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Transformation of oscillators using Op Amps, unity gain cells and CFOA

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Abstract The realization of two integrator loop oscillators using Operational Amplifiers (Op Amps) is reviewed and a new additional circuit to provide independent control on the oscillation condition is proposed. Four new grounded capacitor oscillator circuits using unity gain cells and having independent control on the condition of oscillation and on the frequency of oscillation are introduced. The link between the Op Amp based two integrator loop oscillators and three Current Feedback Operational Amplifier (CFOA) based oscillators is detected and clearly explained. This paper serves also as a tutorial paper in introducing the subject of second order two integrator loop oscillators using state variable matrix equation and Nodal Admittance Matrix (NAM) equation.

Keywords Two integrator loop oscillators · Op Amp · Unity gain cells · Current feedback operational amplifier (CFOA)

1 Introduction

Real oscillators are nonlinear circuits. Several Op Amp RC sinusoidal oscillator circuits are included in Textbooks and are analyzed using Barkhausen criteria [1–3]. Due to the frequency dependent nature of the Op Amp gain [4], the actual performance of the Op Amp RC oscillators differs from the ideal performance. Active compensation methods of the Op Amp finite gain bandwidth product have been used to improve the performance of Op Amp oscillators [5, 6].

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Recently there has been a great interest in realizing sinusoidal oscillator circuits using the Current Feedback Operational Amplifier (CFOA) [7–16]. The CFOA is a very versatile building block and is now commercially available from several manufactures.

Most of the CFOA based oscillators given in the literature are introduced without explaining their link to the original Op Amp based oscillators. One of the objectives of this paper is to show the link between Op Amp based two integrator loop oscillators and the corresponding CFOA based oscillators.

The state equations and the Nodal Admittance Matrix (NAM) equation are used throughout this paper which is partially a review paper.

This paper may also serve as a tutorial paper in introducing the subject of second order two integrator loop oscillators using state equations and NAM equations.

2 Oscillator state equations

The oscillators considered in this paper are second order oscillators having independent control on the condition of oscillation and on the frequency of oscillation by varying two different resistors. The state equation for the generalized oscillator circuit shown in Fig. 1(a) is descried by the following matrix equation [15, 17]:

$$\begin{bmatrix} \frac{dv_1}{dt} \\ \frac{dv_2}{dt} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \tag{1}$$

The condition of oscillation and the radian frequency of oscillation are given by:

$$a_{11} + a_{22} = 0 \tag{2}$$

$$\omega_O = \sqrt{a_{11}a_{22} - a_{12}a_{21}} \tag{3}$$

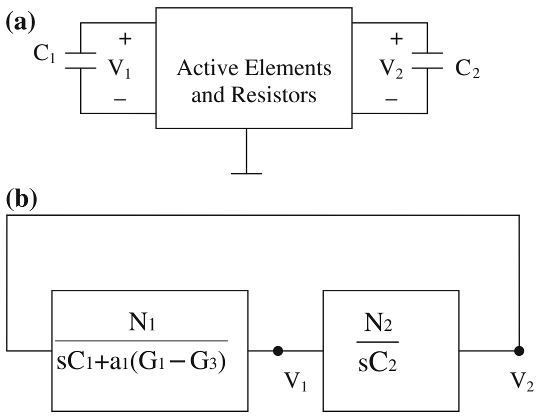

Fig. 1 **a** Generalized diagram of second order oscillator circuit. **b** Block diagram of two integrator loop oscillator

If both a_{11} and a_{22} are zero there will be no control on the condition of oscillation. On the other hand if both a_{11} and a_{22} are nonzero there will be no independent control on the condition of oscillation.

The class of oscillators considered in this paper has a_{22} equal to zero and is represented by the block diagram shown in Fig. 1(b).

3 Op Amp based oscillators

The analysis in this section is based on assuming matched Op Amps are used and using the single pole model of the Op Amp which is represented by the following equation [4]:

$$A = \frac{\omega_t}{s} \tag{4}$$

where ω_t is the unity gain bandwidth of the Op Amp.

3.1 Three Op Amp oscillators

The first circuit given in this paper is the three Op Amp two integrator loop circuit shown in Fig. 2(a). It employs three single input Op Amps, two floating capacitors and four floating resistors [17]. The circuit belongs to the block diagram of Fig. 1(b) and its NAM equation based on using Eq. 4 and neglecting second order terms is given by:

$$Y = \begin{bmatrix} sC_1 + \frac{G_1}{\omega_t}s & -G_1 + \frac{2G_1}{\omega_t}s \\ G_2 & sC_2 + \frac{G_2}{\omega_t}s \end{bmatrix} \tag{5}$$

Assuming ideal Op Amps the NAM equation is simplified to:

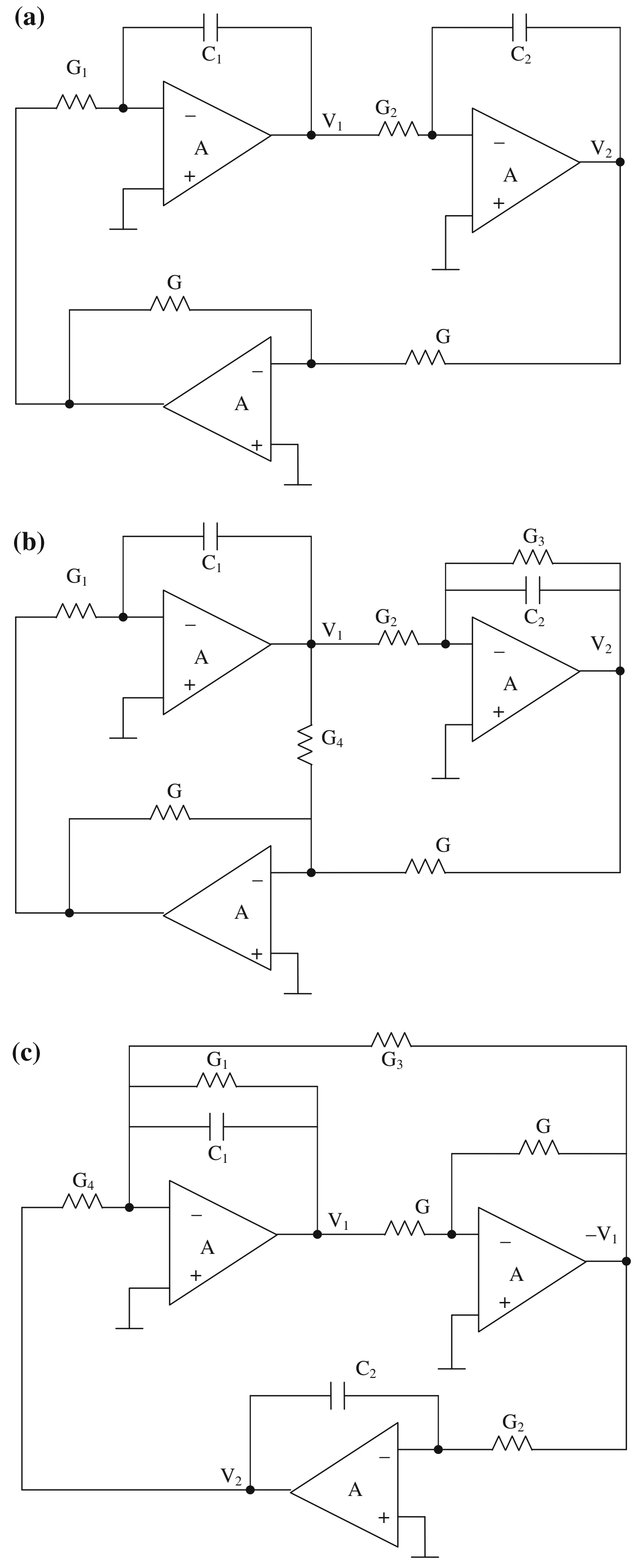

Fig. 2 **a** The three single input Op Amps oscillator. **b** Two integrator loop oscillator proposed in [17]. **c** The proposed modified single input Op Amps oscillator

$$Y = \begin{bmatrix} sC_1 & -G_1 \\ G_2 & sC_2 \end{bmatrix} \quad (6)$$

This circuit has the disadvantage of having no independent control on the oscillation condition. The circuit shown in Fig. 2(b) [17] overcomes this problem and it has the following NAM equation based on using Eq. 4 and neglecting second order terms is given by:

$$Y = \begin{bmatrix} sC_1 - \frac{G_1G_4}{G} + \frac{G_1}{\omega_t}s + \frac{G_1G_4}{G}\left(2 + \frac{G_4}{G}\right)\frac{s}{\omega_t} & -G_1 + G_1\left(2 + \frac{G_4}{G}\right)\frac{s}{\omega_t} \\ G_2 & sC_2 + G_3 + \frac{G_2+G_3}{\omega_t}s \end{bmatrix} \quad (7)$$

Assuming ideal Op Amps the NAM equation is simplified to:

$$Y = \begin{bmatrix} sC_1 - \frac{G_1G_4}{G} & -G_1 \\ G_2 & sC_2 + G_3 \end{bmatrix} \quad (8)$$

From the above equation the state matrix A is obtained and is given by:

$$A = \begin{bmatrix} \frac{G_1G_4}{C_1G} & \frac{G_1}{C_1} \\ -\frac{G_2}{C_2} & -\frac{G_3}{C_2} \end{bmatrix} \quad (9)$$

The radian frequency of oscillation is given by:

$$\omega_o = \sqrt{\frac{G_1G_2 - \frac{G_1G_3G_4}{G}}{C_1C_2}} \quad (10)$$

The frequency of oscillation is independently controlled by varying G_2 without affecting the condition of oscillation which is given by:

$$\frac{C_1}{C_2} = \frac{G_1G_4}{GG_3} \quad (11)$$

The condition of oscillation can not be independently controlled which limits the practicality of this circuit.

This circuit has a nonzero a_{11} and a_{22}. In order to have independent control on both the condition of oscillation and the radian frequency of oscillation the circuit is modified to a new circuit having a_{22} equal to zero as given next.

A new modified oscillator circuit with independent control on the condition of oscillation and on the radian frequency of oscillation is shown in Fig. 2(c).

The NAM equation based on using the single pole model of the Op Amp and neglecting second order terms is obtained as:

$$Y = \begin{bmatrix} sC_1 + G_1 - G_3 + \frac{G_1+3G_3+G_4}{\omega_t}s & G_4 \\ -G_2 + \frac{2G_2}{\omega_t}s & sC_2 + \frac{G_2}{\omega_t}s \end{bmatrix} \quad (12)$$

Assuming ideal Op Amps the NAM equation is simplified to:

$$Y = \begin{bmatrix} sC_1 + G_1 - G_3 & G_4 \\ -G_2 & sC_2 \end{bmatrix} \quad (13)$$

From the above equation the modified state matrix A_m obtained from the state matrix A by multiplying first row by C_1 and second row by C_2 and is given in Table 1. The parameters N_1, N_2 of the two integrators as well as the radian frequency of oscillation are also given in Table 1.

The condition of oscillation is given by:

$$G_3 = G_1 \quad (14)$$

The condition of oscillation is controlled by G_3 or G_1 without affecting the frequency of oscillation which is independently controlled by G_2 or G_4 without affecting the condition of oscillation.

This circuit can be generated from the modified Tow-Thomas filter circuit given in [18, 19].

3.2 Two Op Amp oscillators

The circuit shown in Fig. 3 is the well known quadrature oscillator [1] based on using Deboo noninverting integrator [20]. The first stage consists of a noninverting amplifier of gain two realized by the Op Amp and the two equal resistors connected to its inverting input terminal. In this case the voltage on G_1 is V_1 with the shown polarity; that is C_1 is connected in parallel with $-G_1$.This can be physically explained by the fact that the Op Amp and the two feedback resistors connected around it acts as a Negative Impedance Converter (NIC) reflecting the load conductance G connected between the inverting input and ground to become $-G_1$ at node 1.The second stage is an inverting integrator.

The NAM equation based on using the single pole model of the Op Amp and neglecting second order terms is obtained as:

Table 1 The parameters a_1, N_1, N_2 of the block diagram of Fig. 1(b)

Circuit figure number	a_1	N_1	N_2	$[A_m]$	ω_O	Reference
2(c)	1	$-G_4$	G_2	$\begin{bmatrix} G_3 - G_1 & -G_4 \\ G_2 & 0 \end{bmatrix}$	$\sqrt{\frac{G_2 G_4}{C_1 C_2}}$	New
3	−1	G_3	$-G_2$	$\begin{bmatrix} G_1 - G_3 & G_3 \\ -G_2 & 0 \end{bmatrix}$	$\sqrt{\frac{G_2 G_3}{C_1 C_2}}$	[1]
4(a), (c)	1	$-G_4$	G_2	$\begin{bmatrix} G_3 - G_1 & -G_4 \\ G_2 & 0 \end{bmatrix}$	$\sqrt{\frac{G_2 G_4}{C_1 C_2}}$	New
4(b), (d)	1	G_4	$-G_2$	$\begin{bmatrix} G_3 - G_1 & G_4 \\ -G_2 & 0 \end{bmatrix}$	$\sqrt{\frac{G_2 G_4}{C_1 C_2}}$	New
5	1	$-G_4$	G_2	$\begin{bmatrix} G_3 - G_1 & -G_4 \\ G_2 & 0 \end{bmatrix}$	$\sqrt{\frac{G_2 G_4}{C_1 C_2}}$	New
6(a)	−1	G_3	$-G_2$	$\begin{bmatrix} G_1 - G_3 & G_3 \\ -G_2 & 0 \end{bmatrix}$	$\sqrt{\frac{G_2 G_3}{C_1 C_2}}$	[11, 13]
6(b)	1	$-G_3$	G_2	$\begin{bmatrix} G_3 - G_2 & -G_3 \\ G_2 & 0 \end{bmatrix}$	$\sqrt{\frac{G_2 G_3}{C_1 C_2}}$	[13–15]
7(b)	1	$-G_4$	G_2	$\begin{bmatrix} G_3 - G_1 & -G_4 \\ G_2 & 0 \end{bmatrix}$	$\sqrt{\frac{G_2 G_4}{C_1 C_2}}$	[15]

$$Y = \begin{bmatrix} sC_1 + G_3 - G_1 + \frac{4G_1}{\omega_t}s & -G_3 \\ G_2 - \frac{2G_2}{\omega_t}s & sC_2 + \frac{G_2}{2\omega_t}s \end{bmatrix} \quad (15)$$

Assuming ideal Op Amps the NAM equation is simplified to:

$$Y = \begin{bmatrix} sC_1 + G_3 - G_1 & -G_3 \\ G_2 & sC_2 \end{bmatrix} \quad (16)$$

The characteristic equation in this case is given by:

$$s^2C_1C_2 + sC_2(G_3 - G_1) + G_2G_3 = 0 \quad (17)$$

The condition of oscillation is the same as given by Eq. 14 and the modified state matrix A_m, a_1, N_1 and N_2 and the radian frequency of oscillation are given in Table 1.

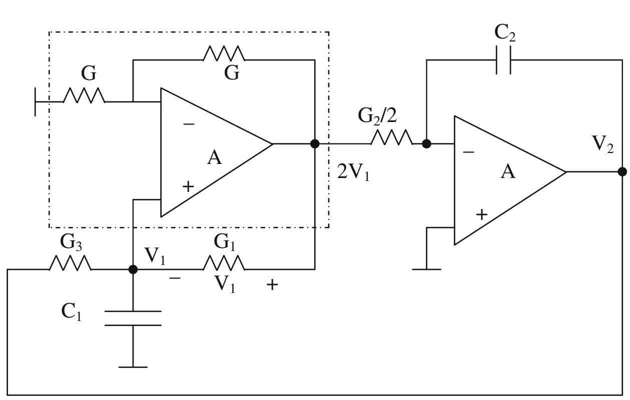

Fig. 3 Two Op Amp oscillator using Deboo integrator [1]

4 Unity gain cell oscillators

An active RC oscillator using two voltage followers was introduced in [21]. The use of combination of unity gain cells in oscillator circuits has been given in [22, 23].

The definition of the four types of unity gain cells [24] is summarized next. The Voltage Follower (VF) is defined by:

$$\begin{bmatrix} I_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} V_1 \\ I_2 \end{bmatrix} \quad (18)$$

The Voltage Inverter (VI) is defined by:

$$\begin{bmatrix} I_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} V_1 \\ I_2 \end{bmatrix} \quad (19)$$

The Current Follower (CF) is defined by:

$$\begin{bmatrix} V_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} I_1 \\ V_2 \end{bmatrix} \quad (20)$$

The Current Inverter (CI) is defined by:

$$\begin{bmatrix} V_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} I_1 \\ V_2 \end{bmatrix} \quad (21)$$

Figure 4(a) represents a new oscillator circuit using unity gain cells and is generated from the three Op Amp circuit of Fig. 2(c).

Three more new circuits are given in Fig. 4(b)–(d) and their modified state matrix Am; are summarized in Table 1.

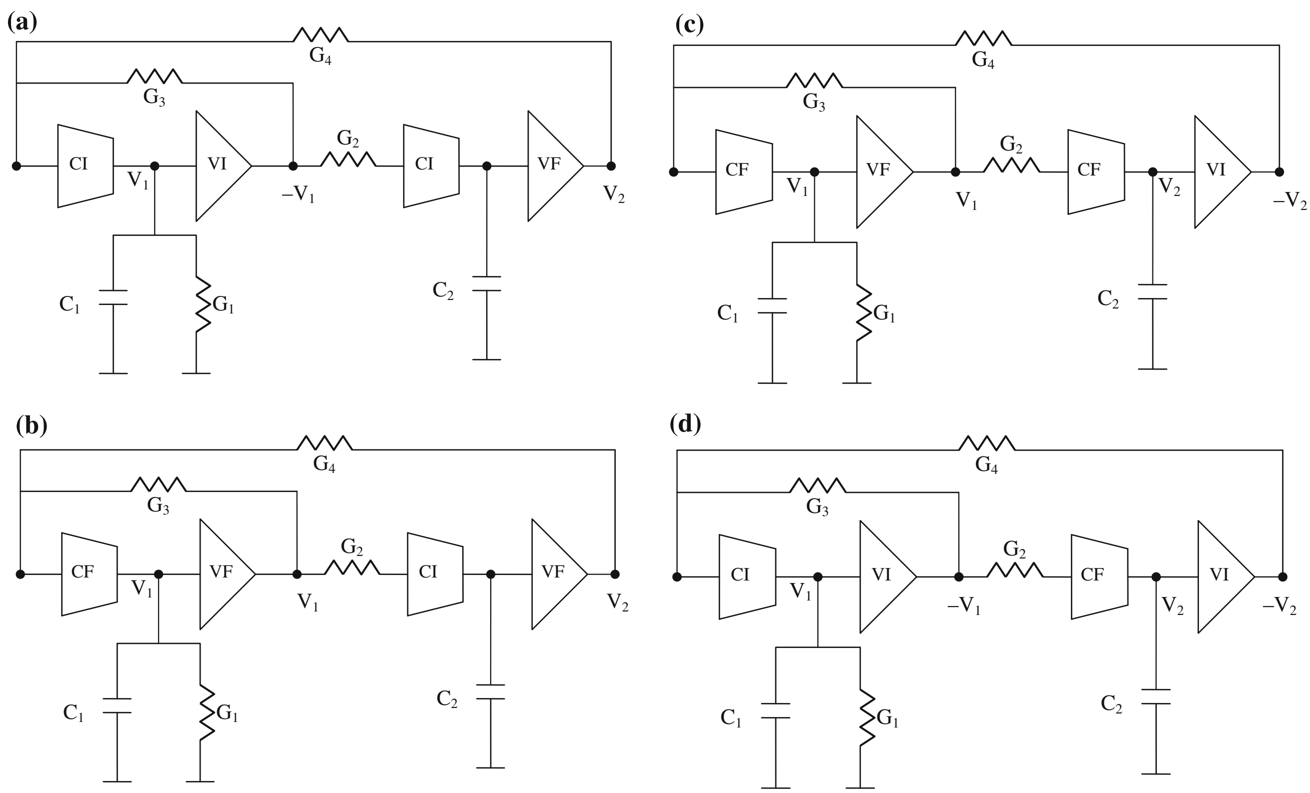

Fig. 4 Four equivalent unity gain cells grounded capacitor oscillators

5 CFOA based oscillators

The CFOA is a four-terminal active building block and is described by the following matrix equation:

$$\begin{bmatrix} V_x \\ I_y \\ I_z \\ V_o \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} = \begin{bmatrix} I_x \\ V_y \\ V_z \\ I_o \end{bmatrix} \quad (22)$$

The first circuit in this section is shown in Fig. 5 and it uses three CFOA having grounded Y terminals. The transformation of single input Op Amp circuits to a CFOA circuit with a grounded Y input is a straight forward as given before in [25]. In fact it is obtained from Fig. 2(c) by replacing Op Amps by CFOA and it has identical equations. It also belongs to the circuits in the previous section and is equivalent to the circuit of Fig. 4(a) but it employs 3 CI and 3 VF. In fact the circuit of Fig. 4(a) is a simplified version of this circuit.

The two main parasitic elements affecting the circuit are R_{X1} and C_{Z2}.

5.1 The two CFOA oscillator circuits

The quadrature oscillator circuit given in Fig. 3 is realizable using two CFOA as shown in Fig. 6(a). This circuit was reported in [11, 13] without any reference to the Op Amp equivalent circuit of Fig. 3.

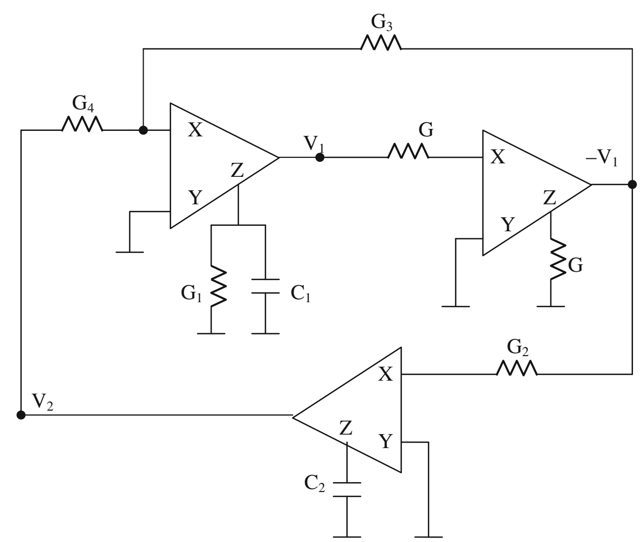

Fig. 5 Three CFOA grounded capacitor oscillator

It should be noted that the parasitic capacitances C_{Z1} and C_{Z2} can be compensated by subtracting their values from the design values of C_1 and C_2 respectively. The parasitic resistances R_{X1} and R_{X2} can be compensated by subtracting their values from R_1 and R_2 respectively.

The second two CFOA oscillator circuit shown in Fig. 6(b) was introduced independently in [13–15] without any reference to its origin. In fact in [13] the circuit of

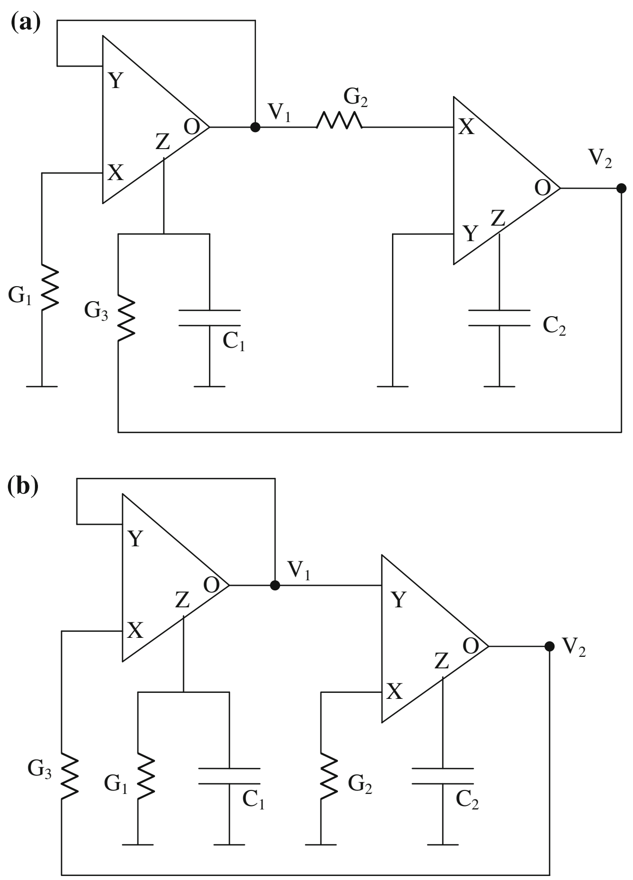

Fig. 6 **a** Two CFOA grounded capacitor oscillator [11, 13]. **b** Two CFOA grounded capacitor oscillator [13–15]

Fig. 6(a) was generated from the circuit of Fig. 6(b). The natural sequence of generation in this paper is to obtain the circuit of Fig. 6(b) from the circuit of Fig. 6(a) by changing the signs of G_1, G_2 and G_3 in Eq. 16 which represents the circuits in Fig. 3 as well as the circuit in Fig. 6(a). The NAM equation of the circuit of Fig. 6(b) is given by:

$$Y = \begin{bmatrix} sC_1 + G_1 - G_3 & G_3 \\ -G_2 & sC_2 \end{bmatrix} \tag{23}$$

The characteristic equation in this case is given by:

$$s^2C_1C_2 + sC_2(G_1 - G_3) + G_2G_3 = 0 \tag{24}$$

The properties for this circuit are summarized in Table 1. This circuit has the same condition of oscillation as the circuits of Figs. 3 and 6(a) and given by Eq. 14. It should be noted however that the start up condition of oscillation is adjusted by taking R_1 slightly larger than R_3 which is opposite to the case of the two equivalent circuits of Figs. 3 and 6(a) in which R_1 is adjusted to be slightly smaller than R_3.

It should be noted that the parasitic capacitances C_{Z1} and C_{Z2} can be compensated by subtracting their values from the design values of C_1 and C_2 respectively.

The parasitic resistances R_{X1} and R_{X2} can be compensated by subtracting their values from R_3 and R_2 respectively.

5.2 The three CFOA oscillator circuit

The grounded passive components three positive current conveyors (CCII+) or three CFOA circuit shown in Fig. 7(a) and (b) can be generated from the new three Op Amp oscillator circuit shown in Fig. 2(c) using NAM expansion [26–30] as explained below.

From the NAM Eq. 13 adding a third blank row and column and connecting a nullator between nodes 1 and 3 and

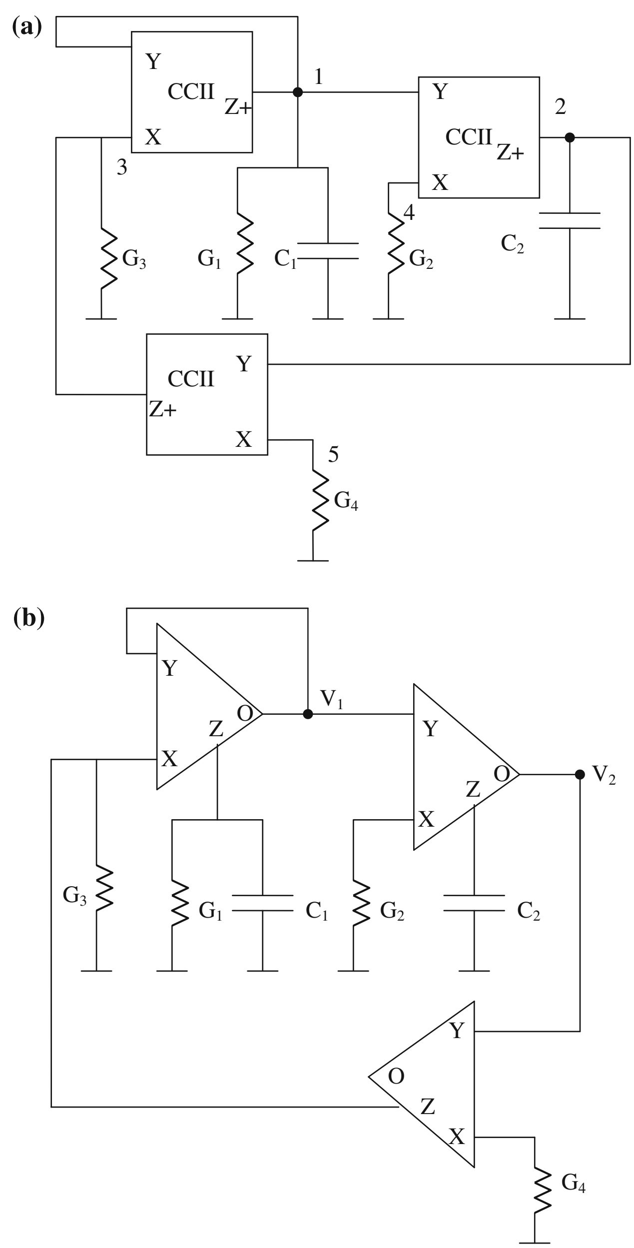

Fig. 7 **a** Three CCII grounded passive element oscillator. **b** Three CFOA grounded passive element oscillator [15]

a Current Mirror (CM) [31] between nodes 1 and 3 to move $-G_3$ from 1, 1 position to become G_3 at the diagonal position 3, 3. Also G_4 will be moved by same CM from the position 1, 2 to become $-G_4$ at the position 3, 2 as follows:

$$Y = \begin{bmatrix} sC_1+G_1 & 0 & 0 \\ -G_2 & sC_2 & 0 \\ 0 & -G_4 & G_3 \end{bmatrix} \tag{25}$$

Adding a fourth blank row and column and connecting a nullator between nodes 1 and 4 and a CM between nodes 2 and 4 to move $-G_2$ from the 2, 1 position to become G_2 at the diagonal position 4, 4 it follows that:

$$Y = \begin{bmatrix} sC_1+G_1 & 0 & 0 & 0 \\ 0 & sC_2 & 0 & 0 \\ 0 & -G_4 & G_3 & 0 \\ 0 & 0 & 0 & G_2 \end{bmatrix} \tag{26}$$

Finally adding a fifth blank row and column and connecting a nullator between nodes 2 and 5 and a CM between nodes 3 and 5 to move $-G_4$ from the 3, 2 position to become G_4 at the diagonal position 5, 5 it follows that:

$$Y = \begin{bmatrix} sC_1+G_1 & 0 & 0 & 0 & 0 \\ 0 & sC_2 & 0 & 0 & 0 \\ 0 & 0 & G_3 & 0 & 0 \\ 0 & 0 & 0 & G_2 & 0 \\ 0 & 0 & 0 & 0 & G_4 \end{bmatrix} \tag{27}$$

The above equation is realizable using three; CCII+ as shown in Fig. 7(a). Adding a VF after each CCII+ to provide a voltage buffered output results in the circuit shown in Fig. 7(b) [15].

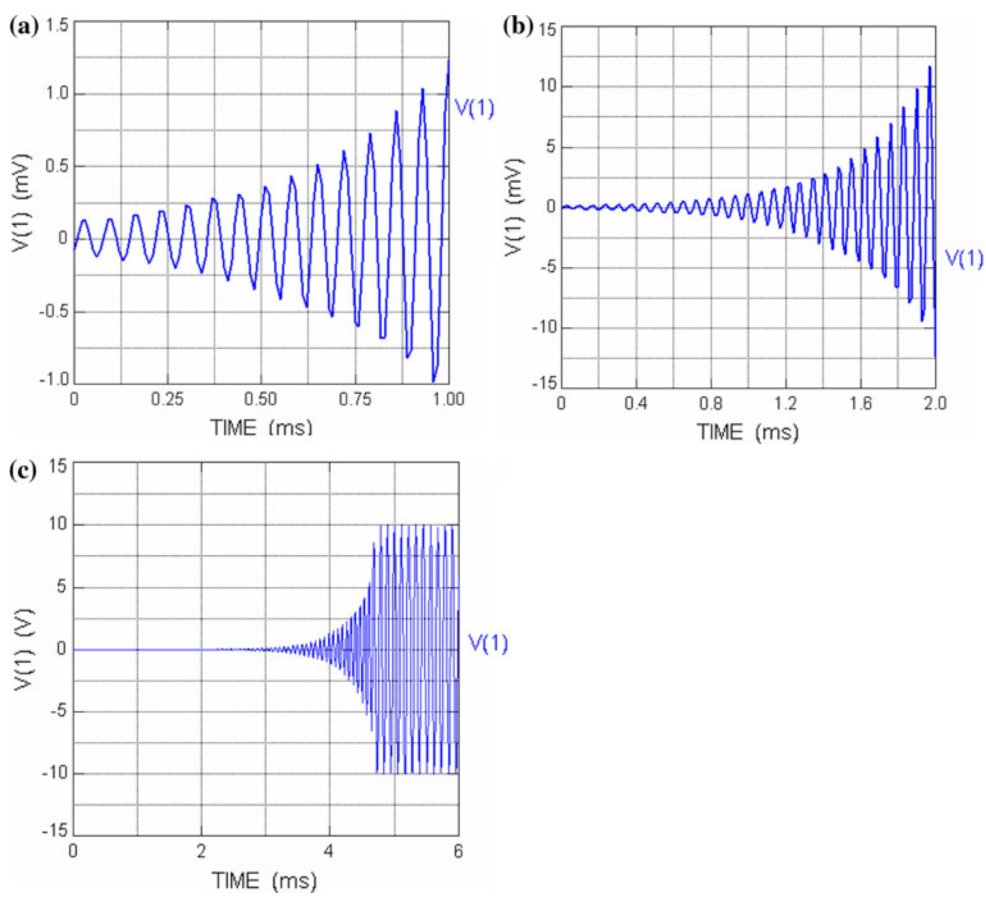

Fig. 8 Simulation results of the oscillator of Fig. 2(c)

The two main parasitic elements affecting the circuit are R_{X1} and C_{Z3}.

6 Simulation results

Simulation results for the circuit of Fig. 2(c) using three μA741 Op Amps biased with 12 and −12 V and using equal resistors of 10 k Ω each and two equal capacitors of 1 nF each. Figure 8 shows the simulation results and the start up of the growing oscillations by taking the stop time to be 1, 2 and 6 ms respectively. The simulated frequency is slightly less than its ideal value of 15.9 kHz due to the finite gain-bandwidth of the Op Amp. The total power dissipation in the circuit is 95.794 m W.

Simulation results for the circuit of Fig. 3 using two μA741 Op Amps biased with 12 and −12 V and taking $R_1 = R_2 = R_3 = R = 10$ k Ω, and two equal capacitors of 1 nF each. Figure 9 shows the simulation results and the start up of the growing oscillations by taking the stop time to be 1, 2 and 6 ms respectively. The simulated frequency is slightly less than its ideal value of 15.9 kHz due to the finite gain-bandwidth of the Op Amp. The total power dissipation in the circuit is 63.8627 m W.

It should be noted that simulation and experimental results for the circuit of Fig. 6(b) are given in [15] and simulation results for the circuit of Fig. 7(b) are also given in [15].

7 Conclusions

Op Amp two integrator loop oscillators are reviewed and one new circuit is introduced in Fig. 2(c). It is worth noting that the oscillator structure with two active RC integrators and an inverter shown in Fig. 2(a) is based on the differential equations which define the sine and cosine functions. Recently this non-linear oscillator circuit is treated as a linear time-varying circuit in [32]. The parameters are chosen in such a way that the imaginary part of the poles of the linear time-varying circuit is as close as possible to ω_O over a period.

Four new oscillators using unity gain cells are introduced and Table 1 includes details about the oscillator circuits.

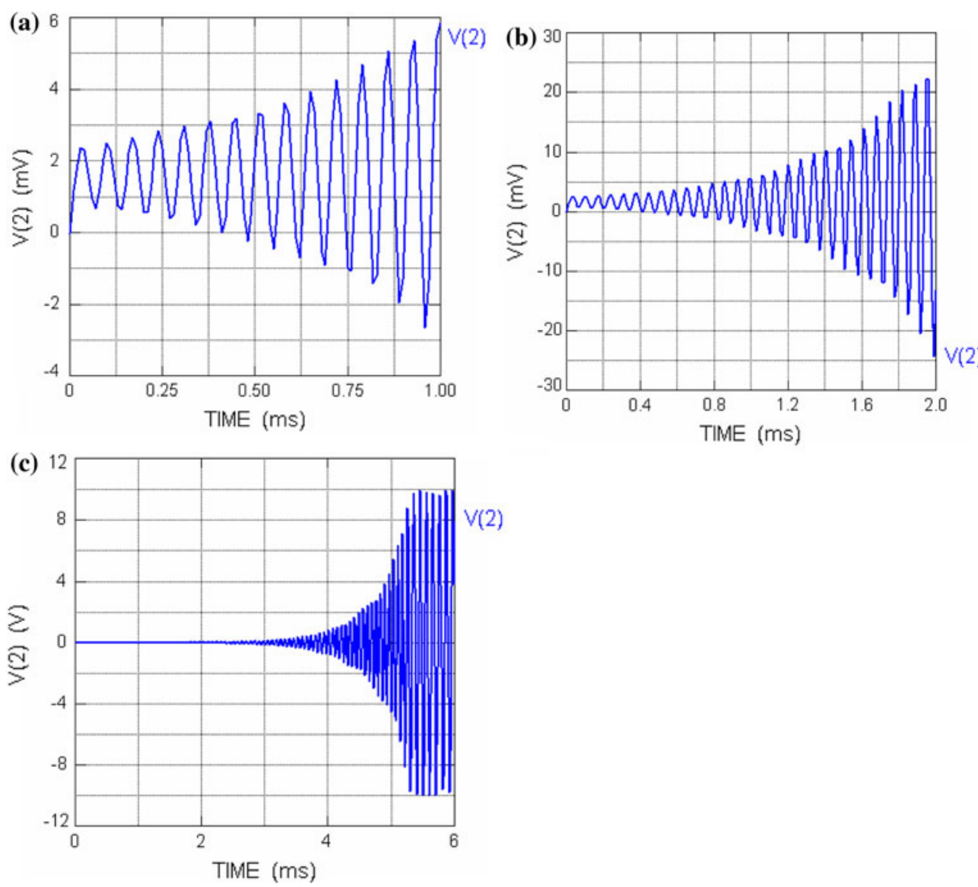

Fig. 9 Simulation results of the oscillator of Fig. 3

The CFOA circuit of Fig. 6(a) is equivalent to and has identical NAM equation to the Op Amp circuit of Fig. 3.The NAM equation of the CFOA circuit of Fig. 6(b) is obtained from that of the circuit of Fig. 6(a) by interchange of the signs of the three G terms but has no equivalent Op Amp circuit.

The three CFOA oscillator circuit of Fig. 7(b) is generated from the new three Op Amp oscillator circuit of Fig. 2(c) using NAM expansion [30]. Spice simulation results are included for the circuits of Figs. 2(c) and 3.

Finally it is stated that the characteristic equation of an oscillator should be found from the state equations or from the NAM equation. Besides the Barkhausen criterion a better choice is the extended node equations (modified nodal approach, controlled source approach) where a set of first order nonlinear differential equations is obtained based on the node voltages and the currents in the impedance elements as variables [33].

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