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New Op-Amp Circuits Realizations Using Genetic Algorithm*

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Genetic Algorithm (GA) applications in analog design circuits play an important role with promising results. This paper introduces a proposed methodology based on the genetic algorithm and the symbolic representation to generate equivalent op-amp configurations for well-known filters. The proposed methodology is applied to the Tow-Thomas (TT) filter to generate 168 different configurations. Moreover, it is also applied on the KHN filter resulting in 30 equivalent circuits for each type. A part of the generated realizations is tested through simulations using PSPICE simulator and the simulation results determine the number of accepted circuits. A simulation comparison between the original filter configuration and some of the accepted configurations is done. Fortunately, a better performance compared to the original configuration is obtained from some generated circuits.

Keywords: Nullor; symbolic analysis; genetic algorithm; TT filter; KHN filter; analog filters.

1. Introduction

The symbolic analysis is a powerful tool to analyze electronic circuits, where all part of the circuit elements are considered as symbols. The nullor is quite useful for the analysis, synthesis, and design procedures, as it facilitates modeling the behavior of any active device disregarding the particular realization of the active blocks.[1–6]

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For instance, synthesis methodologies based on symbolic representation and Genetic Algorithms (GAs) have been introduced in Refs. 7 and 8.

The GA is such an optimization technique which operates on the principle of "survival of the fittest". GA has the capability to generate new design solutions from a population of existing solutions, and discarding the solutions which have an inferior performance or fitness.[7] GA starts from high-level descriptions to automatically synthesize analog circuits. However, the automatic synthesis of analog circuits from high-level specifications is recognized yet as a challenging problem.[7–10] It is worth noting that the GA with nullator-based descriptions was applied to generate Voltage Followers (VFs) circuits as in Ref. 9. This method described how an automatic system can deal with huge search spaces to design practical VFs by performing evolutionary operations from nullator-based descriptions. Also, generation of Voltage Mirrors (VMs) circuits based on the GA was presented in Ref. 10. Authors in Ref. 7 introduced a new GA to synthesis the negative type CCII-blocks by superimposing VFs and Current Followers (CF).

The GA is utilized in this work to propose a genetic-based methodology to generate equivalent op-amp configurations for a specific op-amp filter. The proposed methodology is applied to two well-known filter Tow-Thomas (TT) filter and KHN filter.

The TT second-order filter using operational amplifiers (op-amps) has been reviewed in Refs. 11 and 12. TT bi-quad of Fig. 1 is an active-RC topology used to realize both low pass and band pass bi-quadratic filtering. This topology has been widely used because it is simple, versatile, and requires few components.

The KHN filter[13,14] provides simultaneously the three basic filtering functions namely the high-pass (HP), band-pass (BP) and low-pass (LP) responses at three different outputs. The circuit uses three op-amps as shown in Fig. 2. The input voltage is applied to the non-inverting input terminal of the op-amp as shown in Fig. 2(a) and this is defined as KHN of type A. It is also possible to apply the input
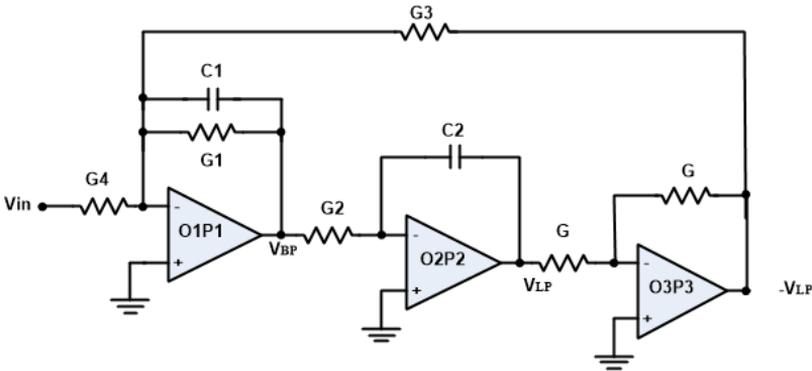

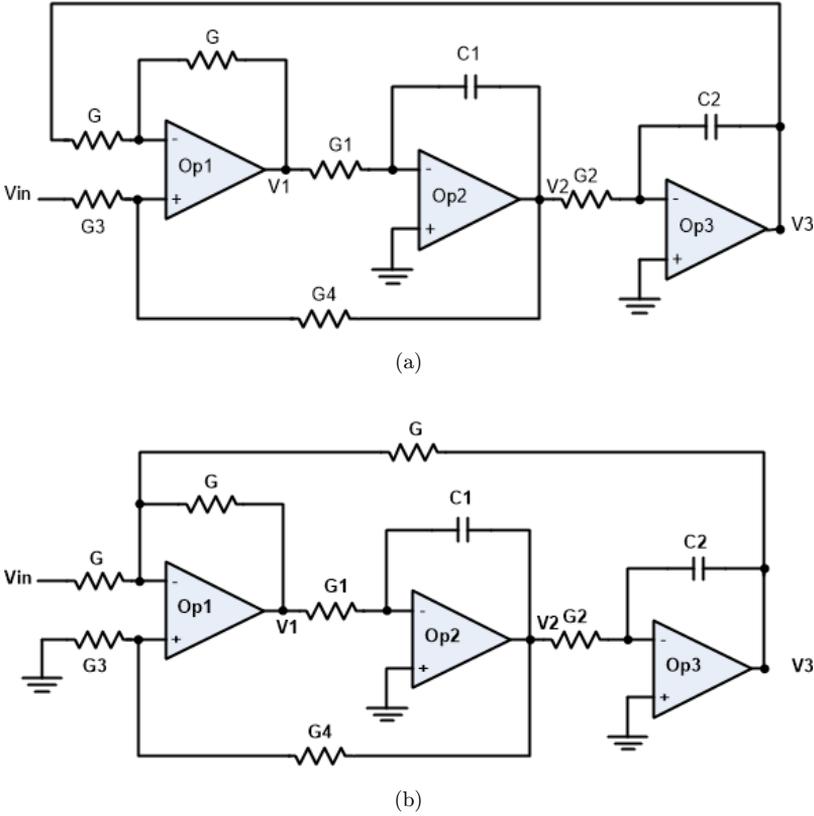Fig. 1.   TT second-order filter using three op-amps.[11,12]

(a)

(b)

Fig. 2. (a) Type A KHN circuit using three op-amps.[13,14] (b) Type B inverted KHN circuit using three op-amps.[15]

voltage to the inverting terminal resulting in the inverted KHN filter shown in Fig. 2(b) and this is defined as KHN of type-B.[15]

The paper is organized as follows; the proposed methodology is described in Sec. 2. In Sec. 3, the methodology is applied to TT filter to get the equivalent circuits. The proposed methodology is also applied to the KHN filter to get the equivalent circuits in Sec. 4. To proof the work, some of the generated circuits are simulated in Sec. 5. Finally, Sec. 6 concludes the work.

2. Methodology

The flowchart of the proposed algorithm is shown in Fig. 3. First, draw the pathological equivalent circuit of the target filter by replacing the op-amps with their pathological representation as shown in Fig. 4. Then number all the nodes of the equivalent circuit. Second, write the gene code of each op-amp in the form $\text{Gen}|_{opn} = Y.X.O_n.Z.0.P_n$ where Y and X are the interconnecting nodes of the nullator,
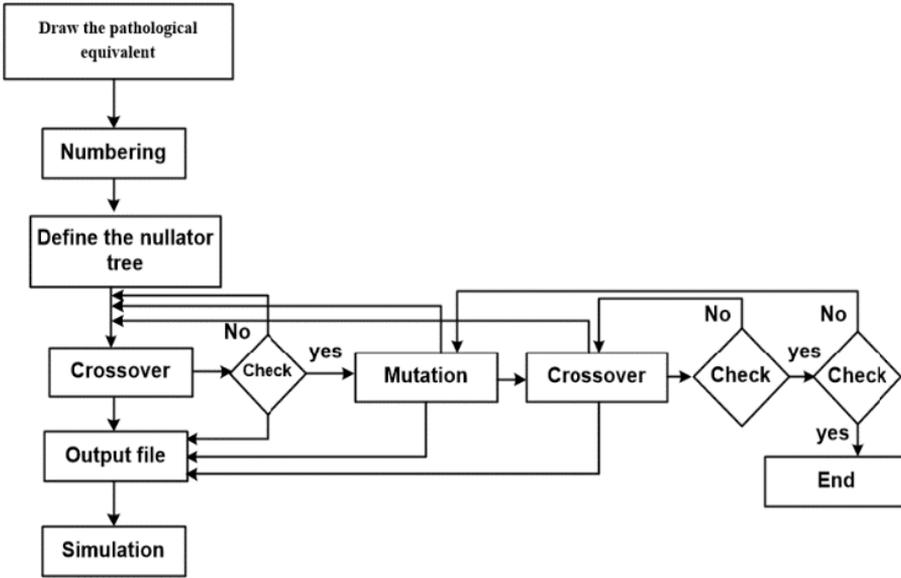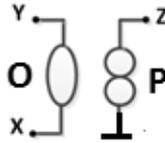
Fig. 3. Flow chart for the proposed algorithm.

Fig. 4. The nullor representation of op-amp.[16]

O represents a nullator, Z and 0 are the interconnecting nodes of the norator and P represents a norator. The genes then are arranged together to form a chromosome. Then write the chromosome for the circuit in the form: Chromosome= $\text{Gen}|_{op1}.\text{Gen}|_{op2}.\text{Gen}|_{op3}\ldots\text{Gen}|_{opn}$.

Third, using these gens, we can define the number of nullators "m" that contain a common node and draw the nullator tree for this circuit.

Fourth, for the chromosome of the original circuit, apply crossover between norators to get all possible equivalent circuit. Note all passive elements change their position as the norator change its position. The number of generated circuits is equal to $n!$ as in Ref. 16 where n is the number of norators.

Fifth, the generated circuits are then tested for the optimum ω_o and Q to get the best realizations and reject the bad ones.

Sixth, utilizing the pass circuits and based on nullator tree, apply genetic operations (mutation and crossover) to the interconnecting nodes of the nullators to generate new Chromosome. Then, repeat step four and five to get new configurations.

Repeat step six by changing the nullator tree and then step four and five.

The number of resulted circuits depends on number of norators in the chromosome and the number of nullators and nodes in the nullator tree. It can be calculated as follows:

no. of generated circuits = (no. of norators)!$(1 + $(no. of nullators$)^{\text{number of nodes}-1}$

3. Different Realizations for the TT Circuit

The TT filter is shown in Fig. 1. The transfer functions of the two output responses (BP and LP responses) are given by

$$\frac{V_{\text{BP}}}{V_{\text{in}}} = -\frac{s\dfrac{G_4}{C_1}}{s^2 + \dfrac{G_1}{C_1}s + \dfrac{G_2 G_3}{C_2 C_1}} \qquad \frac{V_{\text{LP}}}{V_{\text{in}}} = \frac{\dfrac{G_2 G_4}{C_2 C_1}}{s^2 + \dfrac{G_1}{C_1}s + \dfrac{G_2 G_3}{C_2 C_1}}. \tag{1}$$

The center frequency and the quality factor are as follows:

$$\omega_0 = \sqrt{\frac{G_2 G_3}{C_1 C_2}} \tag{2}$$

and

$$Q = \frac{1}{G_1}\sqrt{\frac{G_2 G_3 C_1}{C_2}}. \tag{3}$$

The proposed methodology is applied to the TT circuit configuration as follows:

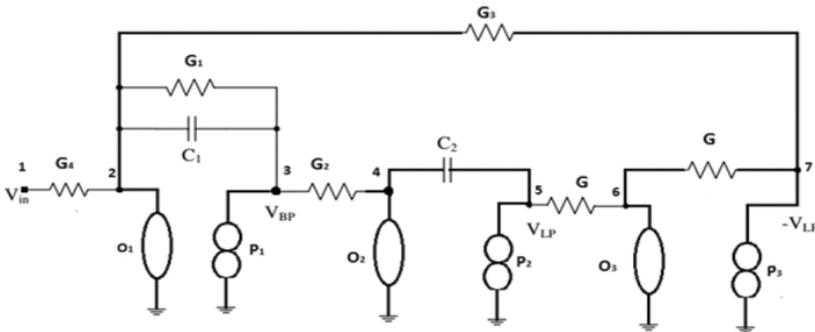**Step 1:** Draw the pathological equivalent circuit as shown in Fig. 5.

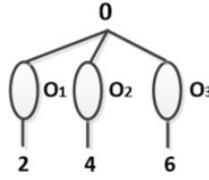Fig. 5. The nullor representation of TT filter.

Fig. 6. Nullator tree for the TT filter.

Step 2: Number all nodes then, write the chromosome for the circuit in the form like this

$$\text{Gen}|_{op1} = 2.0.\mathbf{O_1}.3.0.\mathbf{P_1}$$
$$\text{Gen}|_{op2} = 4.0.\mathbf{O_2}.5.0.\mathbf{P_2}$$
$$\text{Gen}|_{op3} = 6.0.\mathbf{O_3}.7.0.\mathbf{P_3}$$
$$\text{Chromosome1}|_{TT} = 2.0.\mathbf{O_1}.3.0.\mathbf{P_1}.4.0.\mathbf{O_2}.5.0.\mathbf{P_2}.6.0.\mathbf{O_3}.7.0.\mathbf{P_3}$$

Step 3: Draw the nullator tree for nullators O_1, O_2 and O_3 which have the same reference node (0) as shown in Fig. 6.

Step 4: Apply crossover between norators to get all possible solutions for the original nullator tree as follows:

$$\text{Chromosome1}|_{TT} = 2.0.\mathbf{O_1}.3.0.\mathbf{P_1}.4.0.\mathbf{O_2}.5.0.\mathbf{P_2}.6.0.\mathbf{O_3}.7.0.\mathbf{P_3}$$
$$\text{Chromosome2}|_{TT} = 2.0.\mathbf{O_1}.3.0.\mathbf{P_1}.4.0.\mathbf{O_2}.5.0.\mathbf{P_3}.6.0.\mathbf{O_3}.7.0.\mathbf{P_2}$$
$$\text{Chromosome3}|_{TT} = 2.0.\mathbf{O_1}.3.0.\mathbf{P_2}.4.0.\mathbf{O_2}.5.0.\mathbf{P_1}.6.0.\mathbf{O_3}.7.0.\mathbf{P_3}$$
$$\text{Chromosome4}|_{TT} = 2.0.\mathbf{O_1}.3.0.\mathbf{P_2}.4.0.\mathbf{O_2}.5.0.\mathbf{P_3}.6.0.\mathbf{O_3}.7.0.\mathbf{P_1}$$
$$\text{Chromosome5}|_{TT} = 2.0.\mathbf{O_1}.3.0.\mathbf{P_3}.4.0.\mathbf{O_2}.5.0.\mathbf{P_2}.6.0.\mathbf{O_3}.7.0.\mathbf{P_1}$$
$$\text{Chromosome6}|_{TT} = 2.0.\mathbf{O_1}.3.0.\mathbf{P_3}.4.0.\mathbf{O_2}.5.0.\mathbf{P_1}.6.0.\mathbf{O_3}.7.0.\mathbf{P_2}$$

All passive components that connecting to norators change their position as the norator change its position.

Step 5: Using the six chromosomes, there are six possible realizations for the TT circuits. The first realization is the original realization shown in Fig. 1 and the other five realizations are shown in Fig. 7.

Step 6: Apply crossover to any node number in the nullators' tree. If nodes 2 and 0 are crossovered, the resulted chromosome is as follows:

$$\text{Chromosome7}|_{TT} = 2.0.\mathbf{O_1}.3.0.\mathbf{P_1}.4.2.\mathbf{O_2}.5.0.\mathbf{P_2}.6.2.\mathbf{O_3}.7.0.\mathbf{P_3}$$
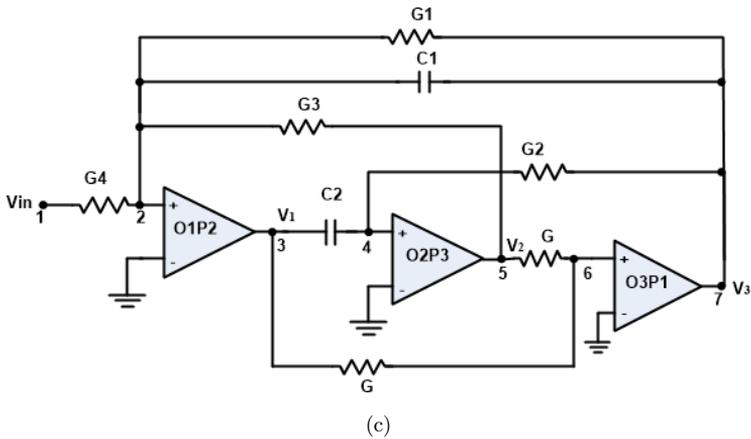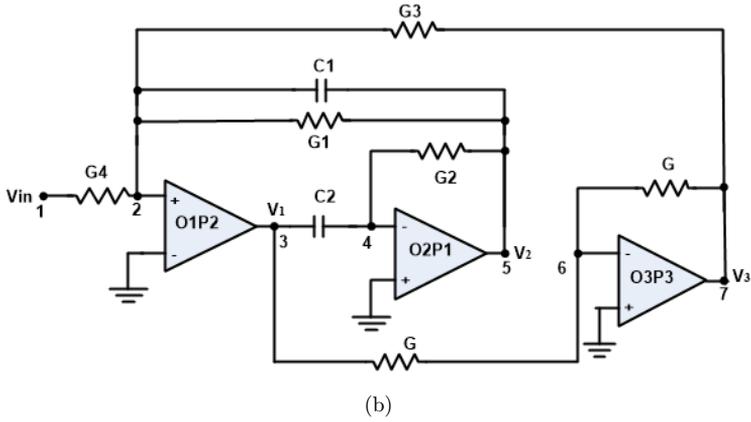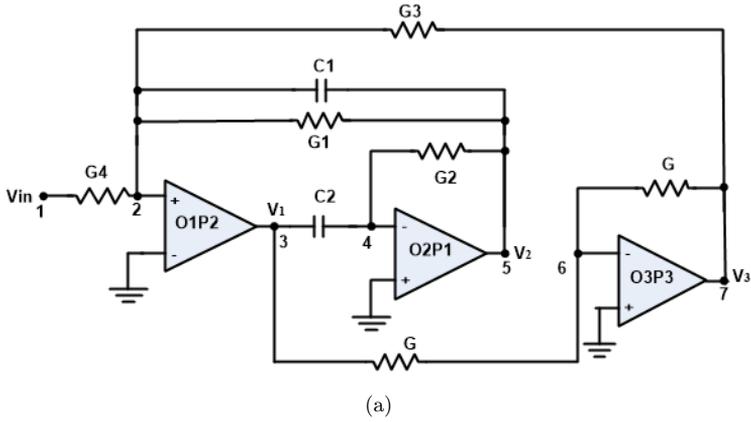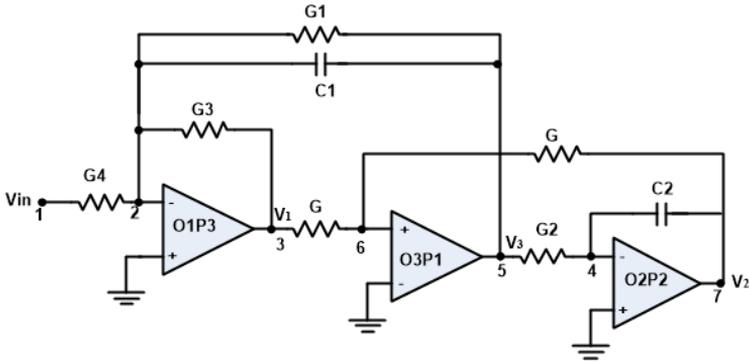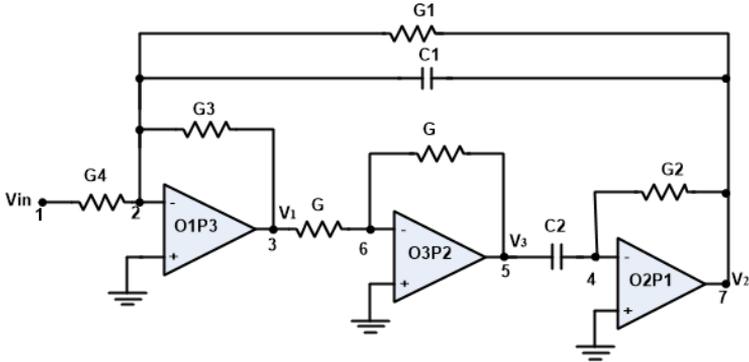
(a)

(b)

(c)

Fig. 7. The op-amp realizations for the TT equivalent circuits. (a) The op-amp realization of chromo-some 2. (b) The op-amp realization of chromosome 3. (c) The op-amp realization of chromosome 4. (d) The op-amp realization of chromosome 5. (e) The op-amp realization of chromosome 6.

(d)

(e)

Fig. 7. (*Continued*)

Repeating steps four and five on the resulted chromosome, the final realizations are shown in Fig. 8. The chromosomes for these configurations are as follows:

$$\text{Chromosome8}|_{\text{TT}} = 2.0.\mathbf{O_1}.3.0.\mathbf{P_1}.4.2.\mathbf{O_2}.5.0.\mathbf{P_3}.6.2.\mathbf{O_3}.7.0.\mathbf{P_2}$$
$$\text{Chromosome9}|_{\text{TT}} = 2.0.\mathbf{O_1}.3.0.\mathbf{P_2}.4.2.\mathbf{O_2}.5.0.\mathbf{P_1}.6.2.\mathbf{O_3}.7.0.\mathbf{P_3}$$
$$\text{Chromosome10}|_{\text{TT}} = 2.0.\mathbf{O_1}.3.0.\mathbf{P_2}.4.2.\mathbf{O_2}.5.0.\mathbf{P_3}.6.2.\mathbf{O_3}.7.0.\mathbf{P_1}$$
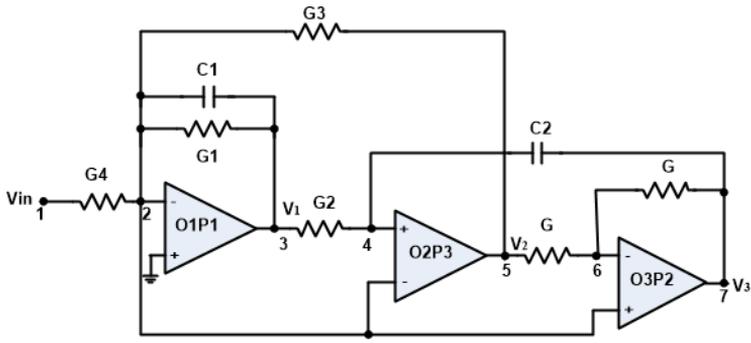$$\text{Chromosome11}|_{\text{TT}} = 2.0.\mathbf{O_1}.3.0.\mathbf{P_3}.4.2.\mathbf{O_2}.5.0.\mathbf{P_2}.6.2.\mathbf{O_3}.7.0.\mathbf{P_1}$$
$$\text{Chromosome12}|_{\text{TT}} = 2.0.\mathbf{O_1}.3.0.\mathbf{P_3}.4.2.\mathbf{O_2}.5.0.\mathbf{P_1}.6.2.\mathbf{O_3}.7.0.\mathbf{P_2}$$
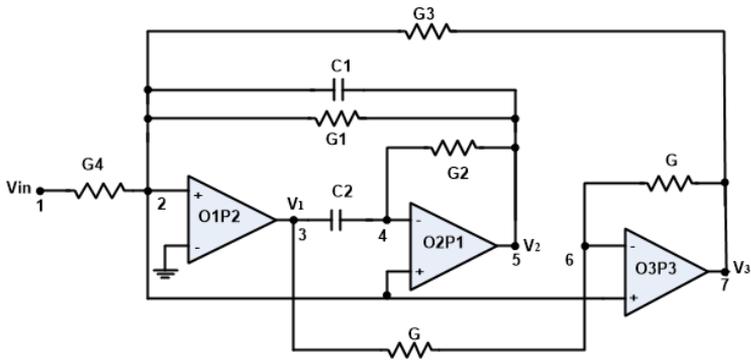
After every generated chromosome, repeat step six for all possible solutions. The total number of generated circuits is $3!(1 + 3^3)$. All possible chromosomes that can be generated from the nullator tree are shown in Table 1 (28 chromosome).
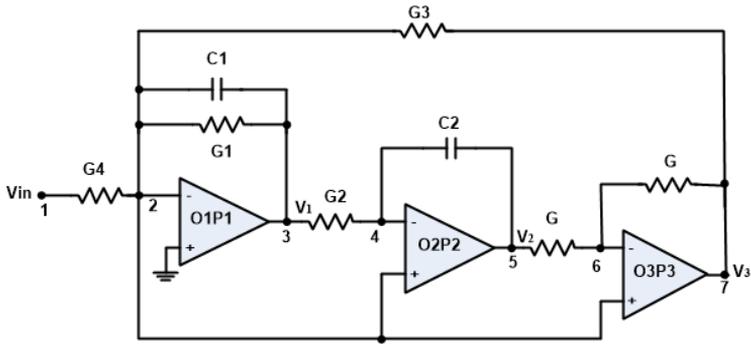
(a)

(b)

(c)

Fig. 8. The op-amp realizations for the TT equivalent circuits. (a) The op-amp realization of chromo-some 7. (b) The op-amp realization of chromosome 8. (c) The op-amp realization of chromosome 9. (d) The op-amp realization of chromosome 10. (e) The op-amp realization of chromosome 11. (f) The op-amp realization of chromosome 12.
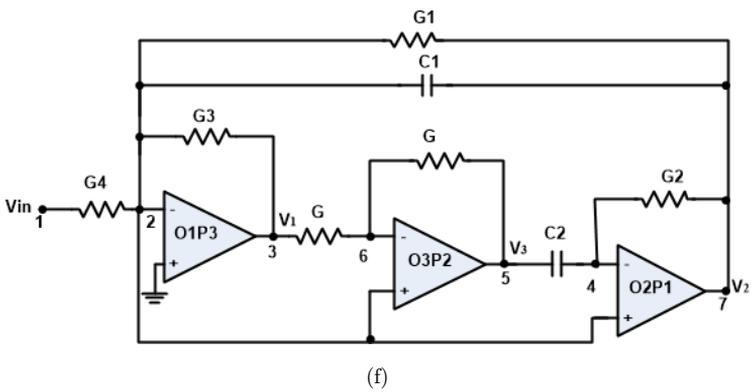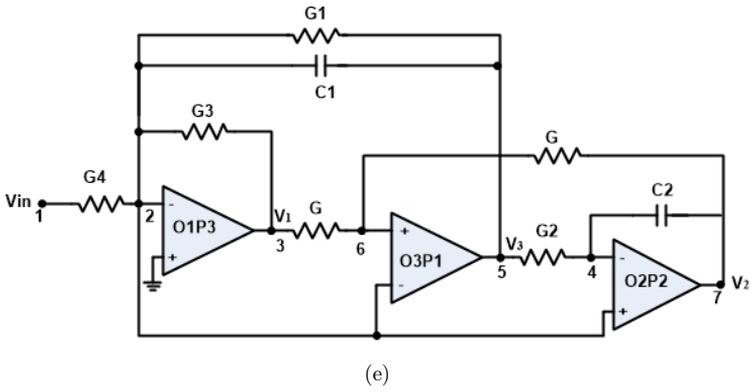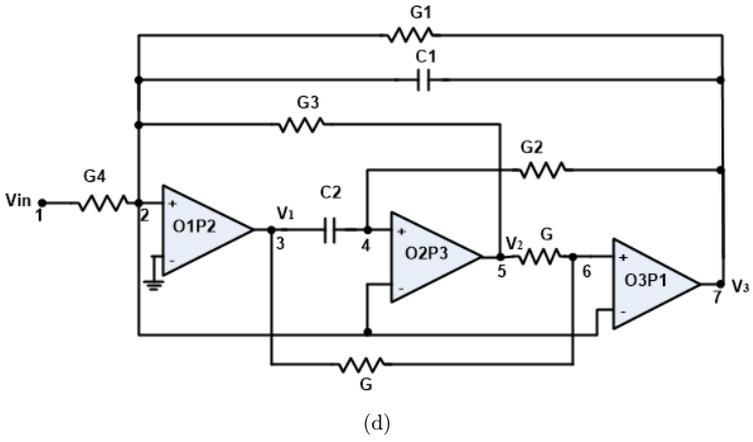
(d)

(e)

(f)

Fig. 8.   (*Continued*)

Table 1. All possible genes for TT after step 6.

2.0.$\mathbf{O_1}$.3.0.$\mathbf{P_1}$.4.0.$\mathbf{O_2}$.5.0.$\mathbf{P_2}$.6.0.$\mathbf{O_3}$.7.0.$\mathbf{P_3}$
2.6.$\mathbf{O_1}$.3.0.$\mathbf{P_1}$.4.6.$\mathbf{O_2}$.5.0.$\mathbf{P_2}$.6.0.$\mathbf{O_3}$.7.0.$\mathbf{P_3}$
2.0.$\mathbf{O_1}$.3.0.$\mathbf{P_1}$.4.2.$\mathbf{O_2}$.5.0.$\mathbf{P_2}$.6.2.$\mathbf{O_3}$.7.0.$\mathbf{P_3}$
2.4.$\mathbf{O_1}$.3.0.$\mathbf{P_1}$.4.0.$\mathbf{O_2}$.5.0.$\mathbf{P_2}$.6.4.$\mathbf{O_3}$.7.0.$\mathbf{P_3}$
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2.4.$\mathbf{O_1}$.3.0.$\mathbf{P_1}$.4.0.$\mathbf{O_2}$.5.0.$\mathbf{P_2}$.6.2.$\mathbf{O_3}$.7.0.$\mathbf{P_3}$
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2.0.$\mathbf{O_1}$.3.0.$\mathbf{P_1}$.4.2.$\mathbf{O_2}$.5.0.$\mathbf{P_2}$.6.0.$\mathbf{O_3}$.7.0.$\mathbf{P_3}$
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2.6.$\mathbf{O_1}$.3.0.$\mathbf{P_1}$.4.0.$\mathbf{O_2}$.5.0.$\mathbf{P_2}$.6.4.$\mathbf{O_3}$.7.0.$\mathbf{P_3}$
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2.6.$\mathbf{O_1}$.3.0.$\mathbf{P_1}$.4.0.$\mathbf{O_2}$.5.0.$\mathbf{P_2}$.6.0.$\mathbf{O_3}$.7.0.$\mathbf{P_3}$
2.0.$\mathbf{O_1}$.3.0.$\mathbf{P_1}$.4.6.$\mathbf{O_2}$.5.0.$\mathbf{P_2}$.6.0.$\mathbf{O_3}$.7.0.$\mathbf{P_3}$
2.4.$\mathbf{O_1}$.3.0.$\mathbf{P_1}$.4.6.$\mathbf{O_2}$.5.0.$\mathbf{P_2}$.6.0.$\mathbf{O_3}$.7.0.$\mathbf{P_3}$
2.6.$\mathbf{O_1}$.3.0.$\mathbf{P_1}$.4.0.$\mathbf{O_2}$.5.0.$\mathbf{P_2}$.6.4.$\mathbf{O_3}$.7.0.$\mathbf{P_3}$
2.0.$\mathbf{O_1}$.3.0.$\mathbf{P_1}$.4.6.$\mathbf{O_2}$.5.0.$\mathbf{P_2}$.6.2.$\mathbf{O_3}$.7.0.$\mathbf{P_3}$
2.6.$\mathbf{O_1}$.3.0.$\mathbf{P_1}$.4.2.$\mathbf{O_2}$.5.0.$\mathbf{P_2}$.6.0.$\mathbf{O_3}$.7.0.$\mathbf{P_3}$

4. Different Realizations for the KHN Circuit

The proposed methodology which introduced before is applied on the KHN filter shown in Fig. 2. The transfer functions of the three outputs (HP, BP and LP responses) of this configuration are given by

$$\frac{V_{\mathrm{HP}}}{V_{\mathrm{in}}} = \frac{s^2\dfrac{2G3}{G3+G4}}{s^2 + \dfrac{2G1G4}{C1(G3+G4)}s + \dfrac{G2G1}{C1C2}}\ , \tag{4}$$

$$\frac{V_{\mathrm{BP}}}{V_{\mathrm{in}}} = -\frac{s\dfrac{G12G3}{c1(G3+G4)}}{s^2 + \dfrac{2G1G4}{C1(G3+G4)}s + \dfrac{G2G1}{C1C2}}\ , \tag{5}$$

$$\frac{V_{\mathrm{LP}}}{V_{\mathrm{in}}} = \frac{\dfrac{2G3}{G3+G4}\dfrac{G1G2}{C1C2}}{s^2 + \dfrac{2G1G4}{C1(G3+G4)}s + \dfrac{G2G1}{C1C2}}, \tag{6}$$

where

$$\omega_0 = \sqrt{\frac{G2G1}{C1C2}}, \tag{7}$$

$$Q = \frac{G3+G4}{2G4}\sqrt{\frac{C1G2}{C2G1}}. \tag{8}$$

4.1. *Applying the methodology for KHN type a filter*

Step 1: Draw the pathological equivalent circuit as shown in Fig. 9(a).

Step 2: Number the nodes then, write the gens and the circuit chromosome in the form like this

(a)

(b)
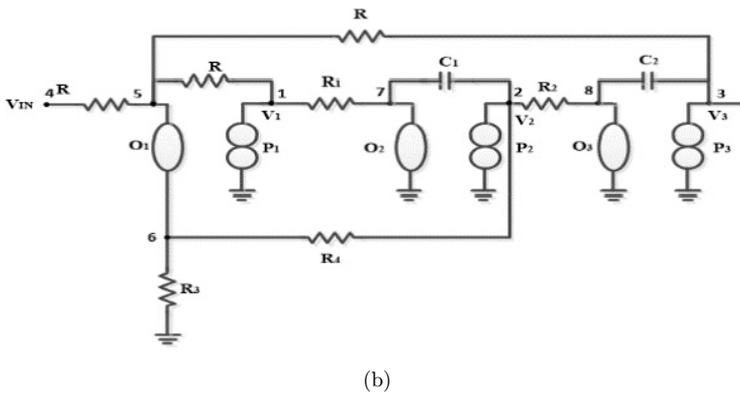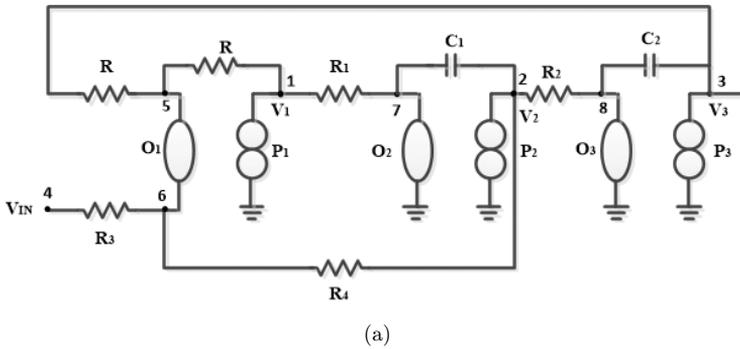
Fig. 9. (a) Type A KHN circuit using nullators and norators. (b) Type B inverted KHN circuit using nullators and norators.

$$\text{Gen}|_{\text{op1}} = 5.6.\mathbf{O_1}.1.0.\mathbf{P_1}$$
$$\text{Gen}|_{\text{op2}} = 7.0.\mathbf{O_2}.2.0.\mathbf{P_2}$$
$$\text{Gen}|_{\text{op3}} = 8.0.\mathbf{O_3}.3.0.\mathbf{P_3}$$
$$\text{Chromosome1}|_{\text{KHNtypeA}} = 5.6.\mathbf{O_1}.1.0.\mathbf{P_1}.7.0.\mathbf{O_2}.2.0.\mathbf{P_2}.8.0.\mathbf{O_3}.3.0.\mathbf{P_3}$$

Step 3: Notice from Gen2 and Gen3 that O_2 and O_3 nullators have the common node (0) as shown in the nullator tree shown in Fig. 10.

Step 4: Crossover between norators to get all possible solutions. Using

$$\text{Chromosome1}|_{\text{KHNtypeA}} = 5.6.\mathbf{O_1}.1.0.\mathbf{P_1}.7.0.\mathbf{O_2}.2.0.\mathbf{P_2}.8.0.\mathbf{O_3}.3.0.\mathbf{P_3}$$
$$\text{Chromosome2}|_{\text{KHNtypeA}} = 5.6.\mathbf{O_1}.1.0.\mathbf{P_2}.7.0.\mathbf{O_2}.2.0.\mathbf{P_1}.8.0.\mathbf{O_3}.3.0.\mathbf{P_3}$$
$$\text{Chromosome3}|_{\text{KHNtypeA}} = 5.6.\mathbf{O_1}.1.0.\mathbf{P_2}.7.0.\mathbf{O_2}.2.0.\mathbf{P_3}.8.0.\mathbf{O_3}.3.0.\mathbf{P_1}$$
$$\text{Chromosome4}|_{\text{KHNtypeA}} = 5.6.\mathbf{O_1}.1.0.\mathbf{P_3}.7.0.\mathbf{O_2}.2.0.\mathbf{P_2}.8.0.\mathbf{O_3}.3.0.\mathbf{P_1}$$
$$\text{Chromosome5}|_{\text{KHNtypeA}} = 5.6.\mathbf{O_1}.1.0.\mathbf{P_3}.7.0.\mathbf{O_2}.2.0.\mathbf{P_1}.8.0.\mathbf{O_3}.3.0.\mathbf{P_2}$$
$$\text{Chromosome6}|_{\text{KHNtypeA}} = 5.6.\mathbf{O_1}.1.0.\mathbf{P_1}.7.0.\mathbf{O_2}.2.0.\mathbf{P_3}.8.0.\mathbf{O_3}.3.0.\mathbf{P_2}$$

Step 5: Using the six chromosomes, the six realizations for the KHN type A circuit are shown in Fig. 11.

Step 6: Apply crossover to any node number in the nullators' tree. The resulted chromosome for crossover between 7 and 0 is as follows:

$$\text{Chromosome7}|_{\text{KHNtypeA}} = 5.6.\mathbf{O_1}.1.0.\mathbf{P_1}.7.8.\mathbf{O_2}.2.0.\mathbf{P_2}.8.0.\mathbf{O_3}.3.0.\mathbf{P_3}$$

Then apply Steps 4 and 5 to get additional five realizations. The resulted six realizations are simulated and two of them are rejected. The accepted chromosomes are as follows:

$$\text{Chromosome7}|_{\text{KHNtypeA}} = 5.6.\mathbf{O_1}.1.0.\mathbf{P_1}.7.8.\mathbf{O_2}.2.0.\mathbf{P_2}.8.0.\mathbf{O_3}.3.0.\mathbf{P_3}$$
$$\text{Chromosome8}|_{\text{KHNtypeA}} = 5.6.\mathbf{O_1}.1.0.\mathbf{P_1}.7.8.\mathbf{O_2}.2.0.\mathbf{P_3}.8.0.\mathbf{O_3}.3.0.\mathbf{P_2}$$
$$\text{Chromosome9}|_{\text{KHNtypeA}} = 5.6.\mathbf{O_1}.1.0.\mathbf{P_1}.7.0.\mathbf{O_2}.2.0.\mathbf{P_2}.8.7.\mathbf{O_3}.3.0.\mathbf{P_3}$$
$$\text{Chromosome10}|_{\text{KHNtypeA}} = 5.6.\mathbf{O_1}.1.0.\mathbf{P_1}.7.0.\mathbf{O_2}.2.0.\mathbf{P_3}.8.7.\mathbf{O_3}.3.0.\mathbf{P_2}$$
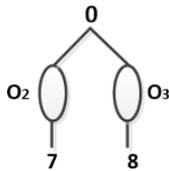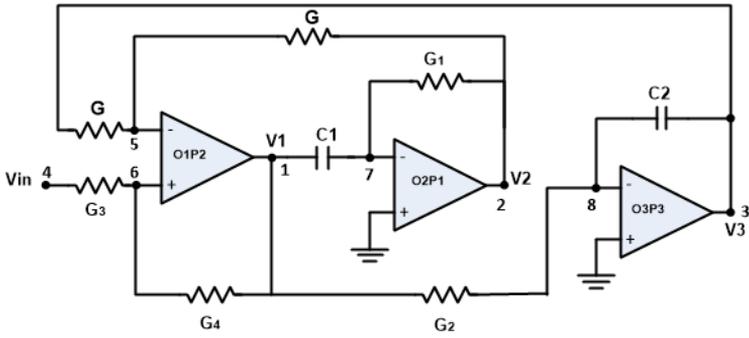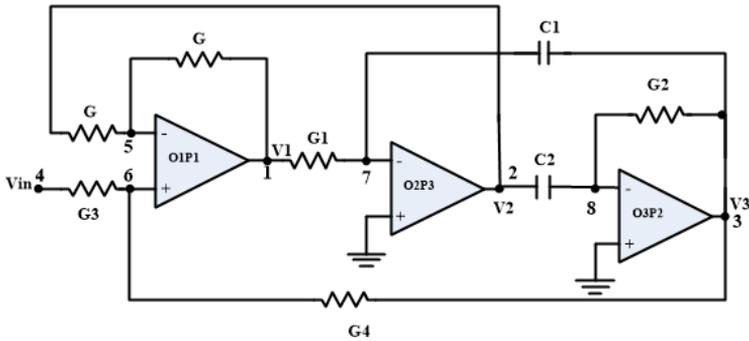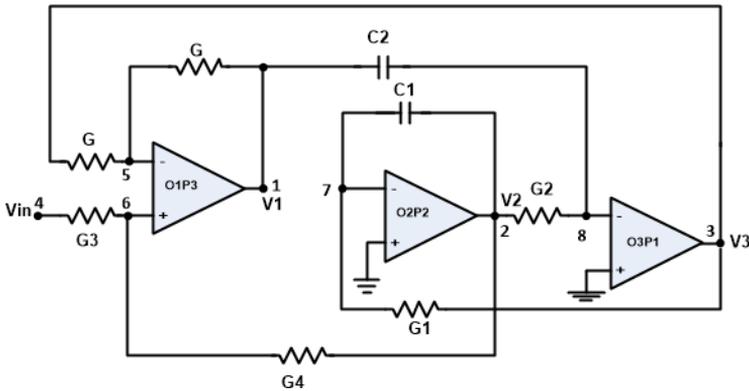

Fig. 10. Nullator tree for the KHN type A filter.

(a)

(b)

(c)

Fig. 11. The op-amp realizations for the KHN equivalent circuits type A. (a) The op-amp realization of chromosome 2. (b) The op-amp realization of chromosome 3. (c) The op-amp realization of chromosome 4. (d) The op-amp realization of chromosome 5. (e) The op-amp realization of chromosome 6.
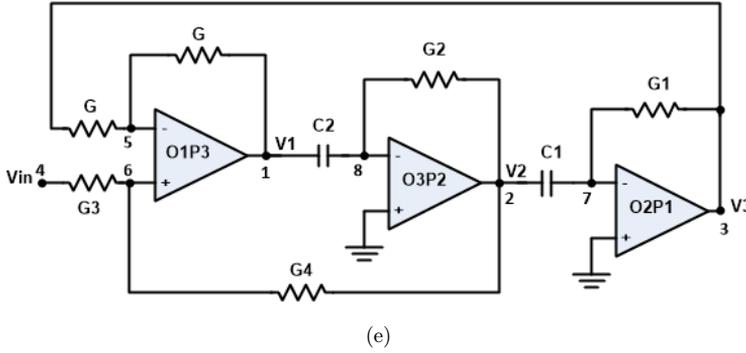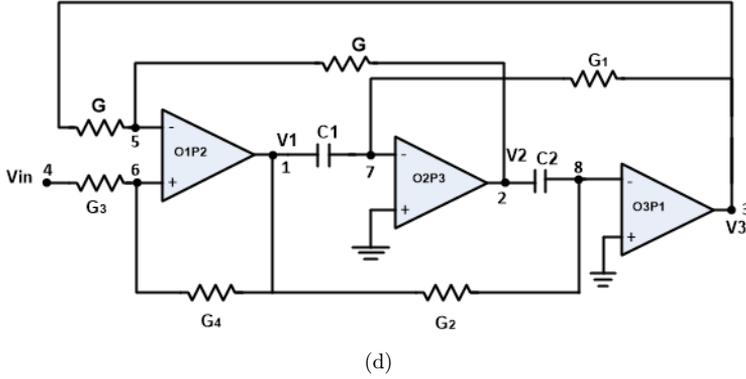
(d)

(e)

Fig. 11. (*Continued*)

The corresponding realizations are shown in Fig. 12.

Note that there are four cases for the nullator tree and each case can generate six configurations using steps four and five. So, the total number of the circuits is $2!(1 + 2^2) = 30$. Unfortunately, there are 20 realizations that fail in the simulation test and only 10 configurations pass.

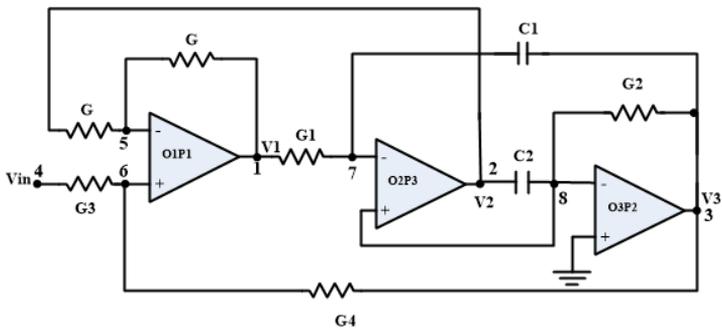## 4.2. *Applying the methodology for KHN type B filter*

The proposed methodology applied on KHN type B is as same as it was applied on type A in the previous subsection. The transfer functions at the three outputs are given as follows:

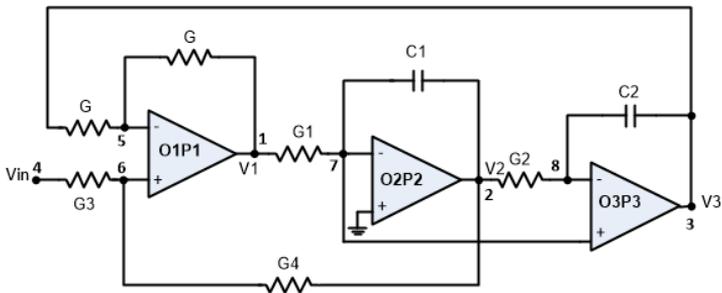$$\frac{V_1}{V\text{in}} = -\frac{s^2}{s^2 + \frac{3G4G1}{C1(G3 + G4)}s + \frac{G2G1}{C1C2}}, \tag{9}$$

$$\frac{V_2}{V\text{in}} = \frac{s\dfrac{G1}{C1}}{s^2 + \dfrac{3G4G1}{C1(G3+G4)}s + \dfrac{G2G1}{C1C2}}, \tag{10}$$
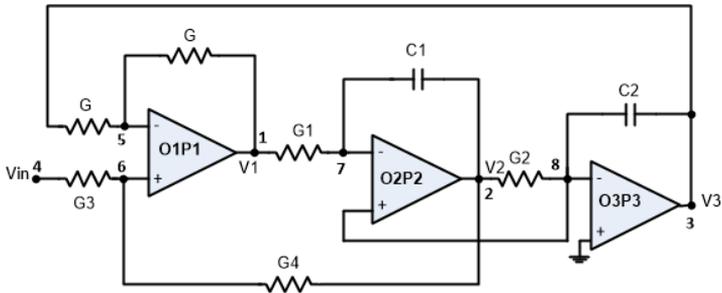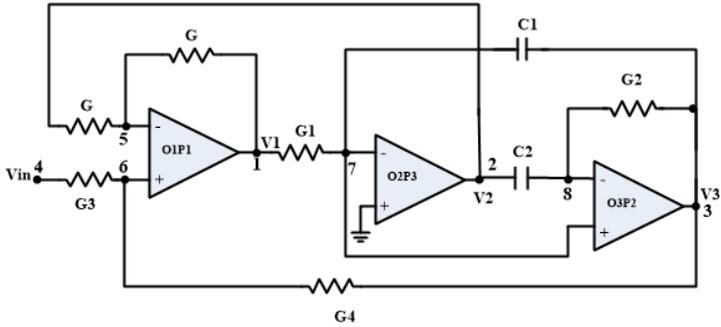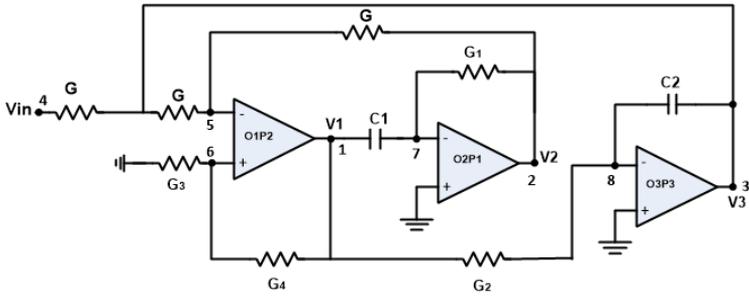

(a)

(b)

(c)

Fig. 12. The op-amp realizations for the KHN equivalent circuits type A. (a) The op-amp realization of chromosome 7. (b) The op-amp realization of chromosome 8. (c) The op-amp realization of chromosome 9. (d) The op-amp realization of chromosome 10.
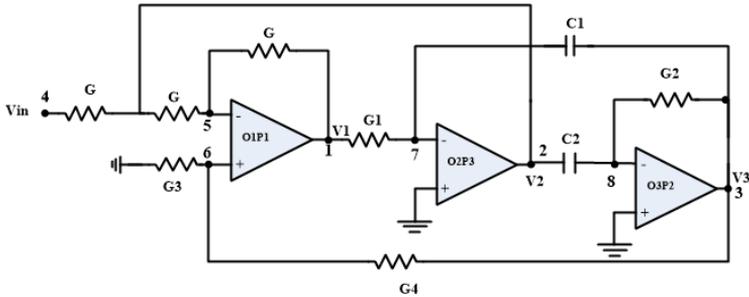
(d)

Fig. 12.   (*Continued*)

(a)

(b)

Fig. 13.   The op-amp equivalent realizations for the KHN type B with the original nullator tree.

$$\frac{V_3}{V\text{in}} = -\frac{\dfrac{G1G2}{C1C2}}{s^2 + \dfrac{3G4G1}{C1(G3+G4)}s + \dfrac{G2G1}{C1C2}}, \tag{11}$$

(c)

(d)

(e)
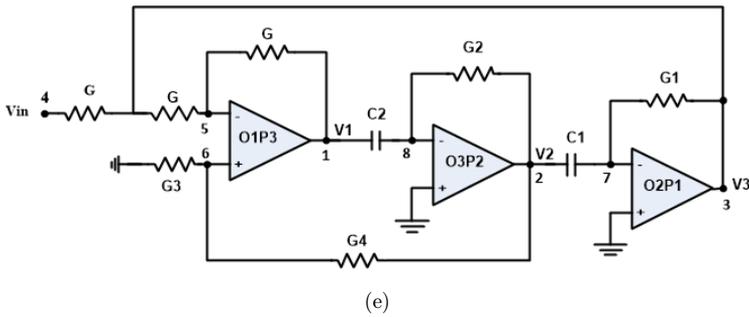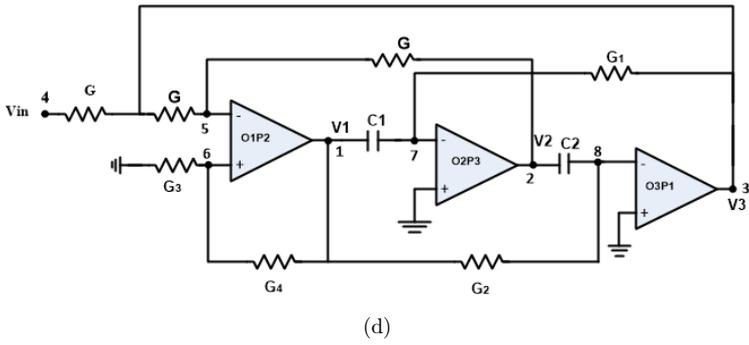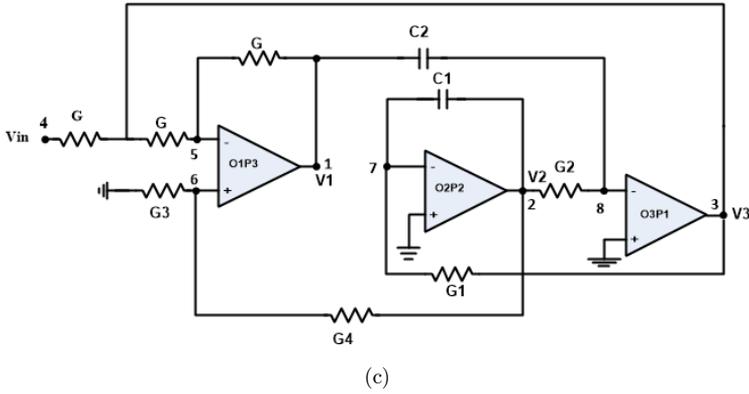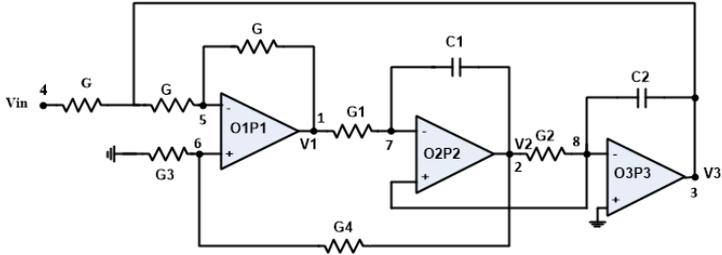
Fig. 13.   (*Continued*)
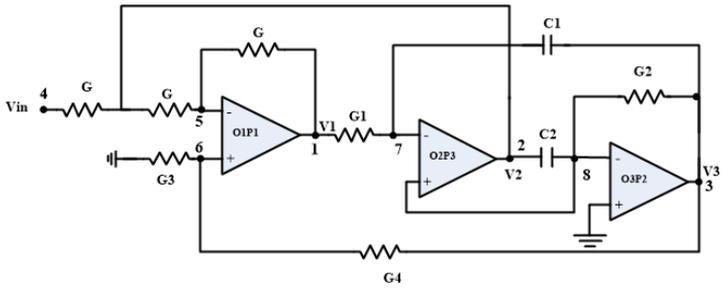
$$\omega_0 = \sqrt{\frac{G2G1}{C1C2}}, \tag{12}$$

$$Q = \frac{G3 + G4}{3G4} \sqrt{\frac{C1G2}{C2G1}}. \tag{13}$$
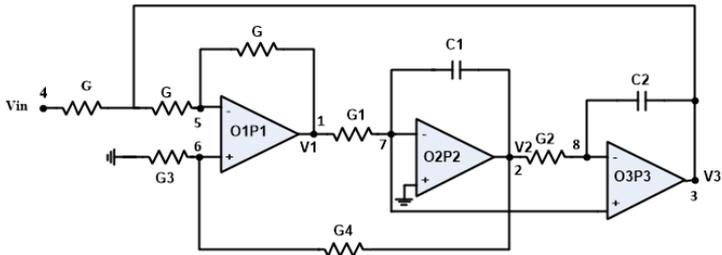
The accepted configurations are shown in Figs. 13 and 14.
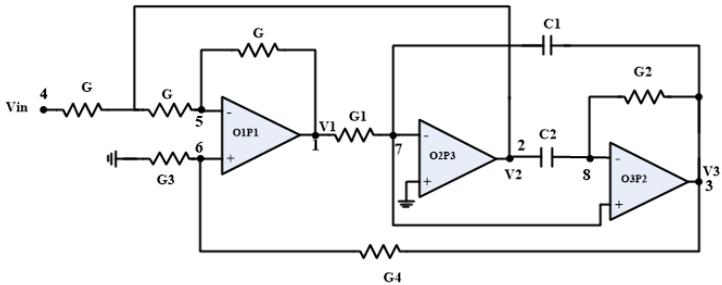
(a)

(b)

(c)

(d)

Fig. 14. The op-amp realizations for the accepted equivalent realizations of KHN type B after applying crossover on the nullators tree.

5. Simulation Results

In this section, PSpice simulations are carried out using the op-amp 741 model with supply voltages of $\pm\,15\,\text{V}$.

5.1. *TT filter simulations*

The TT circuit of Fig. 1 is designed for $Q = 5$ and $f_0 = 10\,\text{kHz}$ taking $C_1 = C_2 = 500\,\text{pF}$, $R_1 = 150\,\text{k}\Omega$, $R_2 = R_3 = R_4 = 31.9\,\text{k}\Omega$ and $R = 10\,\text{k}\Omega$. The input signal is a sinusoidal input voltage source of $1\,\text{V}$ magnitude. Figure 15 represents the magnitude response results of the TT equivalent circuits generated using chromosomes 1–12.

The numerical values of the center frequency and the quality factor for the simulated circuits are given in Table 2. Comparing among these results, one can find that the lowest ΔQ and $\Delta\omega_0$ belongs to the configuration of Chromosome 4 which is shown in Fig. 7(c).

It is amazing result that this configuration has better performance than the original one. The highest error in the quality factor is found in the realization of Chromosome 6 (belongs to Fig. 7(e)) and Chromosome 12 (belongs to Fig. 8(f)). Also, the highest $\Delta\omega_0 = 0.32630\,\text{kHz}$ is found in the realization of Chromosome 6 shown in Fig. 7(e).

5.2. *KHN filter*

The KHN circuit type A of Fig. 2(a) is designed for $Q = 5$ and $f_0 = 10\,\text{kHz}$ taking $C_1 = C_2 = 500\,\text{pF}$, $R_1 = R_2 = 31.9\,\text{k}\Omega$, $R = 10\,\text{k}\Omega$, $R_3 = 10\,\text{k}\Omega$, $R_4 = 90\,\text{k}\Omega$. Also, The KHN circuit type B of Fig. 2(b) is designed for $Q = 5$ and $f_0 = 10\,\text{kHz}$ taking $C_1 = C_2 = 500\,\text{pF}$, $R_1 = R_2 = 31.9\,\text{k}\Omega$, $R = 10\,\text{k}\Omega$, $R_3 = 10\,\text{k}\Omega$, $R_4 = 140\,\text{k}\Omega$. The input signal is a sinusoidal input voltage source of $1\,\text{V}$ magnitude. Figure 16
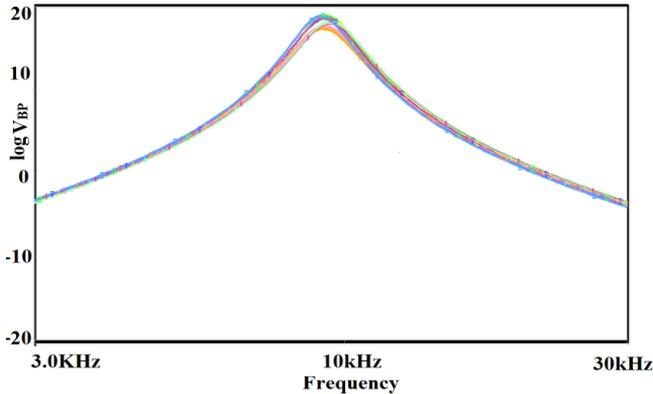

Fig. 15.   Bandpass magnitude response of TT equivalent generated circuits.

Table 2.   Summarized results of simulations for equivalent circuits of TT.

The equivalent configuration	Center frequency (kHz)	Quality factor
Chromosome 1	9.97255	5.10871
Chromosome 2	10.15359	5.08550
Chromosome 3	10.17965	4.92152
Chromosome 4	10.06507	5.02838
Chromosome 5	10.17484	4.32630
Chromosome 6	10.41956	4.65435
Chromosome 7	10.04397	4.87726
Chromosome 8	10.13557	4.84579
Chromosome 9	10.20106	5.15268
Chromosome 10	10.13905	4.83872
Chromosome 11	10.19252	4.48573
Chromosome 12	10.40283	4.44862

represents the PSpice simulation comparison among the accepted KHN equivalent circuits of type A. Also, the PSpice simulation comparison among the accepted KHN equivalent circuits of type B is shown in Fig. 17.

Table 3 summarizes the numerical simulation results of the KHN type A equivalent circuits. From this table, one can deduce that the lowest ΔQ and $\Delta \omega_0$ belongs to the configuration of Chromosome 8 which is shown in Fig. 12(b) and better than the chromosome 1 (original configuration). The highest error in the quality factor is found in the realization of Chromosome 6; In Fig. 11(e), this error is equal to 0.31054, where the highest $\Delta \omega_0 = 0.30966\,\text{kHz}$ is found in the realization of Chromosome 7 related to Fig. 12(a).

Also, Table 4 summarizes the numerical simulation results of the KHN type B accepted equivalent circuits. Using this table, one can conclude that chromosome 8, realized in Fig. 14(b), is better than chromosome 1 which represents the original
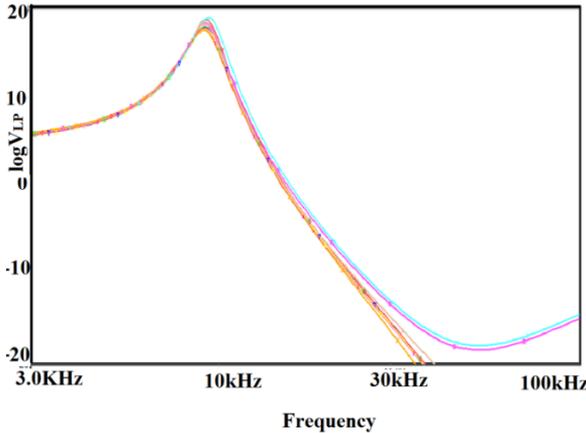

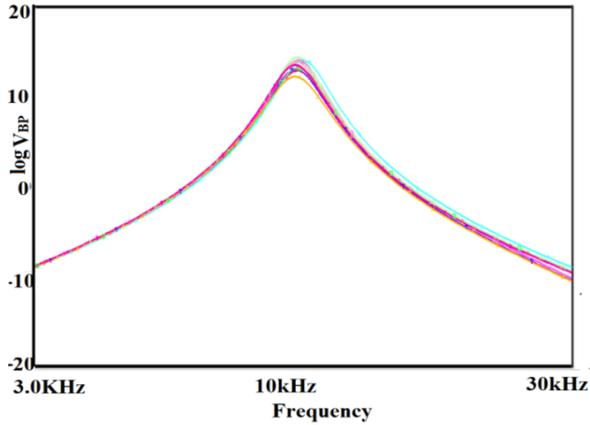Fig. 16.   Response of LP KHN filters type A.

Fig. 17. Response of BP KHN filters type B.

Table 3. Summarized results of simulations for equivalent circuits of KHN type A.

The equivalent configuration	Center frequency (kHz)	Quality factor
Chromosome 1	10.08332	5.08299
Chromosome 2	10.16731	4.91966
Chromosome 3	10.14260	5.34665
Chromosome 4	10.17277	4.99145
Chromosome 5	10.30966	5.30775
Chromosome 6	10.10101	4.68946
Chromosome 7	10.10505	5.31702
Chromosome 8	10.06368	4.90758
Chromosome 9	10.16008	4.93642
Chromosome 10	10.15422	4.88759

Table 4. Summarized results of simulations for equivalent circuits of KHN type B.

The equivalent configuration	Center frequency (kHz)	Quality factor
Chromosome 1	10.06264	5.30619
Chromosome 2	10.21467	4.92968
Chromosome 3	10.20162	4.79888
Chromosome 4	10.15289	5.40975
Chromosome 5	10.36944	5.30888
Chromosome 6	10.12862	4.52735
Chromosome 7	10.08554	5.56163
Chromosome 8	10.04298	5.09454
Chromosome 9	10.11851	4.90117
Chromosome 10	10.13150	4.86668

configuration. It has the lowest $\Delta Q = 0.09454$ and $\Delta \omega_0 = 0.04298$ kHz. The highest $\Delta Q = 0.56163$ is found in the configuration of Chromosome 7 realized in Fig. 14(a). Also, the highest $\Delta \omega_0$ equals to 0.36944 kHz which belongs to the configuration of Chromosome 5 realized in Fig. 13(d).

6. Conclusions

New application for the genetic-based methods to generate equivalent filter circuits based on the nullor representation was presented. The proposed methodology was applied on two well-known filters (TT and KHN) to generate a family of 168 TT and 30 KHN equivalent circuits. Some of the generated TT circuits were confirmed using PSpice simulations and the simulation results showed that some generated circuits have better performance compared with the original configuration. Also, the equivalent KHN realizations are tested and only 10 realizations are accepted. The accepted realizations are simulated and compared with the original configuration. One of the generated circuits has a better performance compared to the original one.

It is worth noting that the greatest benefit of the proposed genetic methodology is to generate a large number of equivalent realizations to the required circuit (e.g., filter) programmatically. Also, the proposed methodology represents a systematic generation method that can be applied to any other op-amp circuit.

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