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A TRANSFORMATION METHOD FROM VOLTAGE-MODE OP-AMP-RC CIRCUITS TO CURRENT-MODE GM-C CIRCUITS*

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Abstract. A new transformation method is presented and used to transform voltage-mode op-amp-RC circuits to current-mode Gm-C ones. The proposed method enables the generation of high-performance Gm-C filters that benefit from the advantages of good and well-known op-amp-RC structures and the advantages of the current-mode circuits, and at the same time feature electronic tunability, high frequency capability, and monolithic integration ability. An attractive feature of the proposed method is that it results in Gm-C structures with only grounded capacitors in spite of the presence of floating capacitors in the original op-amp-RC circuits and it utilizes a small number of transconductors. Moreover, simultaneous multiple outputs are easily available in the transformed current-mode Gm-C circuits.
Key words: Gm-C filters, transformation method, generation of Gm-C circuits.

1. Introduction

The conventional operational amplifier (op amp) is used as the active device in the majority of active filter structures. A huge amount of good op-amp-RC filters are discussed in the literature. These filters have the advantages of low sensitivity and the ability to realize several transfer functions using the same block [3]. It has also become apparent, however, that op-amp limitations preclude the use of these filters at high frequencies. Attempts to integrate these filters lack convenient voltage or current control schemes for externally adjusting the filter characteristics [11].

The Gm-C approach has achieved outstanding performance improvements in structural simplicity, electronic tunability, high frequency capability, and

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monolithic integration ability. This technique has hence received much attention [1]–[4], [6], [8], [9], [11]–[14], [17]–[24], [26]–[33]. Also, current-mode techniques have been recognized to offer potential advantages for applications both in continuous-time and in sampled-data signal processing [19]. In current-mode circuits, summing of current signals requires only a circuit node, current signals can be easily replicated and scaled using current mirrors, and they have the potential to operate at higher signal bandwidths [31]. Due to the simplicity of the building blocks used, current-mode circuits can be very compact and operate with low voltages. This leads to reduced area and power consumption requirements as well as to improved high frequency performance [1], [6], [8], [28]. Moreover, integrated circuit implementation necessitates circuits using grounded capacitors, to eliminate the effect of bottom-plate parasitic capacitances [1]. Based on all these considerations, the current-mode Gm-C using only grounded capacitors approach is the optimum solution for VLSI techniques. A transformation method to obtain current-mode circuits from voltage-mode circuits and vice versa using the concept of generalized duals and inverses was proposed in [30]. There is also plenty of published work in the literature on obtaining current-mode Gm-C circuits from voltage-mode counterparts using the duality theorem [15] and the transposition theorem [5]. Note that the transformation methods reported in [5], [30] were the first methods proposed in the literature for converting voltage-mode circuits to current-mode circuits and vice versa.

In this paper, a new method for the transformation from op-amp-RC voltage-mode circuits into Gm-C current-mode circuits with only grounded capacitors is presented. This method enables the generation of high-performance Gm-C filters that benefit from the advantages of both good and well-known op-amp-RC structures and current-mode Gm-C circuits. An attractive feature of the proposed method is that it results in Gm-C structures with only grounded capacitors in spite of the presence of floating capacitors in the original op-amp-RC circuits while utilizing a small number of transconductors. Moreover, simultaneous multiple outputs are easily available in the transformed current-mode Gm-C circuits. To demonstrate the generality of the proposed method, the transformation of two well-known op-amp-RC circuits: the Kerwin-Huelsman-Newcomb (KHN) second-order filter [16] and the Friend-Deliyannis second-order filter [7], [10], are given. PSpice simulations are also included to verify the theoretical analysis.

2. The proposed transformation method

In this section it is demonstrated how to transform a voltage-mode op-amp-RC circuit into a current-mode Gm-C circuit. The transformed current-mode Gm-C circuit can be obtained using the following procedure. First, the circuit equations for the original voltage-mode circuit are formulated on a node basis [25]. Second, the equations are rewritten after interchanging voltages to currents and dividing equations that include capacitances by the complex frequency variable s. For the equations that represent voltage amplifiers no division by s is required, and they are realized using current amplifiers in the current-mode circuit. Third, the first-order equations are realized using the basic sections described in Section 2.1. Finally, the transformed current-mode Gm-C circuit is obtained by connecting the sections realized in step three.

The transformed Gm-C current-mode circuits using the proposed method have the same transfer functions as that of the original voltage-mode circuit. Moreover, one can see that the proposed transformation method generates current-mode Gm-C circuits with a minimum number of transconductors. This is a result of interpreting the summation of voltages in the original voltage-mode circuit as a summation of currents, in the current-mode counterpart, which needs only a circuit node.

Multiple outputs in the voltage-mode circuit are interpreted as multiple output currents in the transformed current-mode Gm-C circuit; so, simultaneous multiple outputs are easily available in the transformed current-mode Gm-C circuit.

Note that the proposed transformation method can be applied to any active or passive voltage-mode circuit because the above-described procedure starts by obtaining the voltage-mode equations describing a network and then uses them to generate the current-mode circuit.

2.1. First-order current-mode sections

The general first-order current-mode equation is

$$\frac{I_i}{G_i} = \pm \sum_j \frac{I_j}{sC_j} \pm \sum_k \frac{I_k}{G_k}. \tag{1}$$

The circuit of Figure 1a is the realization of equation (1). Special cases from this general equation can be as follows:

$$\frac{I_i}{G_i} = \frac{I_1}{G_1} - \frac{I_2}{G_2} \tag{2}$$

$$\frac{I_i}{G_i} = \frac{I_1}{sC_1} - \frac{I_2}{sC_2} \tag{3}$$

$$I_i = I_1 + I_2. \tag{4}$$

Equations (2)–(4) are realized using the circuits in Figures 1b–1d.

Because the transformation method is based on using those simple current-mode sections, it is obvious that the generated Gm-C realization utilizes only grounded capacitors. These grounded capacitors can be implemented on a smaller area than the floating ones, and they can absorb equivalent shunt parasitic capacitances [29] in spite of the presence of floating capacitors in the original op-amp-RC circuit.

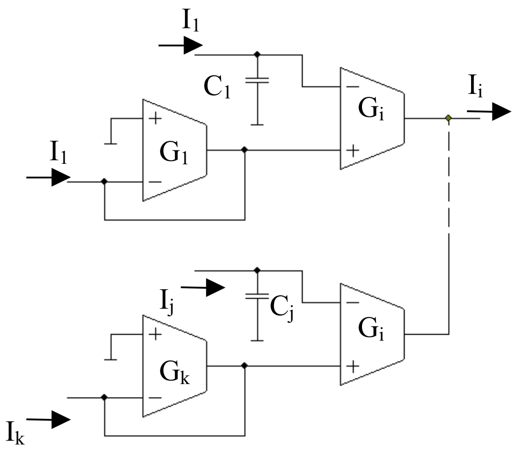

Figure 1a. Circuit realization of equation (1).

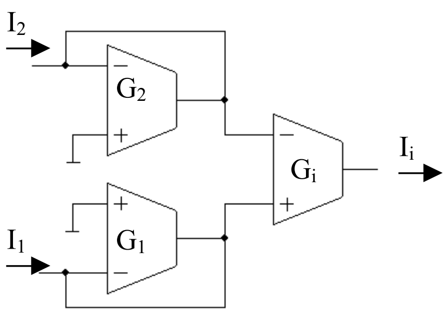

Figure 1b. Circuit realization of equation (2).

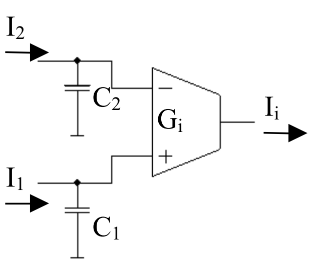

Figure 1c. Circuit realization of equation (3).

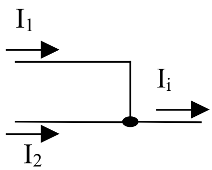

Figure 1d. Circuit realization of equation (4).

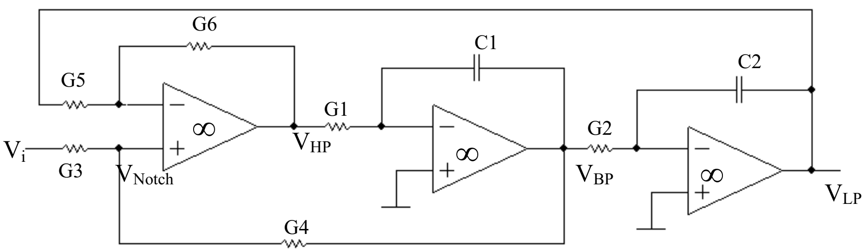

Figure 2. The KHN active op-amp filter [16].

2.2. *Transformation of the KHN op-amp voltage-mode filter*

The transformation of the KHN op-amp voltage-mode filter shown in Figure 2 is taken as an example to illustrate the proposed method. The same filter was transformed to a voltage-mode Gm-C filter using the method presented in [3] and shown in Figure 3.

The new KHN current mode Gm-C filter is obtained from the voltage-mode KHN op-amp-RC filter of Figure 2 by following our proposed method. The nodal equations representing the voltage-mode filter of Figure 2 are written as

$$sC_1 V_{\mathrm{BP}} = -G_1 V_{\mathrm{HP}} \tag{5}$$

$$sC_2 V_{\mathrm{LP}} = -G_2 V_{\mathrm{BP}} \tag{6}$$

$$G_3(V_i - V_{\mathrm{Notch}}) = G_4(V_{\mathrm{Notch}} - V_{\mathrm{BP}}) \tag{7}$$

$$G_5(V_{\mathrm{LP}} - V_{\mathrm{Notch}}) = G_6(V_{\mathrm{Notch}} - V_{\mathrm{HP}}). \tag{8}$$

Replacing V_{HP}, V_{BP}, V_{LP}, and V_{Notch} by I_{HP}, I_{BP}, I_{LP}, and I_{Notch} and dividing

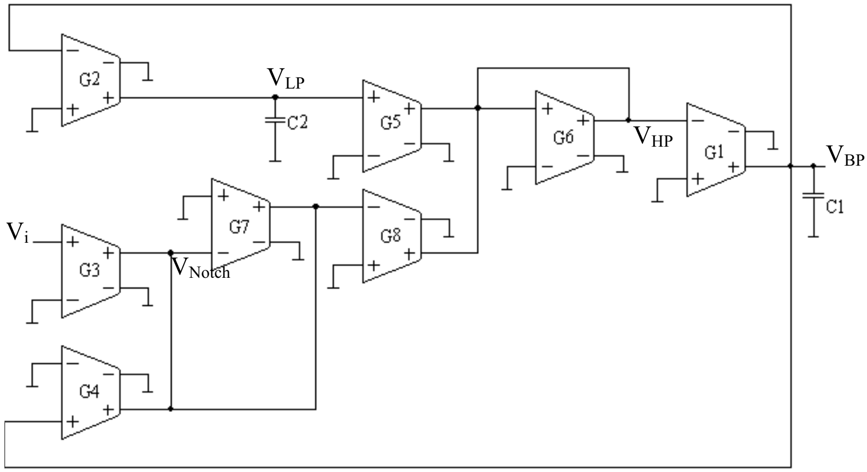

Figure 3. The voltage-mode Gm-C version of the KHN active filter [3].

equations (5), (6) by s, the new set of nodal equations is obtained as

$$C_1 I_{\mathrm{BP}} = -\frac{G_1}{s} I_{\mathrm{HP}} \tag{9}$$

$$C_2 I_{\mathrm{LP}} = -\frac{G_2}{s} I_{\mathrm{BP}} \tag{10}$$

$$G_3(I_i - I_{\mathrm{Notch}}) = G_4(I_{\mathrm{Notch}} - I_{\mathrm{BP}}) \tag{11}$$

$$G_5(I_{\mathrm{LP}} - I_{\mathrm{Notch}}) = G_6(I_{\mathrm{Notch}} - I_{\mathrm{HP}}). \tag{12}$$

Defining $\hat{C}_1 = \frac{CG}{G_1}$, $\hat{C}_2 = \frac{CG}{G_2}$, $\hat{G}_1 = \frac{CG}{C_1}$, $\hat{G}_2 = \frac{CG}{C_2}$, $\hat{G}_3 = \frac{G^2}{G_3}$, $\hat{G}_4 = \frac{G^2}{G_4}$, $\hat{G}_5 = \frac{G^2}{G_5}$, and $\hat{G}_6 = \frac{G^2}{G_6}$, and using the above transformation definitions, equations (9) through (12) are rewritten in the following form:

$$\frac{1}{\hat{G}_1} I_{\mathrm{BP}} = -\frac{1}{s\hat{C}_1} I_{\mathrm{HP}} \tag{13}$$

$$\frac{1}{\hat{G}_2} I_{\mathrm{LP}} = -\frac{1}{s\hat{C}_2} I_{\mathrm{BP}} \tag{14}$$

$$\frac{1}{\hat{G}_4} I_{\mathrm{Notch}} = \frac{1}{\hat{G}_3}(I_i - I_{\mathrm{Notch}}) + \frac{1}{\hat{G}_4} I_{\mathrm{BP}} \tag{15}$$

$$\frac{1}{\hat{G}_6} I_{\mathrm{HP}} = \frac{1}{\hat{G}_5}(I_{\mathrm{Notch}} - I_{\mathrm{LP}}) + \frac{1}{\hat{G}_6} I_{\mathrm{Notch}}. \tag{16}$$

Equations (13) through (16) are realizable using transconductors and capacitors as shown in Figures 4a through 4d, respectively.

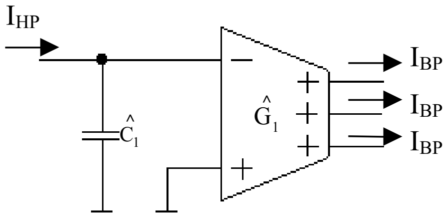

Figure 4a. The Gm-C realization of equation (13).

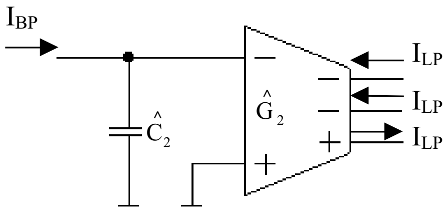

Figure 4b. The Gm-C realization of equation (14).

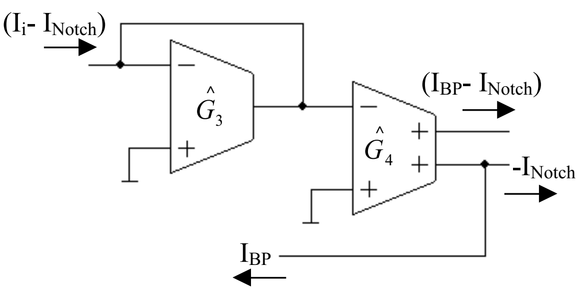

Figure 4c. The Gm-C realization of equation (15).

The complete current-mode Gm-C filter structure is shown in Figure 4e and is obtained by combining the four circuits of Figures 4a through 4d.

It is seen that the realization of Figure 4e uses two grounded capacitors and six transconductors. Also, the four output responses (lowpass, bandpass, highpass, and notch) are available simultaneously.

A more simplified Gm-C current-mode circuit can be obtained by making the assumption $G_5 = G_6$ in equation (12). Then, equations (11) and (12) can be

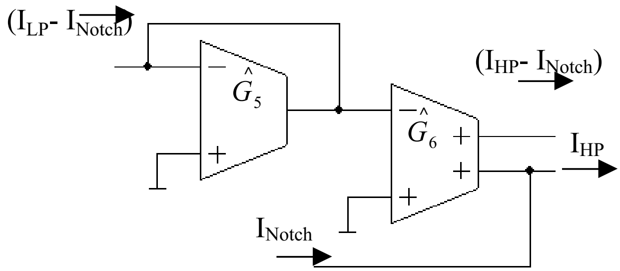

Figure 4d. The Gm-C realization of equation (16).

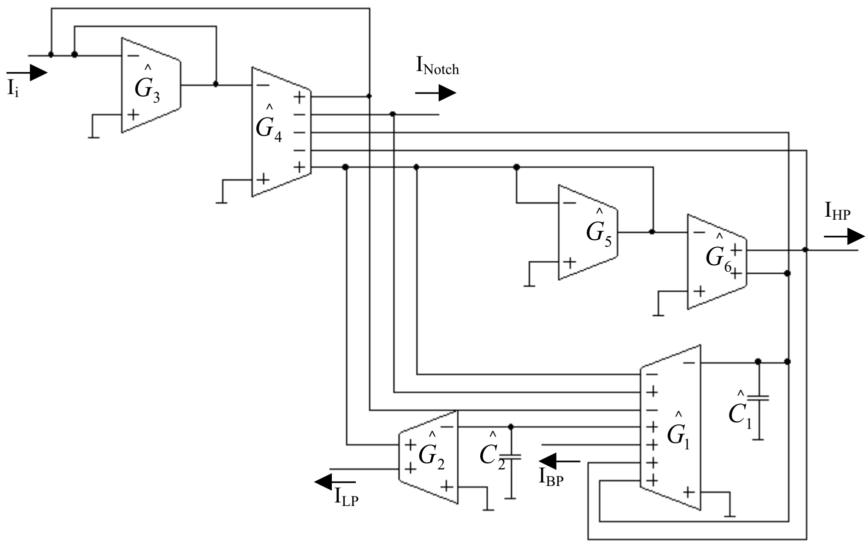

Figure 4e. The transformed Gm-C current-mode KHN circuit.

rewritten as follows:

$$2I_{\text{Notch}}\frac{(G_3+G_4)}{2} = G_3 I_{\text{i}} + G_4 I_{\text{BP}} \tag{17}$$

$$I_{\text{HP}} = 2I_{\text{Notch}} - I_{\text{LP}}. \tag{18}$$

Defining $\hat{G}_3 = \frac{G^2}{G_3}$, $\hat{G}_4 = \frac{G^2}{G_4}$, and $\hat{G}_5 = \frac{2G^2}{(G_3+G_4)}$, equation (17) reduces to

$$2I_{\text{Notch}}\frac{1}{\hat{G}_5} = \frac{1}{\hat{G}_3} I_i + \frac{1}{\hat{G}_4} I_{\text{BP}}. \tag{19}$$

From equations (13), (14), (18), and (19) the simplified Gm-C current mode circuit is obtained and is shown in Figure 5. Note that this circuit also has the

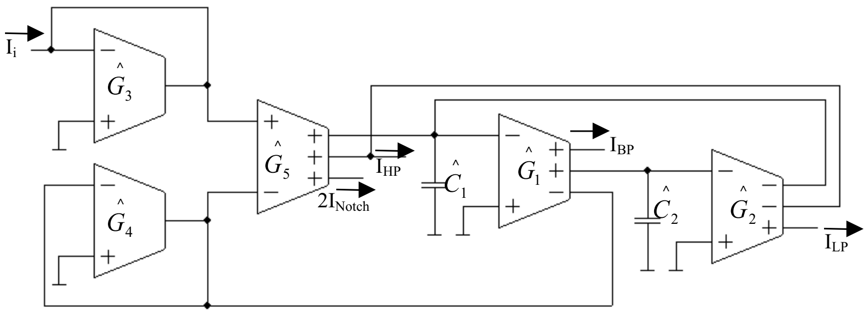

Figure 5. The simplified KHN Gm-C circuit.

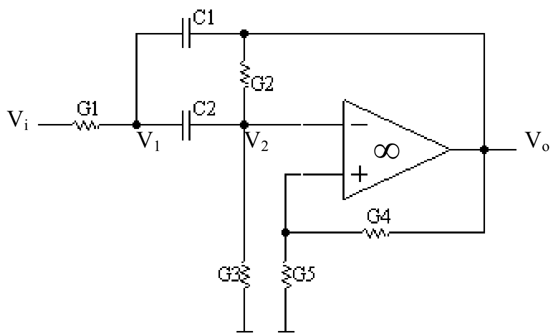

Figure 6. The Deliyannis BP filter [7].

four output responses (lowpass, bandpass, highpass, and notch) simultaneously. Note also that taking $G_5 = G_6$ is very common in the design of the classical KHN op-amp-RC circuit.

2.3. Transformation of the Deliyannis bandpass filter

The Deliyannis op-amp-RC voltage-mode bandpass (BP) filter is shown in Figure 6 [7]. The nodal equations representing the voltage-mode filter of Figure 6 are written as

$$(V_\mathrm{i} - V_1)G_1 = (V_1 - V_2)sC_2 + (V_1 - V_\mathrm{o})sC_1 \tag{20}$$

$$(V_1 - V_2)sC_2 = (V_2 - V_\mathrm{o})G_2 + V_2 G_3 \tag{21}$$

$$V_2 G_5 = (V_\mathrm{o} - V_2)G_4. \tag{22}$$

Replacing V_i, V_1, V_2, and V_o by I_i, I_1, I_2, and I_o, respectively, and dividing

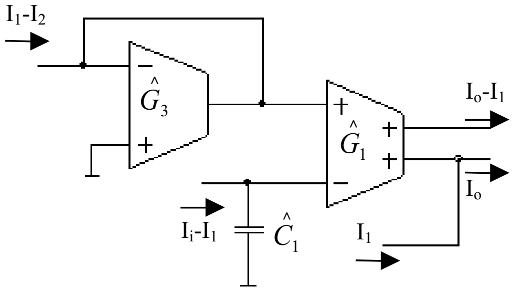

Figure 7a. The Gm-C realization of equation (26) with $\hat{G}_3 = \hat{G}_2$.

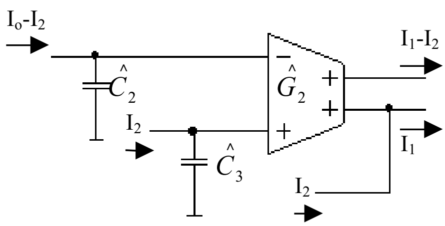

Figure 7b. The Gm-C realization of equation (27).

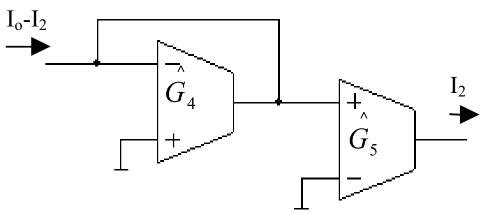

Figure 7c. The Gm-C realization of equation (28).

equations (20)–(21) by s, the following equations are obtained:

$$\frac{G_1}{s}(I_i - I_1) = C_2(I_1 - I_2) + C_1(I_1 - I_o) \tag{23}$$

$$C_2(I_1 - I_2) = \frac{G_2}{s}(I_2 - I_o) + \frac{G_3}{s}I_2 \tag{24}$$

$$G_5 I_2 = G_4(I_o - I_2). \tag{25}$$

Defining $\hat{C}_1 = \frac{CG}{G_1}$, $\hat{C}_2 = \frac{CG}{G_2}$, $\hat{C}_3 = \frac{CG}{G_3}$, $\hat{G}_1 = \frac{CG}{C_1}$, $\hat{G}_2 = \frac{CG}{C_2}$, $\hat{G}_4 = \frac{G^2}{G_4}$, and $\hat{G}_5 = \frac{G^2}{G_5}$, and using the above transformation definitions, equations (23) through

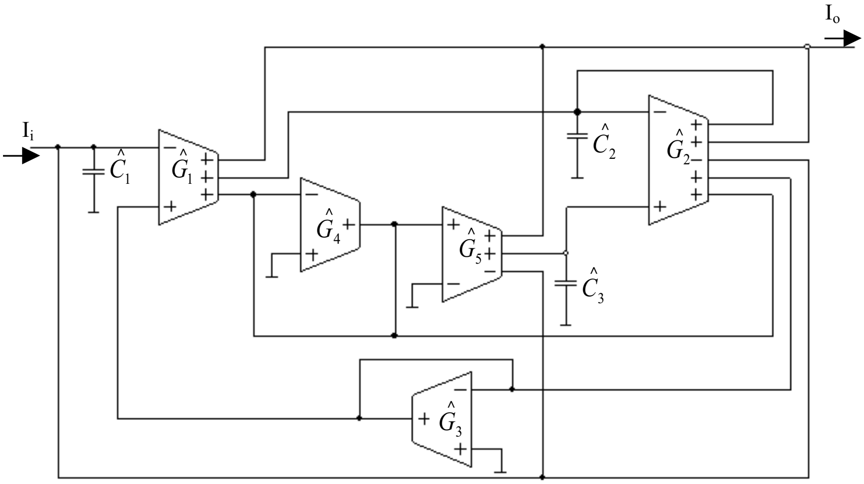

Figure 7d. The transformed Gm-C current-mode circuit with $\hat{G}_3 = \hat{G}_2$.

(25) are rewritten in the following form:

$$\frac{1}{\hat{G}_1} I_1 = \frac{1}{s\hat{C}_1}(I_{\rm i} - I_1) + \frac{1}{\hat{G}_2}(I_2 - I_1) + \frac{1}{\hat{G}_1} I_{\rm o} \tag{26}$$

$$\frac{1}{\hat{G}_2} I_2 = \frac{1}{s\hat{C}_2}(I_{\rm o} - I_2) - \frac{1}{s\hat{C}_3} I_2 + \frac{1}{\hat{G}_2} I_1 \tag{27}$$

$$\frac{1}{\hat{G}_4} I_{\rm o} = \frac{1}{\hat{G}_5} I_2 + \frac{1}{\hat{G}_4} I_2. \tag{28}$$

Equations (26) through (28) are realizable using transconductors and capacitors, as shown in Figures 7a through 7c, respectively. The complete current-mode Gm-C filter structure is shown in Figure 7d and is obtained by combining the three circuits of Figures 7a through 7c. It is seen that the circuit shown in Figure 7d uses three capacitors and five multiple output transconductors, that is, one capacitor more than the op-amp canonic RC filter.

2.4. *Transformation of the Friend-Deliyannis generalized filter*

The Friend-Deliyannis op-amp-RC voltage-mode generalized second-order filter is shown in Figure 8 [10]. The nodal equations representing this filter are given by

$$(V_i - V_1)G_1 = (V_1 - V_2)sC_2 + (V_1 - V_o)sC_1 + V_1G_7 \tag{29}$$

$$(V_1 - V_2)sC_2 = (V_2 - V_o)G_2 + V_2G_3 + (V_2 - V_i)G_8 \tag{30}$$

$$V_2G_5 = (V_o - V_2)G_4 + (V_i - V_2)G_6. \tag{31}$$

Replacing V_i, V_1, V_2, and V_o by I_i, I_1, I_2, and I_o, respectively, and dividing equations (29), (30) by s, the following equations are obtained:

$$\frac{G_1}{s}(I_i - I_1) = C_2(I_1 - I_2) + C_1(I_1 - I_o) + \frac{G_7}{s}I_1 \tag{32}$$

$$C_2(I_1 - I_2) = \frac{G_2}{s}(I_2 - I_o) + \frac{G_3}{s}I_2 + \frac{G_8}{s}(I_2 - I_i) \tag{33}$$

$$G_5I_2 = G_4(I_o - I_2) + G_6(I_i - I_2). \tag{34}$$

Defining $\hat{C}_1 = \frac{CG}{G_1}$, $\hat{C}_2 = \frac{CG}{G_2}$, $\hat{C}_3 = \frac{CG}{G_3}$, $\hat{C}_4 = \frac{CG}{G_7}$, $\hat{C}_5 = \frac{CG}{G_8}$, $\hat{G}_1 = \frac{CG}{C_1}$, $\hat{G}_2 = \frac{CG}{C_2}$, $\hat{G}_4 = \frac{G^2}{G_4}$, $\hat{G}_5 = \frac{G^2}{G_5}$, and $\hat{G}_6 = \frac{G^2}{G_6}$, and using the above transformation definitions, equations (32) through (34) are rewritten in the following form:

$$\frac{1}{\hat{G}_1}I_1 = \frac{1}{s\hat{C}_1}(I_i - I_1) + \frac{1}{\hat{G}_2}(I_2 - I_1) + \frac{1}{\hat{G}_1}I_o - \frac{1}{s\hat{C}_4}I_1 \tag{35}$$

$$\frac{1}{\hat{G}_2}I_2 = \frac{1}{s\hat{C}_2}(I_o - I_2) - \frac{1}{s\hat{C}_3}I_2 + \frac{1}{\hat{G}_2}I_1 + \frac{1}{s\hat{C}_5}(I_i - I_2) \tag{36}$$

$$\frac{1}{\hat{G}_4}I_o = \frac{1}{\hat{G}_5}I_2 + \frac{1}{\hat{G}_4}I_2 + \frac{1}{\hat{G}_6}(I_2 - I_i). \tag{37}$$

The complete current-mode Gm-C filter structure, which is shown in Figure 9, is derived from equations (35) through (37), noting that $G_a = G_b$ and $\hat{G}_3 = \hat{G}_2$. It is seen that the circuit includes eight multiple output transconductances and five grounded capacitors. Note that the realization given in [1] employs twelve single output transconductances, an op-amp (used as a voltage buffer), three grounded capacitors, and one floating capacitor.

3. PSpice simulations

PSpice simulations were performed for the proposed current-mode Gm-C structure of Figure 4e and the voltage-mode Gm-C structure given in [3] and shown in Figure 3. The two filter structures are designed to realize second-order LP, BP, HP, and Notch responses with quality factor equal to 30, and a center frequency of 100 kHz. The values of capacitors C_1 and C_2 are set to 5.36 nF and 5.96 pF, respectively. The transconductance values of G_1 through G_8 in the voltage-mode Gm-C circuit of Figure 3 are set to 112.5 μA/V. The same transconductance value is used for $\hat{G}_1$ through $\hat{G}_6$ in the proposed current-mode Gm-C circuit of

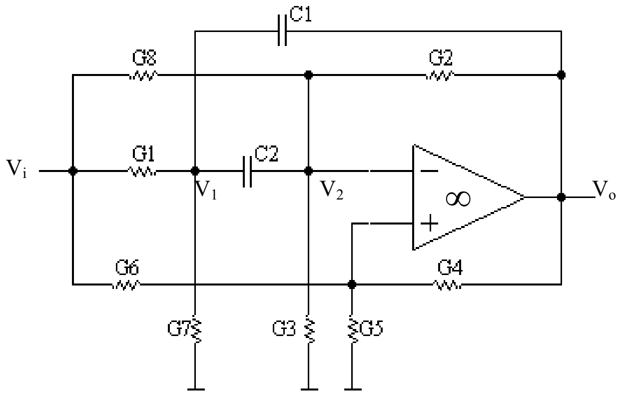

Figure 8. The Friend-Deliyannis active op-amp general filter [10].

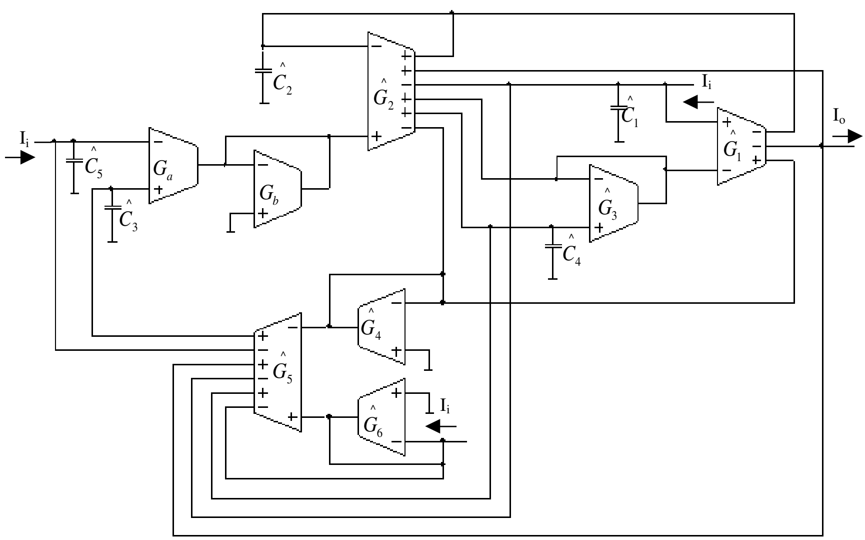

Figure 9. The transformed Gm-C current-mode circuit with $\hat{G}_3 = \hat{G}_2$ and $G_a = G_b$.

Figure 4e. The transconductance amplifiers in Figures 3 and 4e are simulated using the CMOS realization given in [9].

Figures 10a, 10b, 10c, and 10d show the LP, BP, HP, and Notch magnitude responses of the two structures of Figures 3 and 4e. As shown in Figure 10, the proposed transformed Gm-C structure of Figure 4e and the voltage-mode Gm-C structure of Figure 3 feature magnitude responses that nearly match the

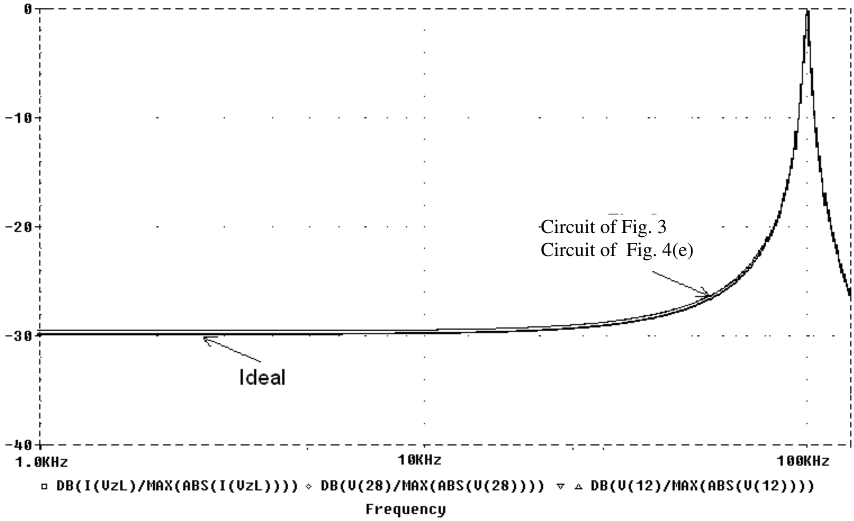

Figure 10a. The LP magnitude response of structures of Figures 3 and 4e at $f_o = 100$ kHz and $Q = 30$.

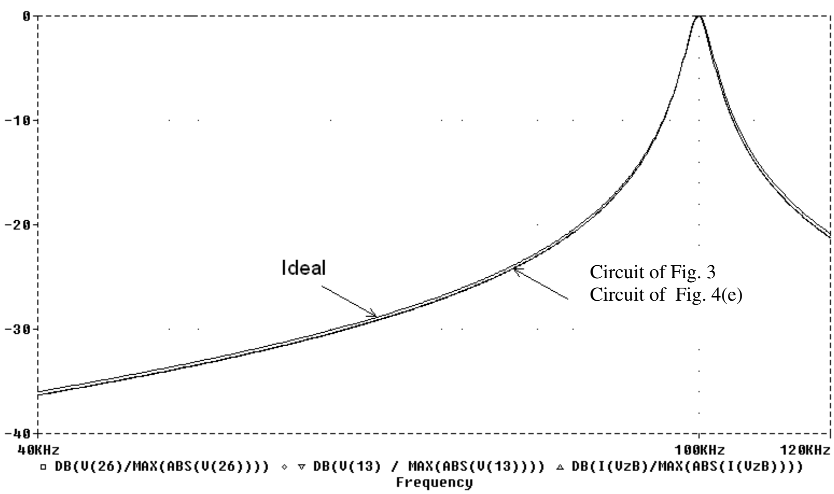

Figure 10b. The BP magnitude response of structures of Figures 3 and 4e at $f_o = 100$ kHz and $Q = 30$.

ideal response up to 100 MHz. The errors in the center frequency and the quality factor for the voltage-mode Gm-C structure of Figure 3 are equal to 0.1% and 4.566%, respectively. On the other hand, the proposed current-mode Gm-C struc-

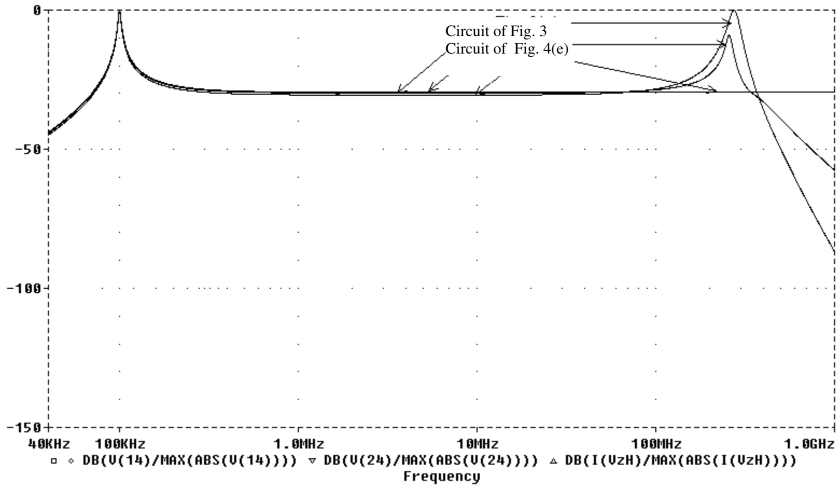

Figure 10c. The HP magnitude response of structures of Figures 3 and 4e at $f_o = 100$ kHz and $Q = 30$.

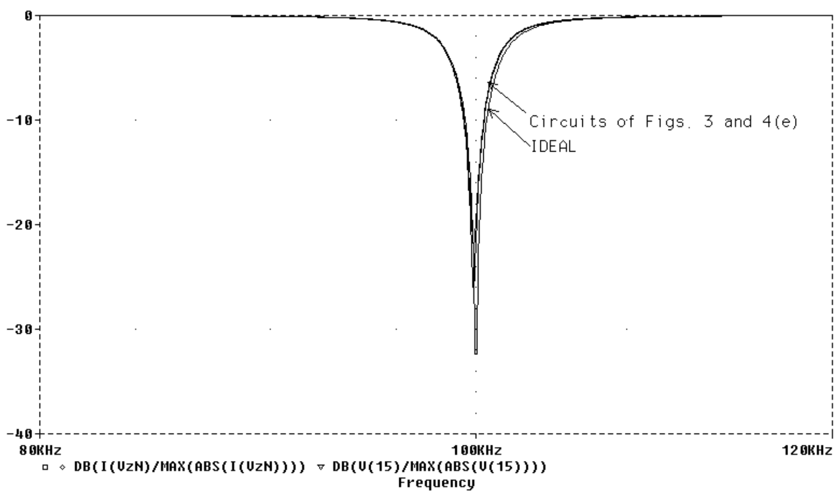

Figure 10d. The Notch magnitude response of structures of Figures 3 and 4e at $f_o = 100$ kHz and $Q = 30$.

ture shown in Figure 4e has lower errors for both the center frequency and the quality factor: 0.09% and 3.9%, respectively.

PSpice simulations were also performed for the proposed current-mode Gm-C structure of Figure 7d. The filter structure is designed to realize a second-order BP

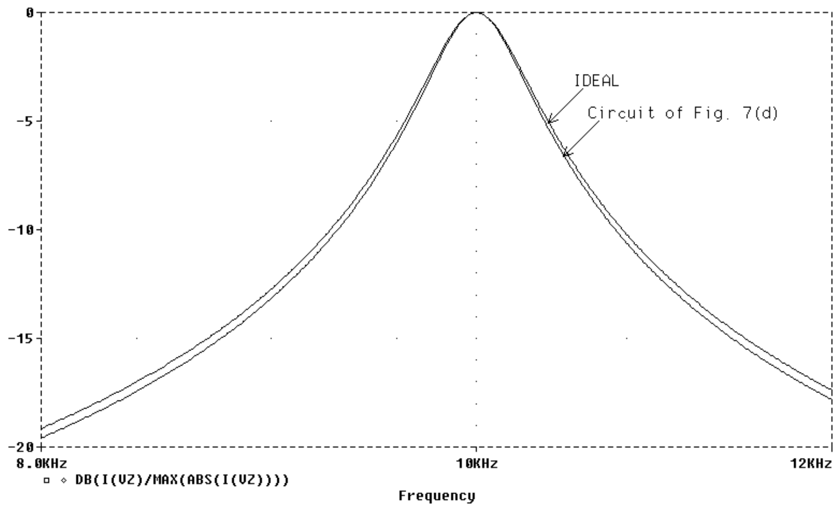

Figure 11. The BP magnitude response of the structure of Figure 7d at $f_o = 10$ kHz and $Q = 20$.

response with quality factor equal to 20, and a center frequency of 10 kHz. The values of capacitors $\hat{C}_1$ and $\hat{C}_2$ are set to 1.2875 nF, and the value of capacitor $\hat{C}_3$ is set to 2.6711296 nF. The transconductance values of $\hat{G}_1$ through $\hat{G}_5$ are set to 112.4 μA/V. The transconductance amplifiers are simulated using the CMOS realization given in [9].

Figure 11 shows the BP magnitude response of the circuit of Figure 7d. As shown in Figure 11, this structure features a magnitude response that nearly matches the ideal response up to 100 MHz. The errors in the center frequency and the quality factor are equal to 0.1% and 5%, respectively.

4. Conclusions

A new voltage-mode op-amp-RC into current-mode Gm-C transformation method has been presented. The transformation, based on basic current-mode first-order sections, is applied on the nodal equations representing the original voltage-mode network. The resulting current-mode Gm-C circuits have the same transfer functions as their op-amp-RC counterparts. Moreover, they utilize a small number of transconductors and only grounded capacitors even though there are existing floating capacitors in the original circuit. PSpice simulations were performed to verify the theoretical analysis. The simulation results showed that the current-mode Gm-C filter structure obtained using the proposed method features a high-performance frequency response. We note that the proposed method can be applied to any active or passive circuit to obtain current-mode

Gm-C circuit. Op-amp-RC circuits have been chosen to illustrate the usefulness of the proposed method. The effect of the nonidealities of the transconductances which include nonideal current mirrors for multiple outputs and a limited frequency response are open research areas for future work.

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