chosen according to this initial value while the application studies were carried out.

Table 1. Calculated gain, normalized gain and decibel (dB) values for different frequency values in passive high-pass filter circuit. ($V_{in}(p-p) = 1V, A_{V_{mid}}{}_{M-C} = 1{,}04 \quad A_{V_{mid}}{}_{R-C} = 1{,}04$)

Frequency (Hz)	Vout(p-p) (V)		Gain		Normalized Gain		Desibel (dB)	
	M-C	R-C	M-C	R-C	M-C	R-C	M-C	R-C
5	0.16	0.2	0.16	0.2	0.15	0.19	-16.25	- 14.32
10	0.4	0.36	0.4	0.36	0.38	0.34	-8.29	-9.21
15	0.56	0.52	0.56	0.52	0.53	0.5	-5.37	-6.02
20	0.72	0.6	0.72	0.6	0.69	0.57	-3.19	-4.77
25	0.74	0.64	0.74	0.64	0.71	0.61	-2.95	-4.21
30	0.76	0.7	0.76	0.7	0.73	0.67	-2.72	-3.43
35	0.84	0.74	0.84	0.74	0.80	0.71	-1.85	-2.95
40	0.88	0.76	0.88	0.76	0.84	0.73	-1.45	-2.72
45	0.92	0.84	0.92	0.84	0.88	0.8	-1.06	-1.85
50	0.96	0.88	0.96	0.88	0.92	0.84	-0.69	-1.45
100	1.04	1.04	1.04	1.04	1	1	0	0
150	1.04	1.04	1.04	1.04	1	1	0	0
200	1.04	1.04	1.04	1.04	1	1	0	0

It is seen that there is a clear difference between the Bode plot responses of M-C and R-C circuits in the frequency range of approximately 10-100Hz, values in Table 1. It is seen that the Passive high-pass R-C filter circuit works more ideally than the M-C filter circuit at 10Hz and higher frequencies. It is also observed in Figure 4 that the M-C filter has a steeper slope in the 0-10Hz frequency range.

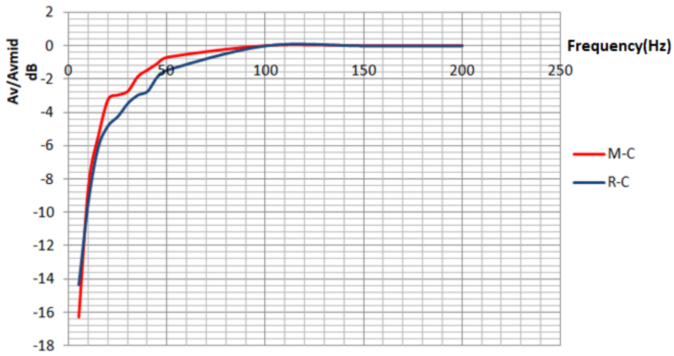

Figure 4. Bode plot of passive high-pass M-C and R-C circuits

Memristor Based Passive Low-Pass Filter

In this section, the effects of the memristor-based passive low-pass filter circuit shown in Figure 5 under low frequency are investigated. In this case, it is mutually seen in the M-C and R-C circuits in Table 2 that in the low-pass passive filter circuit, it attenuates the input signal at frequencies above the cut-off frequency and gives it to the output below the determined cut-off frequency, without weakening the input signal. In both circuits, the memristor-based passive low-pass filter circuit and the normal passive low-pass filter circuit, the frequency-dependent output responses were measured.

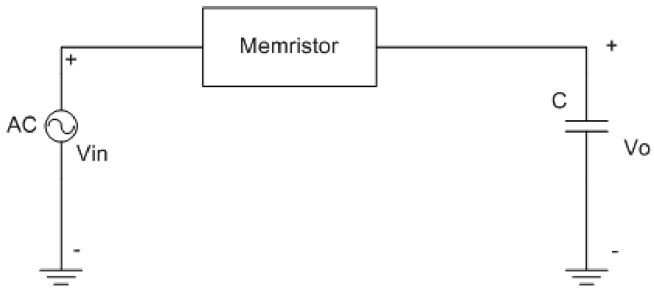

Figure 5. Memristor Based Passive Low-Pass Filter Schematic

The input-output voltage expressions, cut-off frequency and quality factor equations of the system given in Figure 5 are given below.

$$\frac{V_o}{V_{in}} = \frac{jX_C}{jX_C+R_M} \tag{10}$$

The transfer function of the Memristor Based Passive Low-Pass Filter system can be expressed as;

$$\frac{V_o(s)}{V_{in}(s)} = \frac{1}{sR_MC+1} \tag{11}$$

Cut-off frequency and quality factor of Memristor Based Passive Low-Pass Filter system. It is expressed as in (8) and (9): In the schematic above, the input and output biases of the memristor-based passive low-pass filter are given. The memristor circuit, which is tried to be shown as a subsystem here, is the integrated representation of the circuit proposed by Mutlu et al. In this circuit, a low-pass filter is designed by connecting the memristor imitation circuit and the capacitor in series. Since the capacitor is connected to the chassis at high frequencies, high frequencies are minimized.

Table 2. Calculated gain, normalized gain and decibel (dB) values for different frequency values in passive low-pass filter circuit. $V_{in}(p-p) = 1V, A_{V_{mid_{M-C}}} = 480mV \quad A_{V_{mid_{R-C}}} = 480mV)$

Frequency(Hz)	Vout(p-p) (V)		Gain		Normalized Gain		Desibel (dB)	
	M-C	R-C	M- C	R- C	M-C	R-C	M-C	R-C
5	0.48	0.48	0.48	0.48	1	1	0	0
10	0.48	0.48	0.48	0.48	1	1	0	0
15	0.48	0.48	0.48	0.48	1	1	0	0
20	0.48	0.48	0.48	0.48	1	1	0	0
25	0.48	0.48	0.48	0.48	1	1	0	0
30	0.32	0.36	0.32	0.36	0.667	0.75	-3.5	-2.49
35	0.28	0.3	0.28	0.3	0.58	0.62	-4.68	-4.08
40	0.24	0.26	0.24	0.26	0.5	0.54	-6.02	-5.33
45	0.20	0.23	0.20	0.23	0.41	0.47	-7.6	-6.39
50	0.16	0.22	0.16	0.22	0.33	0.45	-9.54	-6.77
100	0.12	0.16	0.12	0.16	0.25	0.33	- 12.04	-9.54
150	0.1	0.1	0.1	0.1	0.2	0.2	- 13.62	- 13.62
200	0.1	0.07	0.1	0.07	0.2	0.14	- 13.62	- 16.72

When we interpret the data in Table 2 graphically in the Excel program; It has been observed in Figure 6 that there is no difference in the Bode plot responses of M-C and R-C circuits in the frequency range of approximately 0-25Hz, but the slope of the M-C filter is steeper and the quality factor is higher than the R-C filter circuit in the frequency range of 25-200Hz.

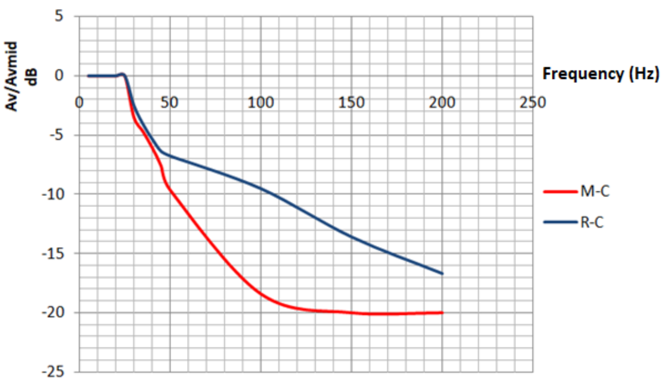

Figure 6. Bode Plot of Passive Low-Pass M-C and R-C Circuits

This should explore the significance of the results of the work, not repeat them. The results should be drawn together, compared with prior work and/or theory and interpreted to present a clear step forward in scientific understanding. Combined results and discussion sections comprising a list of results and individual interpretations in isolation are particularly discouraged.

Memristor Based Active Low-Pass Filter

In the low-pass active filter circuit in Figure 7, at frequencies above the cut-off frequency, it attenuates the input signal and gives it to the output, if it is below the cut-off frequency, it gives the output without weakening the input signal.

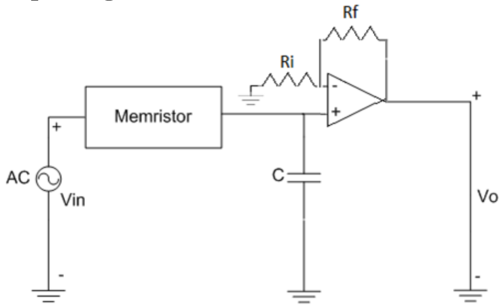

Figure 7. Memristor-Based Active Low-Pass Filter Schematic

The input-output voltage expressions, cut-off frequency and quality factor equations of the system given in Figure 7 are given below.

$$\frac{V_O}{V_{in}} = \frac{jX_C(R_i+R_f)}{R_i(jX_C+R_M)} \tag{12}$$

The transfer function of the memristor-based active low-pass filter system can be expressed as:

$$\frac{V_O(s)}{V_{in}(s)} = \frac{R_i+R_f}{sCR_M R_i+R_i} \tag{13}$$

The cut-off frequency and quality factor of the memristor-based active low-pass filter system are expressed in Equations (8) and (9).

Table 3. Calculated gain, normalized gain and decibel (dB) values for different frequency values in Active Low Pass filter circuit. $(V_{in}(p-p) = 1V, A_{V_{mid_{M-C}}} = 296mV \quad A_{V_{mid_{R-C}}} = 356mV)$

Frequency (Hz)	Vout(p-p) (V)		Gain		Normalized Gain		Desibel (dB)	
	M-C	R-C	M- C	R-C	M- C	R-C	M-C	R-C
1	0.29	0.35	0.48	0.48	1	1	0	0
2	0.29	0.35	0.48	0.48	1	1	0	0
3	0.29	0.35	0.48	0.48	1	1	0	0
4	0.29	0.35	0.48	0.48	1	1	0	0
5	0.29	0.34	0.48	0.48	0.98	0.96	-0.11	-0.29
6	0.28	0.33	0.32	0.36	0.97	0.94	-0.23	0.5
7	0.27	0.31	0.28	0.30	0.91	0.88	-0.73	-1.03
8	0.26	0.3	0.24	0.26	0.89	0.84	-0.99	-1.48
9	0.25	0.28	0.20	0.23	0.85	0.78	- 1.397	-1.98
10	0.24	0.26	0.16	0.22	0.81	0.75	-9.54	-6.77
100	0.04	0.044	0.12	0.16	0.13	0.12	- 12.04	-9.54
1000	0.012	0.012	0.1	0.10	0.04	0.03	- 13.62	-13.62

In Table 3, after expressing the output voltages for different input frequencies in the active low-pass filter circuit experimentally, the calculated gain and normalized gain values were calculated with reference to these values. The gain values in decibels (dB) are shown in the graph in Figure 8. It was observed that there was no difference in the Bode plot responses of the M-C and R-C circuits in the

0-4Hz frequency range, but the slope of the R-C filter was steeper than the M-C filter circuit in the 4-10Hz frequency range. It was also observed that there are distortions in the Bode plot response of the M-C filter circuit.

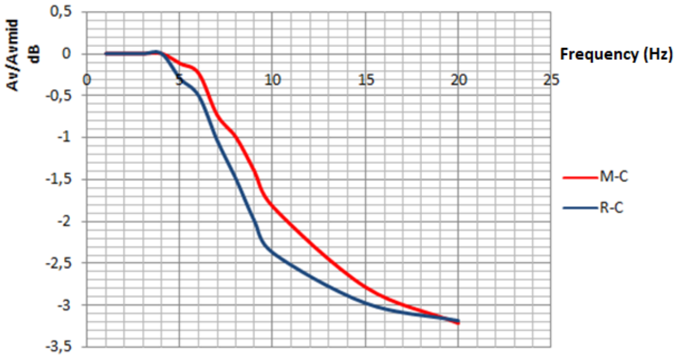

Figure 8. Bode Plot of Active Low-Pass M-C and R-C Circuits.

Memristor Based Active High-Pass Filter

In the schematic given in Figure 9, the input and output tendencies of the memristor-based active high-pass filter are given. The memristor circuit that is tried to be shown as a subsystem here is the integrated representation of the linear drift speed TiO_2 memristor circuit proposed by Mutlu et al. In this circuit, the memristor is given to the non-inverting input of the operational amplifier by connecting the imitation circuit to the ground in the input circuit instead of the resistor R and connecting the capacitor in parallel with the resistor. Since the resistor is connected to the chassis this time instead of the capacitor at high frequencies, the effect of high frequencies on the output can be easily seen.

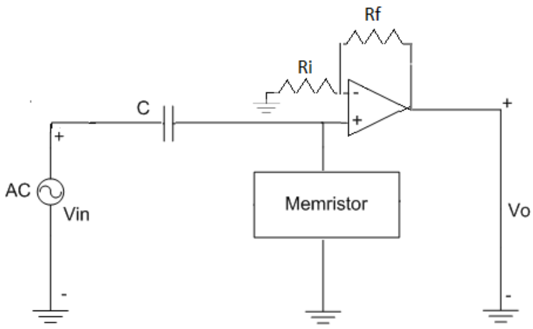

Figure 9. Memristor-Based Active High-Pass Filter Schematic

The input-output voltage expressions, cut-off frequency and quality factor equations of the system given in Figure 9 are given below.

$$\frac{V_o}{V_{in}} = \frac{R_M(R_i+R_f)}{R_i(jX_C+R_M)} \tag{14}$$

The transfer function of the memristor-based active low-pass filter system can be expressed as:

$$\frac{V_o(s)}{V_{in}(s)} = \frac{sCR_M(R_i+R_f)}{sCR_MR_i+R_i} \tag{15}$$

The cut-off frequency and quality factor of the memristor-based active low-pass filter system are expressed in Equations (8) and (9).

Table 4. Calculated gain, normalized gain and decibel (dB) values for different frequency values in Active High Pass filter circuit. $(V_{in}(p-p) = 1V, A_{V_{mid_{M-C}}} = 2 \;\; A_{V_{mid_{R-C}}} = 2)$

Frequency (Hz)	Vout(p-p) V		Gain		Normalized Gain		Desibel (dB)	
	M-C	R-C	M-C	R-C	M-C	R-C	M-C	R-C
0.1	0.04	0,06	0,04	0,06	0,02	0,03	- 31,93	- 28,51
1	0.2	0,14	0,2	0,14	0,1	0,07	- 17,95	- 21,15
2	0.4	0,48	0,4	0,48	0,22	0,24	-11,1	- 10,45
3	0.7	0,74	0.7	0,74	0,35	0,37	-7,07	-6,69
4	0.92	0,96	0,92	0,96	0,46	0,48	-4,69	-4,43
5	1.08	1,16	1,08	1,16	0,54	0,58	-3,3	-2,79
6	1.26	1,32	1,26	1,32	0,63	0,66	-1,965	-1,67
7	1.4	1,4	1,4	1,4	0,7	0,7	-3,09	-3,09
8	1.5	1,5	1,5	1,5	0,75	0,75	-2,49	-2,49
9	1.58	1,6	1,58	1,6	0,79	0,8	-2,04	-1,938
10	1.64	1.66	1,64	1,66	0,82	0,83	-1,723	-1,618
100	2	2	2	2	1	1	0	0
1000	2	2	2	2	1	1	0	0

In Table 4, after expressing the output voltages for different input frequencies in the active high-pass filter circuit experimentally, the calculated gain and normalized gain values were calculated with reference to these values. The gain values in decibels (dB) are shown in the graph in Figure 10. The differences in Bode plot responses of M-C and R-C circuits in the 0-2Hz frequency range were seen more clearly. In the 2-8Hz frequency range, it was observed that the M-C circuit had a better slope than the R-C circuit, thus a higher quality factor. In these studies, the main reason for working especially at low frequencies is that this condition must be met first in order to be suitable for the characteristic feature of the reference memristor emulator circuit.

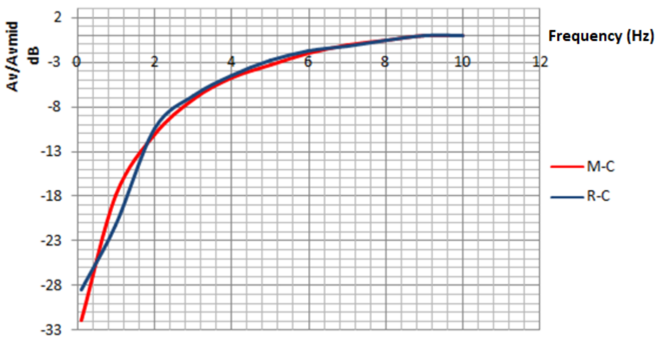

Figure 10. Bode plot of active high-pass M-C and R-C circuits

4. Conclusions

In this study, first of all, the linear drift fast TiO_2 memristor model developed by Mutlu et al. is discussed. The quality factor and cut-off frequencies were investigated by adapting this model to active-passive high-low pass filters. It has been examined in which frequency range it performs a better filter operation. It has been observed that there is a clear difference between the Bode plot responses of M-C and R-C circuits in the frequency range of approximately 10-100Hz in the passive YGF circuit in the voltage control imitation circuit application proposed by Mutlu et al. It has also been observed in the experimental studies that the R-C filter circuit for the passive high-pass filter works more close to the ideal than the M-C filter circuit, and the M-C filter has a steeper slope at lower frequencies. It was observed that there was no difference in the Bode plot responses of M-C and R-C circuits in the 0-25Hz frequency range in the passive AGF circuit, but the slope of the M-C filter was steeper and had a higher quality factor than the R-C filter circuit in the 25-200Hz frequency range. In the active AGF circuit, it is seen that there is no difference in the Bode plot responses of the M-C and R-C circuits in the 0-4Hz frequency range, but the R-C filter has a steeper slope and has a higher quality factor compared to the M-C filter circuit in the 4-10Hz frequency range. It has also been observed that there are distortions in the Bode plot response of the M-C filter circuit. In the active YGF circuit, on the other hand, the differences in the Bode plot responses of the M-C and R-C circuits in the 0-2Hz frequency range were seen more clearly. In the 2-8Hz frequency range, it was observed that the M-C circuit had a better slope and therefore a more robust quality factor (Q) than the R-C circuit.

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