Two Integrator Loop Quadrature Oscillators: A Review

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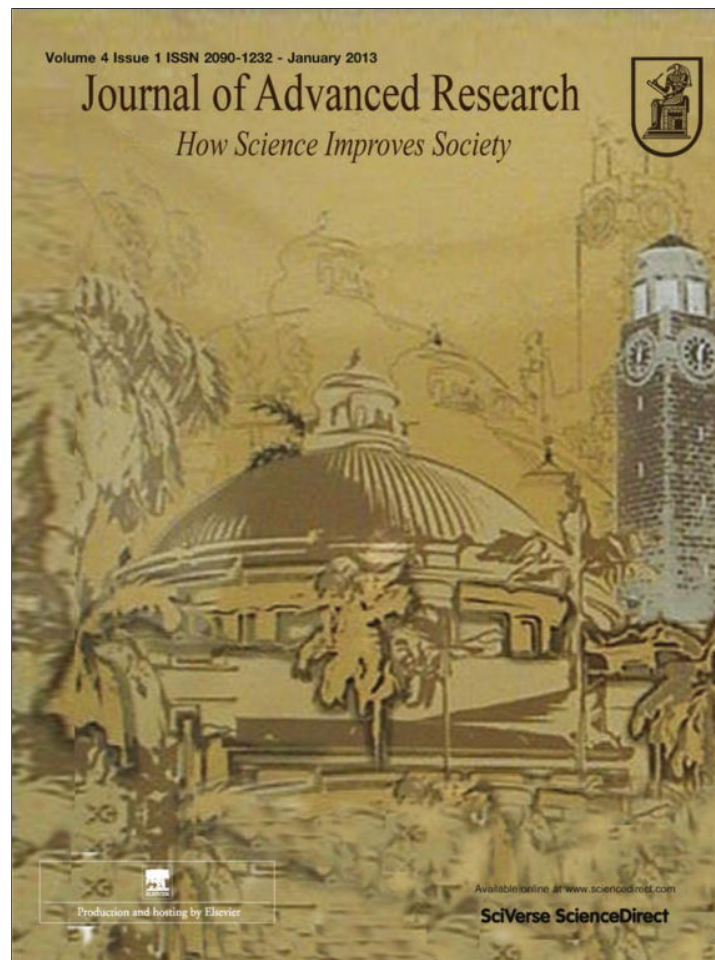Cairo University
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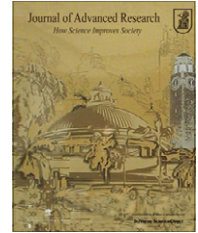
REVIEW

Two integrator loop quadrature oscillators: A review

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Abstract   A review of the two integrator loop oscillator circuits providing two quadrature sinusoidal output voltages is given. All the circuits considered employ the minimum number of capacitors namely two except one circuit which uses three capacitors. The circuits considered are classified to four different classes. The first class includes floating capacitors and floating resistors and the active building blocks realizing these circuits are the Op Amp or the OTRA. The second class employs grounded capacitors and includes floating resistors and the active building blocks realizing these circuits are the DCVC or the unity gain cells or the CFOA. The third class employs grounded capacitors and grounded resistors and the active building blocks realizing these circuits are the CCII. The fourth class employs grounded capacitors and no resistors and the active building blocks realizing these circuits are the TA. Transformation methods showing the generation of different classes from each other is given in details and this is one of the main objectives of this paper.

Introduction

Sinusoidal oscillators are basic building blocks in active circuits and have several applications in electronics and communication circuits [1–3]. The oscillator circuits are available in different forms which includes Colpitts oscillator, Hartely oscillator, two integrator loop oscillators, Wien bridge oscillator and

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phase shift oscillators [1–3]. This paper is limited to the two integrator loop oscillators realized using different active building blocks.

The first active building block used in this paper is the Operational Amplifier (Op Amp) and four circuits are given [1–5]. Next the Operational Transresistance Amplifier (OTRA) [6–8] is used as the active element and two circuits are reviewed both employ two floating capacitors and four floating resistors [9]. Both of the Op Amp and the OTRA oscillators represent the first class of oscillators considered in this paper. The second class of oscillator circuit considered employ grounded capacitors [10] and includes floating resistors. The active element employed is the Differential Current Voltage Conveyor (DCVC) [11] also known as the Current Differencing Buffered Amplifier (CDBA) [12], the unity gain cells and the Current Feedback Operational Amplifier (CFOA) [13]. The third class of oscillator circuit considered employ grounded capacitors and grounded resistors. The active element employed is the single output current conveyor (CCII) [14] or the two output

CCII. The fourth class considered employs grounded capacitors and no resistor, the active element employed is the transconductance amplifier (TA) [15]. Transformation methods using Nodal Admittance Matrix (NAM) expansion to show how the CFOA oscillator circuits leads to the generation of CCII oscillators are given.

Op Amp based oscillators

The analysis in this section is based on assuming ideal Op Amp having infinite gain which forces the two input voltages to be equal. The two input currents are zero due to the very high input impedance at both input nodes.

Four alternative circuits are given in Fig. 1a–d and will be summarized next.

(i) Three Op Amp oscillator circuits

The first circuit given in this paper is the three Op Amp two integrator loop circuit shown in Fig. 1a. It employs three single input Op Amps, two floating capacitors and four floating resistors [1], its NAM equation is given by:

$$Y = \begin{bmatrix} sC_1 & -G_1 \\ G_2 & sC_2 \end{bmatrix} \qquad (1)$$

The radian frequency of oscillation is given by:

$$\omega_o = \sqrt{\frac{G_1 G_2}{C_1 C_2}} \qquad (2)$$

This circuit has the disadvantage of having no independent control on the oscillation condition. A modification to the circuit of Fig. 1a to provide control on the oscillation condition was given in Refs. [4,5].

Fig. 1b represents the recently reported three Op Amp oscillator circuit with independent control on both the condition of oscillation and on the frequency of oscillation, its NAM equation is given by:

$$Y = \begin{bmatrix} sC_1 + G_4 - G_3 & G_1 \\ -G_2 & sC_2 \end{bmatrix} \qquad (3)$$

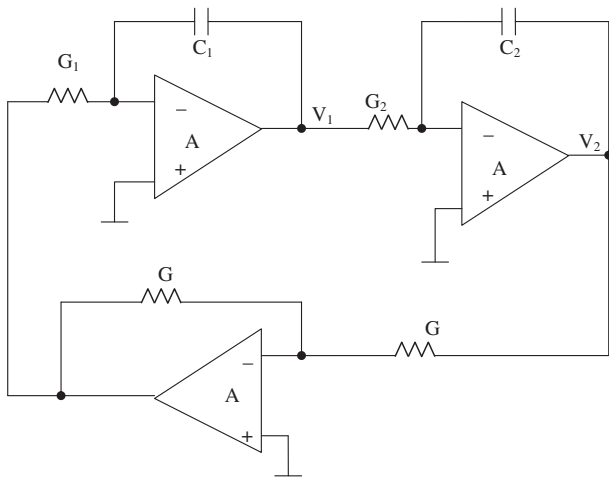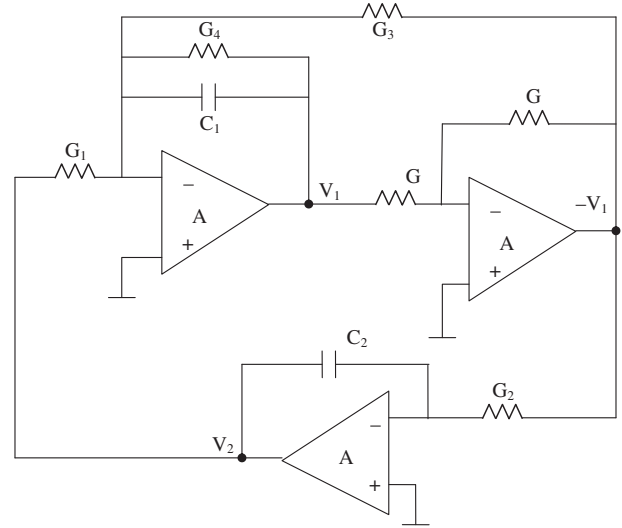**Fig. 1b** Modified three Op Amp oscillator circuit [5].

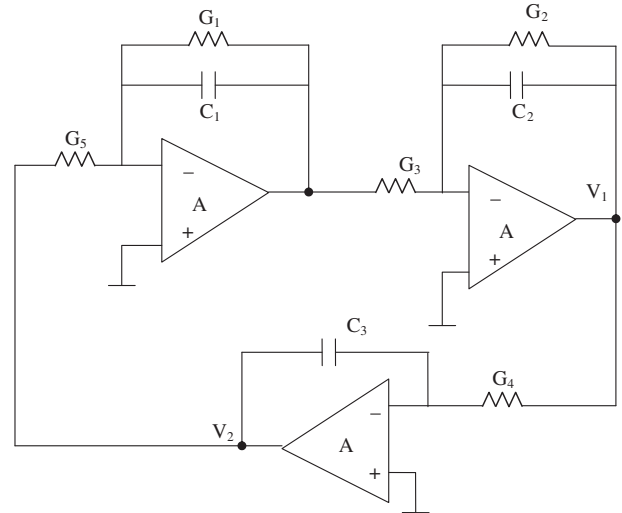**Fig. 1c** Three Op Amp oscillator circuit [16].

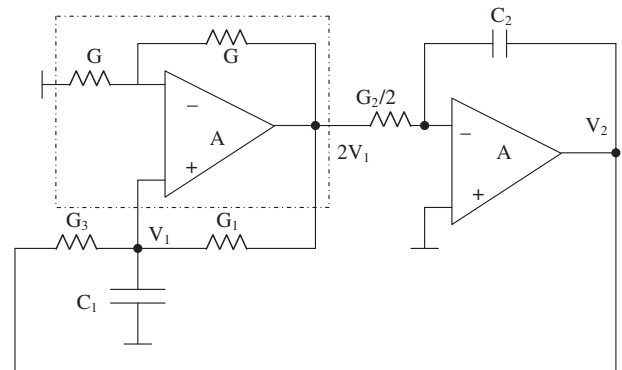**Fig. 1a** Three Op Amp oscillator circuit [1–4].

Fig. 1d Two Op Amp oscillator circuit [1].

It should be noted that the signs of G_1 and G_2 are opposite to their signs in Eq. (1).The characteristic equation in this case is given by:

Table 1 Summary of the class I oscillator circuits.

Circuit figure number	Active element	Number of C	Number of G	Condition of oscillation	ω_O	Ref.
1(a)	3 Op Amp	2 Floating	4 Floating	None	$\sqrt{\frac{G_1 G_2}{C_1 C_2}}$	[1–4]
1(b)	3 Op Amp	2 Floating	6 Floating	$G_4 = G_3$	$\sqrt{\frac{G_1 G_2}{C_1 C_2}}$	[5]
1(c)	3 Op Amp	3 Floating	5 Floating	$\frac{G_3 G_4 G_5}{G_1 G_2 C_3} = \frac{G_1}{C_1} + \frac{G_2}{C_2}$	$\sqrt{\frac{G_1 G_2}{C_1 C_2}}$	[16]
1(d)	2 Op Amp	1 Grounded 1 Floating	1 Grounded 4 Floating	$G_3 = G_1$	$\sqrt{\frac{G_2 G_3}{C_1 C_2}}$	[1]
2(a),(b)	2 OTRA	2 Floating	4 Floating	$G_4 = G_3$	$\sqrt{\frac{G_1 G_2}{C_1 C_2}}$	[9]

$$s^2 C_1 C_2 + s C_2 (G_4 - G_3) + G_1 G_2 = 0 \qquad (4)$$

The condition of oscillation is given by:

$$G_3 = G_4 \qquad (5)$$

The condition of oscillation is controlled by G_3 or G_4 without affecting the frequency of oscillation which is given by Eq. (2) and is independently controlled by G_1 or G_2 without affecting the condition of oscillation.

The third circuit is shown in Fig. 1c which was recently reported by Horng [16]. This circuit is non-canonic as it employs three capacitors. The condition of oscillation and the radian frequency of oscillation are summarized in Table 1. The condition of oscillation is controlled by G_3 or G_4 or G_5 without affecting the frequency of oscillation. There is no independent control on the frequency of oscillation. Another non-canonic quadrature oscillator circuit which uses five capacitors was also introduced by Horng [16].

(ii) Two Op Amp oscillator circuit

The fourth circuit shown in Fig. 1d is the two Op Amp two integrator loop circuit based on using Deboo integrator [1]. It uses one grounded capacitor, one floating capacitor, one grounded resistor and four floating resistors [1]; its NAM equation is given by:

$$Y = \begin{bmatrix} sC_1 + G_3 - G_1 & -G_3 \\ G_2 & sC_2 \end{bmatrix} \qquad (6)$$

The characteristic equation in this case is given by:

$$s^2 C_1 C_2 + s C_2 (G_3 - G_1) + G_2 G_3 = 0 \qquad (7)$$

The condition of oscillation is given by:

$$G_3 = G_1 \qquad (8)$$

$$\omega_o = \sqrt{\frac{G_2 G_3}{C_1 C_2}} \qquad (9)$$

The condition of oscillation is controlled by G_1 without affecting the frequency of oscillation and the frequency of oscillation is controlled by G_2 without affecting the condition of oscillation.

OTRA based oscillators

The second active building block considered in this paper is the OTRA which in the ideal case has the two inputs virtually grounded leading to circuits that are insensitive to stray capacitances. Also ideally the transresistance gain, R_m approaches infinity which forces the input currents to be equal.

The first circuit shown in Fig. 2a is the two OTRA two integrator loop originally introduced in [9]. It uses two floating capacitors and four floating resistors; its NAM equation is given by:

$$Y = \begin{bmatrix} sC_1 + G_3 - G_4 & -G_1 \\ G_2 & sC_2 \end{bmatrix} \qquad (10)$$

The characteristic equation in this case is given by:

$$s^2 C_1 C_2 + s C_2 (G_3 - G_4) + G_1 G_2 = 0 \qquad (11)$$

The condition of oscillation is given by:

$$G_3 = G_4 \qquad (12)$$

The condition of oscillation is controlled by G_3 or G_4 without affecting the frequency of oscillation and the radian frequency of oscillation is given by Eq. (2) and is controlled by G_1 or G_2 without affecting the condition of oscillation.

Fig. 2a Two OTRA oscillator circuit I [9].

Fig. 2b Two OTRA oscillator circuit II [9].

The second circuit which employs the same number of elements is shown in Fig. 2b [9]; its NAM equation is given by:

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

The condition of oscillation and the frequency of oscillation are the same as in the previous circuit and are summarized in Table 1.

The oscillators reported in the next sections of the paper employ grounded capacitors which provide advantages in integrated circuits [10].

DCVC based oscillators

The DCVC was introduced in [11] as a four terminal building block and defined by:

$$\begin{bmatrix} Vx_1 \\ Vx_2 \\ Iz \\ Vo \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} Ix_1 \\ Ix_2 \\ Vz \\ Io \end{bmatrix} \qquad (14)$$

The currents I_{X1} and I_{X2} are pointing inwards at nodes X_1 and X_2 whereas the current I_Z is out words from node Z as shown in Fig. 3a.

The DCVC was independently introduced and defined as a CDBA by Acar and Özoguz [12].

The first oscillator circuit considered in this section is shown in Fig. 3a which uses two DCVC, two grounded capacitors and four virtually grounded resistors and was introduced by Horng [17]; its NAM equation is given by:

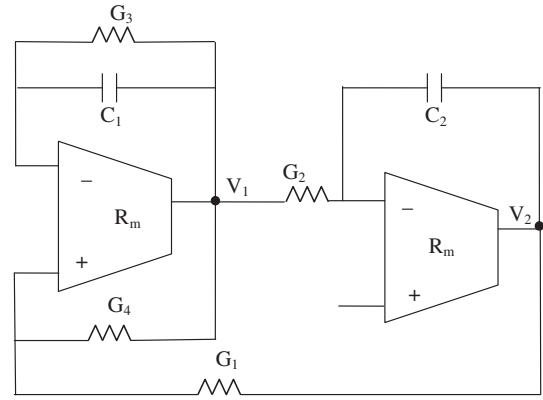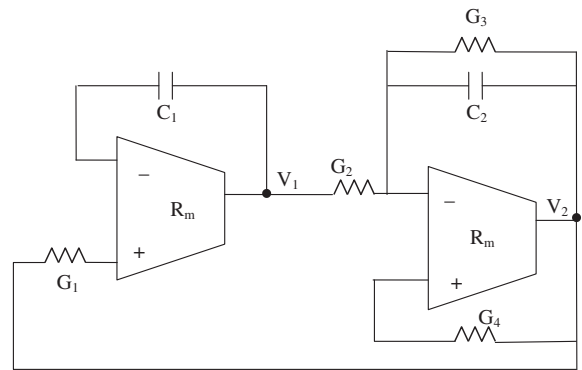$$Y = \begin{bmatrix} sC_1 + G_1 - G_3 & -G_4 \\ G_2 & sC_2 \end{bmatrix} \qquad (15)$$

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

The second oscillator circuit considered in this section is shown in Fig. 3b which uses two DCVC, two grounded capacitors and three virtually grounded resistors was introduced [18,19]; its NAM equation is given by:

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

The condition of oscillation is controlled by varying G_1 without affecting the frequency of oscillation and the frequency
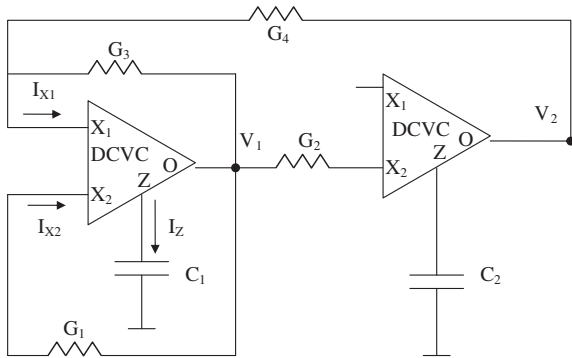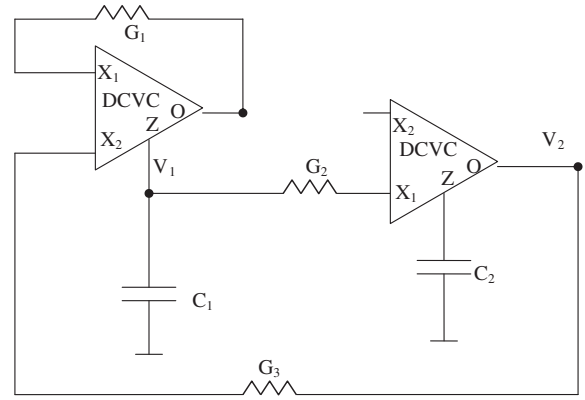

Fig. 3b Two DCVC oscillator circuit II [18,19].

of oscillation is controlled by varying G_3 without affecting the condition of oscillation.

Unity gain cells based oscillators

The four types of the unity gain cells are defined as follows [20,21].

The Voltage Follower (VF) is defined by:

$$\begin{bmatrix} I_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} V_1 \\ I_2 \end{bmatrix} \qquad (17)$$

The Voltage Inverter (VI) is defined by:

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

The Current Follower (CF) is defined by:

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

The Current Inverter (CI) is defined by:

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

Oscillators using unity gain cells were introduced in the literature [22].

The first oscillator circuit considered in this section is shown in Fig. 4a. This is equivalent to the circuit shown in Fig. 3a and Eq. (15) applies to this circuit.

Fig. 3a Two DCVC oscillator circuit I [17,19].

Fig. 4a Unity gain cells oscillator circuit equivalent to Fig. 3a [5,19].
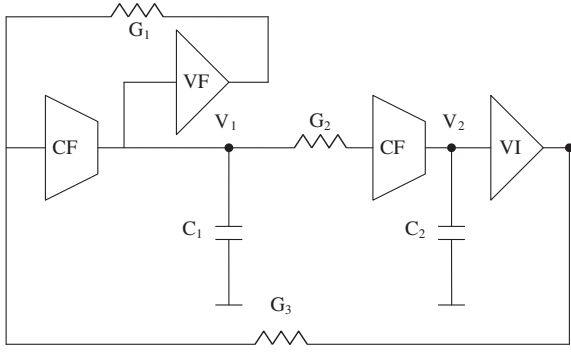
Fig. 4b Unity gain cells oscillator circuit equivalent to Fig. 3b [19].

Fig. 5b Two CFOA grounded capacitor oscillator circuit II [25].

The second oscillator circuit considered in this section is shown in Fig. 4b.

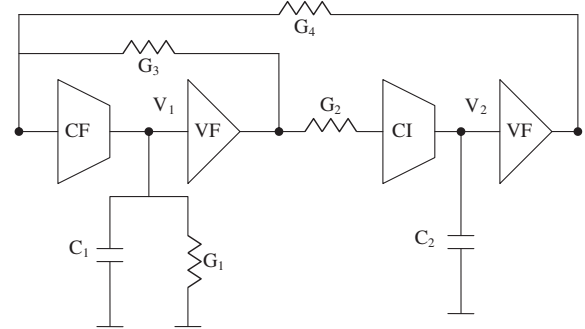This is equivalent to the circuit shown in Fig. 3b and Eq. (16) applies to this circuit.

CFOA based oscillators

The CFOA is a four-terminal active building block and is described by the following matrix equation [13]:

$$\begin{bmatrix} Vx \\ Iy \\ Iz \\ Vo \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} Ix \\ Vy \\ Vz \\ Io \end{bmatrix} \tag{21}$$

The first oscillator circuit considered in this section is shown in Fig. 5a [23–25]; its NAM equation is given by:

$$Y = \begin{bmatrix} sC_1 + G_1 - G_3 & G_3 \\ -G_2 & sC_2 \end{bmatrix} \tag{22}$$

The condition of oscillation is given by Eq. (8) and the radian frequency of oscillation is given by Eq. (9).

The second oscillator circuit considered in this section is shown in Fig. 5b [25]. This is equivalent to the circuit shown in Fig. 1d and Eq. (6) applies to this circuit. The results of this class of oscillators are summarized in Table 2.

Single output CCII based oscillators
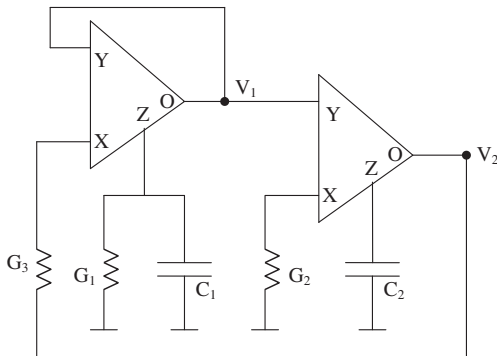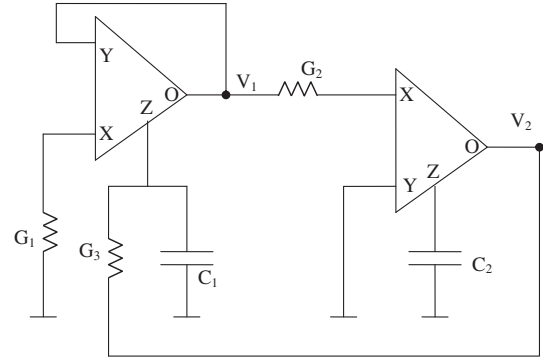
The single output CCII is defined by:

Fig. 5a Two CFOA grounded capacitor oscillator circuit I [23–25].

$$\begin{bmatrix} Vx \\ Iy \\ Iz \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ \pm 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} Ix \\ Vy \\ Vz \end{bmatrix} \tag{23}$$

The positive sign in the third row applies to CCII+ whereas the negative sign is for CCII−.

In this section, the conventional systematic synthesis framework using NAM expansion [26–30] to synthesize oscillator circuits is used to transform the CFOA oscillators to single output CCII oscillators using grounded capacitors and grounded resistors.

Starting from Eq. (22) and add a third blank row and column and then connect a nullator between columns 1 and 3 and a current mirror (CM) between rows 1 and 3 in order to move $-G_3$ from the 1, 1 position to the diagonal position 3, 3 to become G_3 as follows:

$$Y = \begin{bmatrix} sC_1 + G_1 & G_3 & 0 \\ -G_2 & sC_2 & 0 \\ 0 & 0 & G_3 \end{bmatrix} \tag{24}$$

Adding a fourth blank row and column to the above equation and then connect a nullator between columns 1 and 4 and a CM between rows 2 and 4 in order to move $-G_2$ from the 2, 1 position to the diagonal position 4, 4 to become G_2, the following NAM is obtained:

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

Adding a fifth blank row and column to the above equation and then connect a nullator between columns 2 and 5 and a norator between rows 1 and 5 in order to move G_3 from the 1, 2 position to the diagonal position 5, 5 the following NAM is obtained:

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

Table 2 Summary of the class II oscillator circuits.

Circuit Figure Number	Active Element	Number of C	Number of G	Condition of oscillation	ω_O	Ref.
3(a)	2 DCVC	2 Grounded	4 Floating	$G_3 = G_1$	$\sqrt{\frac{G_2 G_4}{C_1 C_2}}$	[17,19]
3(b)	2 DCVC	2 Grounded	3 Floating	$G_2 = G_1$	$\sqrt{\frac{G_2 G_3}{C_1 C_2}}$	[18,19]
4(a)	2VF,CF,CI	2 Grounded	1 Grounded 3 Floating	$G_3 = G_1$	$\sqrt{\frac{G_2 G_4}{C_1 C_2}}$	[5,19]
4(b)	VF, 2 CF, VI	2 Grounded	3 Floating	$G_2 = G_1$	$\sqrt{\frac{G_2 G_3}{C_1 C_2}}$	[19]
5(a)	2 CFOA	2 Grounded	2 Grounded 1 Floating	$G_3 = G_1$	$\sqrt{\frac{G_2 G_3}{C_1 C_2}}$	[23–25]
5(b)	2 CFOA	2 Grounded	1 Grounded 2 Floating	$G_3 = G_1$	$\sqrt{\frac{G_2 G_3}{C_1 C_2}}$	[25]
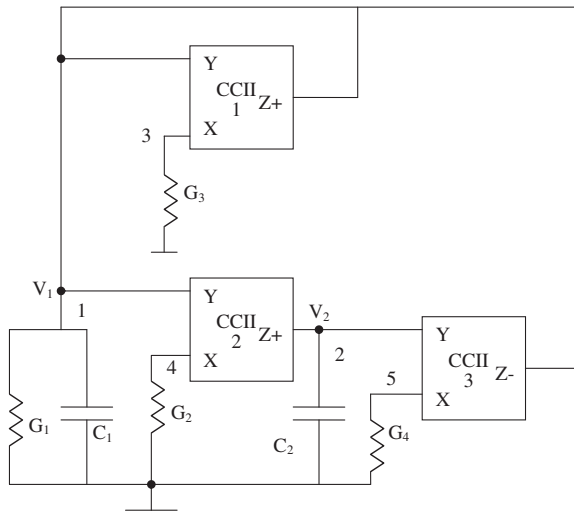
Fig. 6a Three CCII oscillator circuit I [31,32].
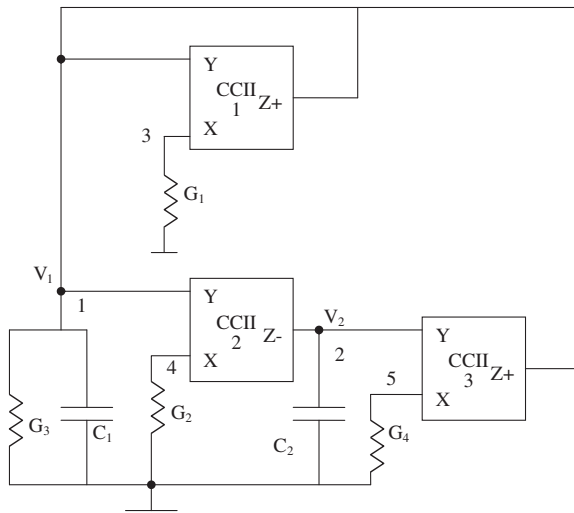
Fig. 6b Three CCII oscillator circuit II [32].

The above equation is realized as a five node circuit using three nullators, one norator and two CM. Noting that the nullator and norator with a common terminal realize a CCII−, the nullator and CM with a common terminal realize a

CCII+, the circuit shown in Fig. 6a using two CCII+ and one CCII− is obtained. It should be noted that the number of resistors is increased to four instead of three in the circuit of Fig. 5a. Note also that the resistors at nodes 3 and 5 are of the same value. This circuit has been introduced originally [31] with four grounded resistors of different values. Changing the magnitude of G_3 at node 5 to become G_4 [31] adds more degrees of freedom in the tuning of the oscillator circuit and the NAM equation will be modified to:

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

This is similar to Eq. (15) except for the signs of G_2 and G_4. In this case the condition of oscillation is controlled by varying G_1 or G_3 and the frequency of oscillation is controlled by varying G_2 or G_4 without affecting the condition of oscillation. Table 3 summarizes these results.

The second CCII oscillator circuit considered in this section is shown in Fig. 6b [31,32] and is generated from Fig. 1d or its equivalent CFOA oscillator circuit shown in Fig. 5b both are represented by Eq. (6) and using NAM expansion as follows.

Starting from Eq. (6) and add a third blank row and column and then connect a nullator between columns 1 and 3 and a current mirror (CM) between rows 1 and 3 in order to move $-G_1$ from the 1, 1 position to the diagonal position 3, 3 to become G_1 therefore:

$$Y = \begin{bmatrix} sC_1 + G_3 & -G_3 & 0 \\ G_2 & sC_2 & 0 \\ 0 & 0 & G_1 \end{bmatrix} \tag{28}$$

Adding a fourth blank row and column to the above equation and then connect a nullator between columns 1 and 4 and a norator between rows 2 and 4 in order to move G_2 from the 2, 1 position to the diagonal position 4, 4 the following NAM is obtained:

$$Y = \begin{bmatrix} sC_1 + G_1 & -G_3 & 0 & 0 \\ 0 & sC_2 & 0 & 0 \\ 0 & 0 & G_1 & 0 \\ 0 & 0 & 0 & G_2 \end{bmatrix} \tag{29}$$

Adding a fifth blank row and column to the above equation and then connect a nullator between columns 2 and 5 and a CM between rows 1 and 5 in order to move $-G_3$ from the 1, 2 position to the diagonal position 5, 5 the following NAM is obtained:

Table 3 Summary of the class III oscillator circuits.

Circuit figure number	Active element	Number of C	Number of G	Condition of oscillation	ω_O	Ref.
6(a)	2 CCII+, 1 CCII−	2 Grounded	4 Grounded	$G_3 = G_1$	$\sqrt{\frac{G_2G_4}{C_1C_2}}$	[31,32]
6(b)	2 CCII+, 1 CCII−	2 Grounded	4 Grounded	$G_3 = G_1$	$\sqrt{\frac{G_2G_4}{C_1C_2}}$	[32]
7(a)	DOCCII, CCII−	2 Grounded	3 Grounded	$G_3 = G_1$	$\sqrt{\frac{G_2G_3}{C_1C_2}}$	[34]
7(b)	BOCCII, CCII+	2 Grounded	3 Grounded	$G_3 = G_1$	$\sqrt{\frac{G_2G_3}{C_1C_2}}$	[34]
8(a)	2 CCII+, 1 CCII−	2 Grounded	4 Grounded	$G_3 = G_1$	$\sqrt{\frac{G_2G_4}{C_1C_2}}$	[31]
8(b)	2 CCII+, 1 CCII−	2 Grounded	4 Grounded	$G_3 = G_1$	$\sqrt{\frac{G_2G_4}{C_1C_2}}$	[32]

$$Y = \begin{bmatrix} sC_1+G_3 & 0 & 0 & 0 & 0 \\ 0 & sC_2 & 0 & 0 & 0 \\ 0 & 0 & G_1 & 0 & 0 \\ 0 & 0 & 0 & G_2 & 0 \\ 0 & 0 & 0 & 0 & G_3 \end{bmatrix} \quad (30)$$

The above equation is realized as shown in Fig. 6b using two CCII+ and one CCII−. Changing the magnitude of G_3 at node 5 to become G_4 adds more degrees of freedom in the tuning the oscillator circuit and the NAM equation in this case will be modified to:

$$Y = \begin{bmatrix} sC_1 + G_3 - G_1 & -G_4 \\ G_2 & sC_2 \end{bmatrix} \quad (31)$$

This is similar to Eq. (15) except for the signs of G_1 and G_3. Table 3 summarizes these results.

It is worth noting that the two circuits of Fig. 6a and b can also be generated from Fig. 1b as given in Soliman [33]. They can also be generated from the circuits given in Soliman [34] as explained in the following section.

Two-output CCII based oscillators

The first type of the two-output CCII is the double output CCII++ which is defined by:

$$\begin{bmatrix} Vx \\ Iy \\ Iz+ \\ Iz+ \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Ix \\ Vy \\ Vz \\ Io \end{bmatrix} \quad (32)$$

The oscillator circuit shown in Fig. 7a using a DOCCII++ and a CCII− was first introduced by Soliman [34]; its NAM equation is given by:

$$Y = \begin{bmatrix} sC_1 + G_1 - G_3 & G_2 \\ -G_3 & sC_2 \end{bmatrix} \quad (33)$$

The second type of the two-output CCII is the balanced output CCII which is defined by:

$$\begin{bmatrix} Vx \\ Iy \\ Iz+ \\ Iz− \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Ix \\ Vy \\ Vz \\ Io \end{bmatrix} \quad (34)$$
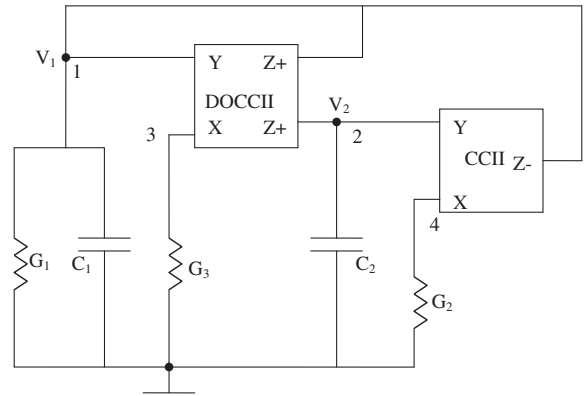
Fig. 7a Grounded passive elements oscillator circuit I [34].
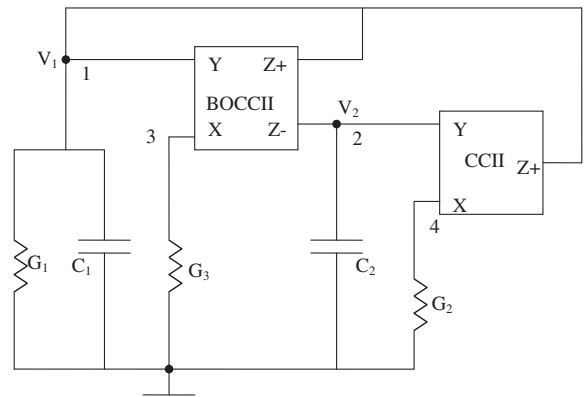
Fig. 7b Grounded passive elements oscillator circuit II [34].

The oscillator circuit shown in Fig. 7b using a BOCCII and a CCII+ was first introduced by Soliman [34]; its NAM equation is given by:

$$Y = \begin{bmatrix} sC_1 + G_1 - G_3 & -G_2 \\ G_3 & sC_2 \end{bmatrix} \quad (35)$$

Replacing the DOCCII++ by its equivalent two single output CCII+ as demonstrated by Soliman [32] results in the circuit of Fig. 8a. Similarly the circuit of Fig. 8b can be generated from Fig. 7b by replacing the BOCCII by its equivalent single output CCII+ and single output CCII−. Note that G_3 at node 5 has been taken as G_4 to increase degrees of freedom in the tuning of the oscillator circuit. The results of this circuit are summarized in Table 3.
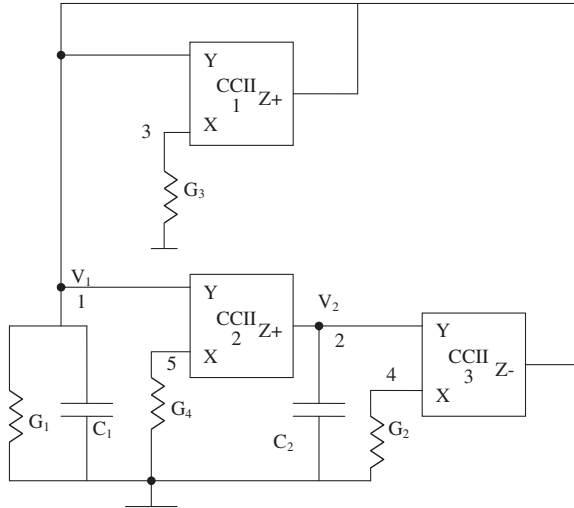
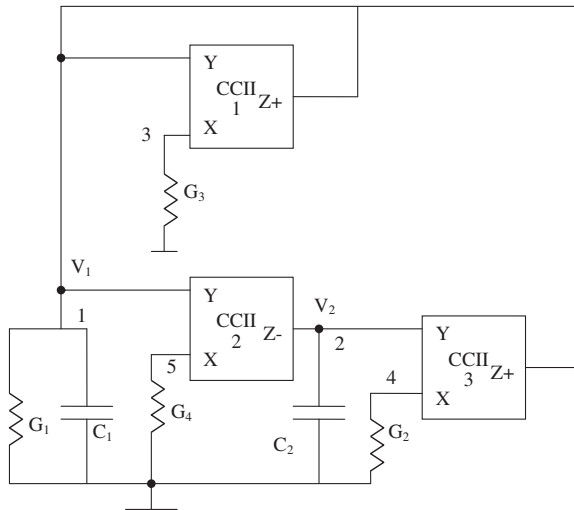**Fig. 8a** Single output CCII equivalent circuit to Fig. 7a [31].

Fig. 8b Single output CCII equivalent circuit to Fig. 7b. [32].

Transconductance amplifier based oscillators

The TA is a very powerful active building block [35–40] in realizing oscillator circuits. Three different types of TA are considered in this section.

(i) Single input single output TA based oscillators

There are two types of the single input single output TA (SISO TA) defined as follows. The TA+ has current pointing outwards and the TA− has current pointing inwards. It is well known that the CCII+ with a conductance connected to its X terminal realizes a TA+ with the same magnitude as the conductance. Similarly a CCII− with a conductance connected to its X terminal realizes a TA−.

The first circuit considered in this section is shown in Fig. 9a and is generated from Fig. 6a by replacing the three CCII by three TA. The conductance G_1 is realized by the TA− shown to the left of Fig. 9a. The four SISO TA circuit is shown in Fig. 9a and has the same equation as that of
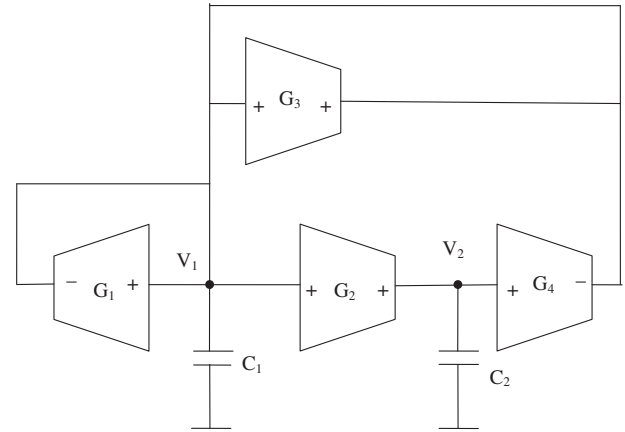

Fig. 9a Four TA grounded capacitors oscillator generated from Fig. 6a.
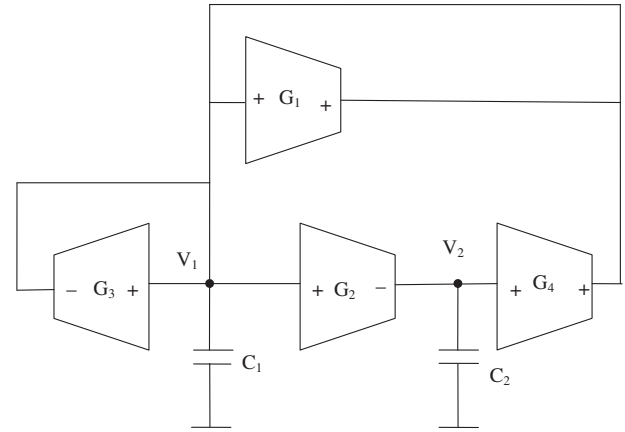

Fig. 9b Four TA grounded capacitors oscillator generated from Fig. 6b.

Fig. 6a and Eq. (27) applies to it as well. It is worth noting that the TA of transconductance G_3 realizes a negative grounded conductance at node 1 of magnitude $-G_3$. This $-G_3$ was realized by the CCII+ number 1 in Fig. 6a acting as a Negative Impedance Converter (NIC), with G_3 acting as its load.

The second SISO TA circuit considered in this section is shown in Fig. 9b and is generated from Fig. 6b; and Eq. (31) applies to this circuit. A TA circuit with the same topology has been reported in [40,41].

(ii) Single input two-output TA based oscillators

The circuit shown in Fig. 10a is generated from Fig. 7a and it employs a Double Output TA with two positive outputs (DOTA+ +) and two-SISO TA. Its NAM equation is the same as given by Eq. (33).

The condition of oscillation is controlled by the TA (G_1) without affecting the frequency of oscillation and the frequency of oscillation is controlled by the TA (G_2) without affecting the condition of oscillation.

The circuit shown in Fig. 10b is generated from Fig. 7b and it employs a Balanced Output TA (BOTA) and two-SISO TA. Its NAM equation is the same as given by Eq. (35).
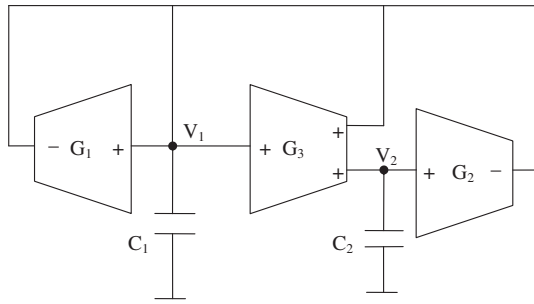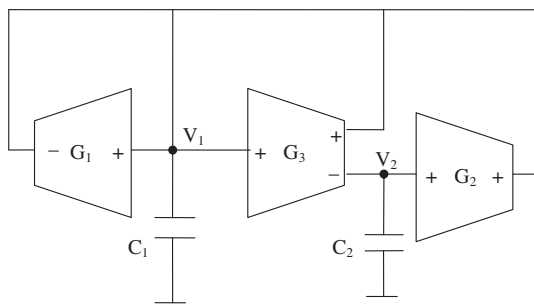
Fig. 10a Three TA oscillator circuit I.

Fig. 10b Three TA oscillator circuit II.

The circuit has the same condition and the radian frequency of oscillation as the previous circuit and is given in Table 4. A TA circuit with the same topology has been reported by Swamy et al. [42].

(iii) Two-input single-output TA based oscillator

The circuit shown in Fig. 11 employs a two input TA and two SISO TA and its NAM equation is given by:

$$Y = \begin{bmatrix} sC_1 + G_1 - G_3 & G_3 \\ -G_2 & sC_2 \end{bmatrix} \qquad (36)$$

This circuit has been reported [42–44] and is the adjoint [45,46] of the circuit shown in Fig. 10b.

Nonlinearity

It is well known that oscillators are nonlinear circuits, and the reported oscillators are based on a two integrator loop. Regarding amplitude control it should be noted that most oscillators rely on output voltage saturation of the active devices as a nonlinear mechanism for amplitude control. Regarding the amplitude control and stability of limit cycle this topic
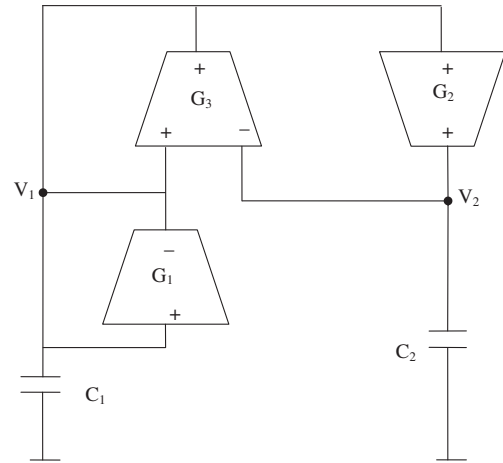

Fig. 11 Three TA oscillator with one two input TA [42–44].

has been demonstrated on a current conveyor oscillator published by Soliman and Elwakil [47].

Discussion of non-idealities

Although the main objective of the paper is to review quadrature oscillators using various active building blocks and to show how they are related to each other, it may be useful to discuss the non-idealities of the active building blocks in the following sections.

(i) Op Amp circuits

The NAM equations of the Op Amp oscillators shown in Fig. 1a–d are based on assuming ideal Op Amps having infinite gain are used. In the actual case the single pole model of the Op Amp gain should be used. This model is represented by the following equation [3]:

$$A = \frac{A_o \omega_o}{s + \omega_o} \cong \frac{\omega_t}{s} \qquad (37)$$

where ω_t is the unity gain bandwidth of the Op Amp; the use of this model in the oscillator circuit analysis affects the NAM equation [5] and hence both the condition of oscillation and the frequency of oscillation are changed from their ideal values.

(ii) OTRA circuits

The main parameter which is affecting the performance of the oscillator circuits of Fig. 2a and b is the finite and

Table 4 Summary of the class IV oscillator circuits.

Circuit figure number	Active element	Number of C	Condition of oscillation	ω_O	Ref.
9(a)	4 SISO TA	2 Grounded	$G_3 = G_1$	$\sqrt{\frac{G2G4}{C1C2}}$	–
9(b)	4 SISO TA	2 Grounded	$G_3 = G_1$	$\sqrt{\frac{G2G4}{C1C2}}$	–
10(a)	2 SISO TA 1 DOTA + +	2 Grounded	$G_3 = G_1$	$\sqrt{\frac{G2G3}{C1C2}}$	–
10(b)	2 SISO TA 1 BOTA	2 Grounded	$G_3 = G_1$	$\sqrt{\frac{G2G3}{C1C2}}$	–
11	2 SISO TA 1 TISO TA	2 Grounded	$G_3 = G_1$	$\sqrt{\frac{G2G3}{C1C2}}$	[42–44]

frequency dependent nature of the transresistance Rm which is represented by:

$$R_m = \frac{R_o \omega_o}{s + \omega_o} \qquad (38)$$

where R_o is the DC value of the transresistance and ω_o is the pole radian frequency of the OTRA.

(iii) DCVC circuits

The non-ideality of the DCVC is mainly due to the parasitic elements that are represented by the two X terminal resistances R_{X1}, R_{X2} and the Z terminal capacitance C_Z. For the circuit of Fig. 3a all the parasitic elements can be absorbed in the circuit parameters except R_{X1} of the first DCVC which affects the circuit operation. On the other hand for the circuit of Fig. 3b all the parasitic elements can be absorbed in the circuit parameters.

(iv) CFOA circuits

The CFOA parasitic elements are mainly represented by the X terminal resistance R_X and the Z terminal capacitance C_Z and the O terminal resistance R_O. For the circuit of Fig. 5a the resistor R_2 value should be adjusted to accommodate the added parasitic resistance R_{X2}, the resistor R_3 value should be adjusted to accommodate the added resistance $(R_{X1} + R_{O2})$. Similarly C_1 and C_2 should be adjusted to accommodate the parasitic capacitances C_{Z1} and C_{Z2} respectively. For the circuit of Fig. 5b the resistor R_1 value should be adjusted to accommodate the added parasitic resistance R_{X1}, the resistor R_2 value should be adjusted to accommodate the added parasitic resistance R_{X2} and the resistor R_3 value should be adjusted to accommodate the added output terminal resistance R_{O2}. Similarly C_1 and C_2 should be adjusted to accommodate the parasitic capacitances C_{Z1} and C_{Z2} respectively. Thus it is seen that the two circuits of Fig. 5a and b have the advantage of absorbing all parasitic elements within the design values of the circuit components.

(v) CCII circuits

The CCII parasitic elements are mainly represented by the X terminal resistance R_X and the Z terminal capacitance C_Z. For the circuit of Fig. 6a the resistor R_3 should be adjusted to accommodate the added parasitic resistance R_{X1}, the resistor R_2 value should be adjusted to accommodate the parasitic resistance R_{X2} and the resistor R_4 should be adjusted to accommodate the parasitic resistance R_{X3}. Similarly C_1 and C_2 should be adjusted to accommodate the parasitic capacitances $(C_{Z1} + C_{Z3})$ and C_{Z2} respectively. Similarly for all other CCII oscillator circuits presented in Figs. 6b–8b. Thus it is seen that the CCII oscillator circuits presented in this paper have the advantage of absorbing all parasitic elements within the design values of the circuit components.

(vi) TA circuits

The main parameter which is affecting the performance of the TA oscillator circuits is the finite and frequency dependent nature of the transconductance G which is represented by:

$$G_m = \frac{G_o \omega_o}{s + \omega o} \qquad (39)$$

where G_o is the DC value of the transconductance G_m and ω_o is the pole radian frequency of the TA.

Conclusions

Quadrature oscillators are reviewed in this paper using several active building blocks namely; operational amplifier, operational transresistance amplifier, differential current voltage conveyor, unity gain cells, current feedback operational amplifier, current conveyors and transconductance amplifiers. Generation methods including nodal admittance matrix expansion shows that many oscillators that are reviewed in this paper can be obtained from each other. Simulation results or experimental for most of the oscillator circuits reviewed are available in the proper references indicated below and are not included to limit the paper length. It is worth noting that the chip size and the power dissipation for each of the reported oscillators will depend on the circuit design and the CMOS analog circuit realizing the active building block used.

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