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State-variable Synthesis of Electronically-Controllable Sinusoidal Oscillators

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Abstract This paper presents a state-variable synthesis of a class of electronically-controllable sinusoidal oscillator circuits which employ Multiple output second generation controlled current conveyors (CCCII) as active elements, do not require any external passive resistors and employ only two grounded capacitors (GC). The systematic synthesis yields a class of fourteen new oscillators all of which provide independent electronic controls of both the frequency of oscillation and condition of oscillation through separate external bias currents. All the aforementioned features make the synthesized oscillators attractive from the view point of integrated circuit implementation. The workability of the derived circuits has been confirmed from SPICE simulations and some sample results are included. Based upon their performance, evaluated through simulations, the new circuits have been compared with those previously known as well as among themselves and the best circuits of the derived set have been identified.

Keywords: *sinusoidal oscillators, controlled current conveyors, electronically-controlled oscillators*

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1. Introduction

Sinusoidal oscillators are needed in a wide range of applications in electronics, communication, instrumentation, measurement, control systems etc. Therefore, sinusoidal oscillators have been extensively investigated and their numerous new types of realisations have been proposed in the past using a variety of active circuit building blocks. The survey of the existing literature shows that a large number of circuits have been proposed to realise voltage-mode, current-mode and mixed-mode sinusoidal oscillator circuits. Moreover, there has been a major emphasis in the earlier literature on the realisation of single-element-controlled oscillators using different active building blocks, such as voltage-mode operational amplifiers (VOA), operational transconductance amplifiers (OTA), different types of current conveyors (CC), current feedback operational amplifiers (CFOA), four terminal floating nullors (FTFN), current followers (CF) and voltage followers (VF), current differencing buffered amplifiers (CDBA), current differencing transconductance amplifiers (CDTA), operational trans-resistance amplifiers (OTRA), differential difference complementary current conveyors (DDCCC), differential difference complementary current feedback amplifiers (DDCCFA), differential difference amplifiers (DDA), differential voltage current feedback amplifiers (DVCFA) etc. for instance, see [1-20] and the references cited therein.

The sinusoidal oscillators being presented in this paper have been synthesized through a state-variable methodology using the translinear second generation current controlled conveyors (CCCIIs) introduced by Fabre-Saaid-Wiest-Boucheron [21,22] as the active building blocks.

A CCCII has finite input resistance R_x looking into the X-terminal of the CCCII which is given by $R_x=V_T/2I_B$ (where V_T is the thermal voltage) which is electronically controllable by an external bias current I_B. Because of this characteristic, the CCCII has been found to be particularly suitable for the realization of *electronically-controllable* functional circuits, including oscillators. Consequently, during the past two decades, a number of sinusoidal oscillator circuits based on CCCIIs have been reported in the literature [23-40]. However, most of the existing CCCII-based oscillators suffer from one or more of the following drawbacks: (i) employment of dissimilar types of building blocks as in [23,29,34], (ii) use of an excessive number of active elements as in [34,36,40] (iii) non-availability of independent electronic controls of the frequency of oscillation (FO) and condition of oscillation (CO) *both* as in [23,28-33,35,36,38] (iv) use of *external* passive resistors also as in [26,35,36] and (v) the use of *floating* capacitor(s) as in [29,35,36], which are not convenient for IC implementation.

This paper presents a systematic *state-variable synthesis* of a class of new CCCII-based sinusoidal oscillator circuits which are free from all the drawbacks mentioned above in that they employ a *minimum* of only three multiple-output CCCIIs (MO-CCCII) as active elements, need no external passive resistors and employ both grounded capacitors (GC), as desirable for IC implementation [8,43,44].

2. State-variable Synthesis of CCCII-based Oscillators

The state-variable approach to oscillator synthesis was introduced by Senani and Gupta in [5] and subsequently extended by Gupta and Senani in [6,7], in the context of CFOA-based oscillators.

Since then, the state-variable approach of [5,6,7] has been subsequently used to synthesize a class of DDCCC-based SRCOs using all grounded passive elements in [8], a class of grounded-capacitor single resistance controlled oscillators (SRCO) using a single DDCCFA in [9], oscillators with explicit-current-output in [10,11], linear VCOs in [12,13], SRCOs using differential difference amplifiers (DDA) in [14], and more recently, SRCOs using third generation current conveyors (CCIII) in [15]. Another extension of the state-variable method was also carried out by Güneş and Toker in [16] to derive a class of oscillators using DVCFAs.

Here, we extend the state-variable synthesis methodology of [5,6,7] for deriving new CCCII-based oscillators.

The CCCII± is characterised by the terminal equations: $I_y = 0,\ V_x = V_y + R_x I_x$ and $I_z = \pm I_x$ where $R_x = V_T/2I_B$ and is, therefore, electronically-controllable through the external dc bias current I_B.

The basic state-variable methodology to synthesize sinusoidal oscillators providing independent controls of FO and CO, as proposed in [5], can be reiterated as follows:

A canonic second-order (i.e. employing only two capacitors) oscillator can be characterized by the following autonomous state equation:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix}=\begin{bmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix}. \tag{1}$$

From the above, the characteristic equation (CE)

$$s^2-(a_{11}+a_{22})s+(a_{11}a_{22}-a_{12}a_{21})=0 \tag{2}$$

gives the CO and FO as

$$(a_{11}+a_{22})=0 \tag{3}$$

and

$$\omega_0^2=(a_{11}a_{22}-a_{12}a_{21}) \tag{4}$$

The state variable synthesis methodology [5] involves, an *a priori* selection of the parameters $a_{ij}, i = 1,2;$ $j = 1,2,$ in accordance with the required features (e.g. independent control for CO and FO through separate resistors), conversion of the resulting state equations into the node equations (NE) and finally, constructing a physical circuit from these NEs by using the chosen active building block and RC elements.

In the following, we choose the same types of matrices as introduced in [5,6,7], but employ the intrinsic input resistances R_x of the CCCIIs instead of the external resistors and demonstrate how a class of new electronically-controlled oscillators, not known earlier, can be systematically synthesized using this approach.

It must be kept in mind that in all the circuits derived in the following, the resistors R_{x1}, R_{x2} and R_{x3} are not the physical resistors but the intrinsic X-port input resistances of the CCCIIs employed which are electronically-controllable by respective external dc bias currents.

In the following, we first show the synthesis of one exemplary circuit *explicitly* and subsequently, the remaining types of [A] matrices suitable for the present purpose, along with the synthesized CCCII-based oscillators resulting therefrom and their COs and FOs would be presented directly in tabular form to conserve space.

For the realization of a current-controlled oscillator providing independent controls of both CO and FO, and following the ideas contained in [5,6,7], let us choose the elements of the [A] matrix as:

$$[A]=\begin{bmatrix}\dfrac{1}{C_1}\left(\dfrac{1}{R_{x1}}-\dfrac{1}{R_{x3}}\right) & -\dfrac{1}{C_1}\left(\dfrac{1}{R_{x1}}+\dfrac{1}{R_{x2}}-\dfrac{1}{R_{x3}}\right)\\ \dfrac{1}{C_2R_{x3}} & -\dfrac{1}{C_2R_{x3}}\end{bmatrix}. \tag{5}$$

From Eqn. 5, the characteristic equation of the oscillator, having [A] matrix as above, is given by

$$s^2-\left(\frac{1}{C_1R_{x1}}-\frac{1}{C_1R_{x3}}-\frac{1}{C_2R_{x3}}\right)s+\frac{1}{C_1C_2R_{x2}R_{x3}}=0 \tag{6}$$

from where the CO and FO are found to be:

$$\frac{1}{R_{x1}}=\frac{1}{R_{x3}}\left(\frac{C_1}{C_2}+1\right) \tag{7}$$

and

$$f_0=\frac{1}{2\pi\sqrt{C_1C_2R_{x2}R_{x3}}}. \tag{8}$$

Thus, *as intended*, indeed, CO and FO both are independently controllable without affecting each other; the former by R_{x1} and the latter by R_{x2}.

Now, substituting eqn. (5) in (1), the resulting NEs can be written as

$$C_1\frac{dx_1}{dt}+\frac{x_2}{R_{x2}}+\frac{x_1-x_2}{R_{x3}}=\frac{x_1-x_2}{R_{x1}}. \tag{9}$$

$$C_2\frac{dx_2}{dt}=\frac{x_1-x_2}{R_{x3}}. \tag{10}$$

By using NEs (9) and (10), a physical oscillator circuit is synthesized as shown in Figure 1, wherein the construction of the circuit can be understood by observing the various currents marked on the diagram itself.

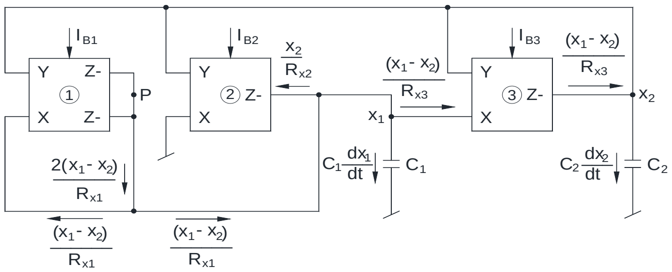

Figure 1. A new oscillator circuit realized by using NEs (9) and (10)

Table 1. Various choices of the elements of the matrix [A] which lead to independent controls of CO and FO both

No.	The selected elements for [A] matrix	CO	FO
1.	$\begin{bmatrix} \frac{1}{C_1}\left(\frac{1}{R_{x1}}-\frac{1}{R_{x3}}\right) & -\frac{1}{C_1}\left(\frac{1}{R_{x1}}+\frac{1}{R_{x2}}-\frac{1}{R_{x3}}\right) \\ \frac{1}{C_2R_{x3}} & -\frac{1}{C_2R_{x3}} \end{bmatrix}$	$\frac{1}{R_{x1}}=\frac{1}{R_{x3}}\left(\frac{C_1}{C_2}+1\right)$	$\frac{1}{2\pi\sqrt{C_1C_2R_{x2}R_{x3}}}$
2.	$\begin{bmatrix} \frac{1}{C_1}\left(\frac{2}{R_{x1}}-\frac{1}{R_{x3}}\right) & -\frac{1}{C_1}\left(\frac{2}{R_{x1}}+\frac{1}{R_{x2}}-\frac{1}{R_{x3}}\right) \\ \frac{1}{C_2R_{x3}} & -\frac{1}{C_2R_{x3}} \end{bmatrix}$	$\frac{2}{R_{x1}}=\frac{1}{R_{x3}}\left(\frac{C_1}{C_2}+1\right)$	$\frac{1}{2\pi\sqrt{C_1C_2R_{x2}R_{x3}}}$
3.	$\begin{bmatrix} \frac{1}{C_1}\left(\frac{1}{R_{x1}}-\frac{1}{R_{x3}}\right) & -\frac{1}{C_1}\left(\frac{1}{R_{x1}}+\frac{2}{R_{x2}}-\frac{1}{R_{x3}}\right) \\ \frac{1}{C_2R_{x3}} & -\frac{1}{C_2R_{x3}} \end{bmatrix}$	$\frac{1}{R_{x1}}=\frac{1}{R_{x3}}\left(\frac{C_1}{C_2}+1\right)$	$\frac{\sqrt{2}}{2\pi\sqrt{C_1C_2R_{x2}R_{x3}}}$
4.	$\begin{bmatrix} -\frac{2}{C_1R_{x1}} & \frac{1}{C_1}\left(\frac{2}{R_{x1}}+\frac{1}{R_{x2}}\right) \\ -\frac{1}{C_2R_{x3}} & \frac{1}{C_2R_{x3}} \end{bmatrix}$	$C_1R_{x1}=2C_2R_{x3}$	$\frac{1}{2\pi\sqrt{C_1C_2R_{x2}R_{x3}}}$
5.	$\begin{bmatrix} \frac{2}{C_1R_{x1}} & -\frac{1}{C_1}\left(\frac{2}{R_{x1}}+\frac{1}{R_{x2}}\right) \\ \frac{1}{C_2R_{x3}} & -\frac{1}{C_2R_{x3}} \end{bmatrix}$	$C_1R_{x1}=2C_2R_{x3}$	$\frac{1}{2\pi\sqrt{C_1C_2R_{x2}R_{x3}}}$
6.	$\begin{bmatrix} \frac{1}{C_1R_{x1}} & -\frac{1}{C_1}\left(\frac{1}{R_{x1}}+\frac{2}{R_{x2}}\right) \\ \frac{1}{C_2R_{x3}} & -\frac{1}{C_2R_{x3}} \end{bmatrix}$	$C_1R_{x1}=C_2R_{x3}$	$\frac{\sqrt{2}}{2\pi\sqrt{C_1C_2R_{x2}R_{x3}}}$
7.	$\begin{bmatrix} -\frac{1}{C_1R_{x3}} & -\frac{1}{C_1}\left(\frac{1}{R_{x1}}+\frac{1}{R_{x2}}-\frac{1}{R_{x3}}\right) \\ \frac{1}{C_2R_{x3}} & -\frac{1}{C_2}\left(\frac{1}{R_{x1}}-\frac{1}{R_{x3}}\right) \end{bmatrix}$	$\frac{1}{R_{x1}}=\frac{1}{R_{x3}}\left(\frac{C_1}{C_2}+1\right)$	$\frac{1}{2\pi\sqrt{C_1C_2R_{x2}R_{x3}}}$
8.	$\begin{bmatrix} \frac{1}{C_1}\left(\frac{2}{R_{x1}}+\frac{1}{R_{x2}}-\frac{1}{R_{x3}}\right) & -\frac{1}{C_1}\left(\frac{2}{R_{x1}}+\frac{1}{R_{x2}}\right) \\ \frac{1}{C_2R_{x2}} & -\frac{1}{C_2R_{x2}} \end{bmatrix}$	$\frac{2}{R_{x1}}=\frac{1}{R_{x2}}\left(\frac{C_1}{C_2}-1\right)+\frac{1}{R_{x3}}$ (with $C_1=C_2=C$, one needs $R_{x1}=2R_{x3}$)	$\frac{1}{2\pi\sqrt{C_1C_2R_{x2}R_{x3}}}$
9.	$\begin{bmatrix} 0 & \frac{1}{C_1R_{x2}} \\ -\frac{1}{C_2R_{x3}} & \frac{1}{C_2}\left(\frac{1}{R_{x3}}-\frac{1}{R_{x1}}\right) \end{bmatrix}$	$R_{x1}=R_{x3}$	$\frac{1}{2\pi\sqrt{C_1C_2R_{x2}R_{x3}}}$
10.	$\begin{bmatrix} 0 & -\frac{1}{C_1R_{x2}} \\ \frac{1}{C_2R_{x3}} & -\frac{1}{C_2}\left(\frac{1}{R_{x3}}-\frac{1}{R_{x1}}\right) \end{bmatrix}$	$R_{x1}=R_{x3}$	$\frac{1}{2\pi\sqrt{C_1C_2R_{x2}R_{x3}}}$
11.	$\begin{bmatrix} -\frac{1}{C_1R_{x1}} & \frac{1}{C_1}\left(\frac{1}{R_{x1}}+\frac{1}{R_{x2}}\right) \\ -\frac{1}{C_2R_{x3}} & \frac{1}{C_2R_{x3}} \end{bmatrix}$	$C_1R_{x1}=C_2R_{x3}$	$\frac{1}{2\pi\sqrt{C_1C_2R_{x2}R_{x3}}}$
12.	$\begin{bmatrix} \frac{1}{C_1R_{x1}} & -\frac{1}{C_1}\left(\frac{1}{R_{x1}}+\frac{1}{R_{x2}}\right) \\ \frac{1}{C_2R_{x3}} & -\frac{1}{C_2R_{x3}} \end{bmatrix}$	$C_1R_{x1}=C_2R_{x3}$	$\frac{1}{2\pi\sqrt{C_1C_2R_{x2}R_{x3}}}$
13.	$\begin{bmatrix} -\frac{1}{C_1}\left(\frac{1}{R_{x1}}+\frac{1}{R_{x2}}-\frac{1}{R_{x3}}\right) & \frac{1}{C_1}\left(\frac{1}{R_{x1}}+\frac{1}{R_{x2}}\right) \\ -\frac{1}{C_2R_{x2}} & \frac{1}{C_2R_{x2}} \end{bmatrix}$	$\frac{1}{R_{x1}}=\frac{1}{R_{x2}}\left(\frac{C_1}{C_2}-1\right)+\frac{1}{R_{x3}}$ with $C_1=C_2=C$, $R_{x1}=R_{x3}$	$\frac{1}{2\pi\sqrt{C_1C_2R_{x2}R_{x3}}}$
14.	$\begin{bmatrix} \frac{1}{C_1}\left(\frac{1}{R_{x1}}+\frac{1}{R_{x2}}-\frac{1}{R_{x3}}\right) & -\frac{1}{C_1}\left(\frac{1}{R_{x1}}+\frac{1}{R_{x2}}\right) \\ \frac{1}{C_2R_{x2}} & -\frac{1}{C_2R_{x2}} \end{bmatrix}$	$\frac{1}{R_{x1}}=\frac{1}{R_{x2}}\left(\frac{C_1}{C_2}-1\right)+\frac{1}{R_{x3}}$ with $C_1=C_2=C$, $R_{x1}=R_{x3}$	$\frac{1}{2\pi\sqrt{C_1C_2R_{x2}R_{x3}}}$

Since the CO is controllable by R_{x1} while FO is independently controlled by $R_{x2,}$ it follows that CO is electronically-controllable by I_{B1} whereas the FO is also *independently* electronically-controllable by I_{B2}.

In Table 1 we now show the fourteen possible choices of the matrices [A] which lead to independent controls of both CO and FO. These matrices have been constructed on the basis of those given in [5,6,7] but here we have used the intrinsic resistances R_{xi}; i=1-3 of the CCCIIs rather than any external resistors. The Table 1 also shows the CO and FO of the synthesized oscillators which result from these matrices using the methodology as explained in the above example.

We can now write the following node equations resulting from the chosen 14 matrices of Table 1.

The NEs from [A] matrix 1

$$C_1\frac{dx_1}{dt}+\frac{x_2}{R_{x2}}+\frac{(x_1-x_2)}{R_{x3}}=\frac{(x_1-x_2)}{Rx_1} \tag{11a}$$

$$C_2\frac{dx_2}{dt}=\frac{(x_1-x_2)}{R_{x3}}. \tag{11b}$$

The NEs from [A] matrix 2

$$C_1\frac{dx_1}{dt}+\frac{x_2}{R_{x2}}+\frac{(x_1-x_2)}{Rx_3}=\frac{2(x_1-x_2)}{R_{x1}} \tag{12a}$$

$$C_2\frac{dx_2}{dt}=\frac{(x_1-x_2)}{R_{x3}}. \tag{12b}$$

The NEs from [A] matrix 3

$$C_1\frac{dx_1}{dt}+\frac{2x_2}{R_{x2}}+\frac{(x_1-x_2)}{R_{x3}}=\frac{(x_1-x_2)}{R_{x1}} \tag{13a}$$

$$C_2\frac{dx_2}{dt}=\frac{(x_1-x_2)}{R_{x3}}. \tag{13b}$$

The NEs from [A] matrix 4

$$C_1\frac{dx_1}{dt}=\frac{2(x_2-x_1)}{R_{x1}}+\frac{x_2}{R_{x2}} \tag{14a}$$

$$C_2\frac{dx_2}{dt}=\frac{(x_2-x_1)}{R_{x3}}. \tag{14b}$$

The NEs from [A] matrix 5

$$C_1\frac{dx_1}{dt}+\frac{x_2}{R_{x2}}=\frac{2(x_1-x_2)}{R_{x1}} \tag{15a}$$

$$C_2\frac{dx_2}{dt}=\frac{(x_1-x_2)}{R_{x3}}. \tag{15b}$$

The NEs from [A] matrix 6

$$C_1\frac{dx_1}{dt}+\frac{2x_2}{R_{x2}}=\frac{(x_1-x_2)}{R_{x1}} \tag{16a}$$

$$C_2\frac{dx_2}{dt}=\frac{(x_1-x_2)}{R_{x3}} \tag{16b}$$

The NEs from [A] matrix 7

$$C_1\frac{dx_1}{dt}+\frac{x_2}{R_{x1}}+\frac{x_2}{R_{x2}}=\frac{(x_2-x_1)}{R_{x3}} \tag{17a}$$

$$C_2\frac{dx_2}{dt}=\frac{(x_1-x_2)}{R_{x3}}+\frac{x_2}{R_{x1}}. \tag{17b}$$

The NEs from [A] matrix 8

$$C_1\frac{dx_1}{dt}+\frac{x_1}{R_{x3}}=\frac{2(x_1-x_2)}{R_{x1}}+\frac{(x_1-x_2)}{R_{x2}} \tag{18a}$$

$$C_2\frac{dx_2}{dt}=\frac{(x_1-x_2)}{R_{x2}}. \tag{18b}$$

The NEs from [A] matrix 9

$$C_1\frac{dx_1}{dt}=\frac{x_2}{R_{x2}} \tag{19a}$$

$$C_2\frac{dx_2}{dt}+\frac{x_2}{R_{x1}}=\frac{(x_2-x_1)}{R_{x3}}. \tag{19b}$$

The NEs from [A] matrix 10

$$C_1\frac{dx_1}{dt}=-\frac{x_2}{R_{x1}} \tag{20a}$$

$$C_2\frac{dx_2}{dt}=\frac{(x_1-x_2)}{R_{x3}}+\frac{x_2}{R_{x1}}. \tag{20b}$$

The NEs from [A] matrix 11

$$C_1\frac{dx_1}{dt}=\frac{(x_2-x_1)}{R_{x1}}+\frac{x_2}{R_{x2}} \tag{21a}$$

$$C_2\frac{dx_2}{dt}=\frac{(x_2-x_1)}{R_{x3}}. \tag{21b}$$

The NEs from [A] matrix 12

$$C_1\frac{dx_1}{dt}+\frac{x_2}{R_{x2}}=\frac{(x_1-x_2)}{R_{x1}} \tag{22a}$$

$$C_2\frac{dx_2}{dt}=\frac{(x_1-x_2)}{R_{x3}}. \tag{22b}$$

The NEs from [A] matrix 13

$$C_1\frac{dx_1}{dt}=\frac{(x_2-x_1)}{R_{x1}}+\frac{(x_2-x_1)}{R_{x2}}+\frac{x_1}{R_{x3}} \tag{23a}$$

$$C_2\frac{dx_2}{dt}=\frac{(x_2-x_1)}{R_{x2}}. \tag{23b}$$

The NEs from [A] matrix 14

$$C_1\frac{dx_1}{dt}+\frac{x_1}{R_{x3}}=\frac{(x_1-x_2)}{R_{x1}}+\frac{(x_1-x_2)}{R_{x2}} \tag{24a}$$

$$C_2\frac{dx_2}{dt}=\frac{(x_1-x_2)}{R_{x2}}. \tag{24b}$$

The oscillators synthesized from the above 14 sets of node equations are shown in Figure 2 – Figure 5. The CO and FO would be as already given in Table 1.

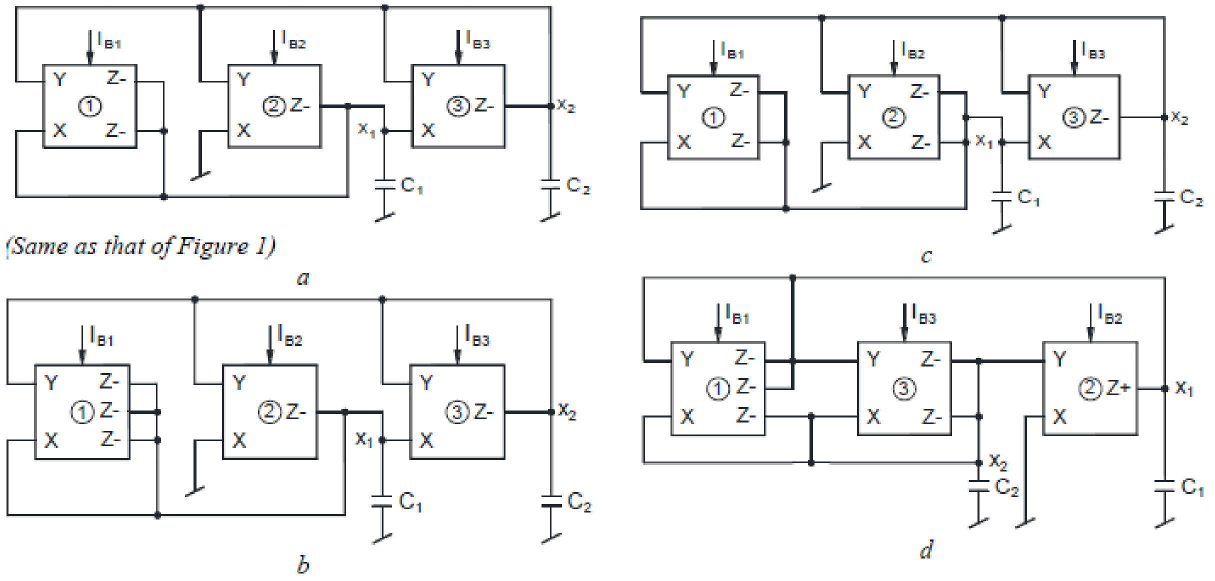

Figure 2. New oscillator circuits realized by using NEs (11) to (14)

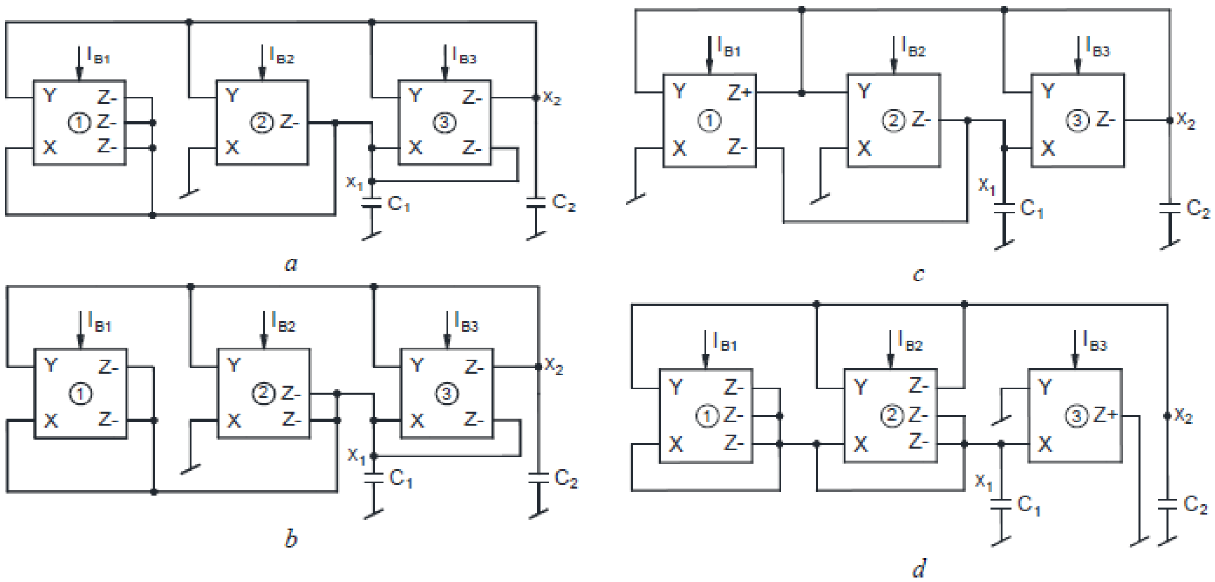

Figure 3. New oscillator circuits realized by using NEs (15) to (18)

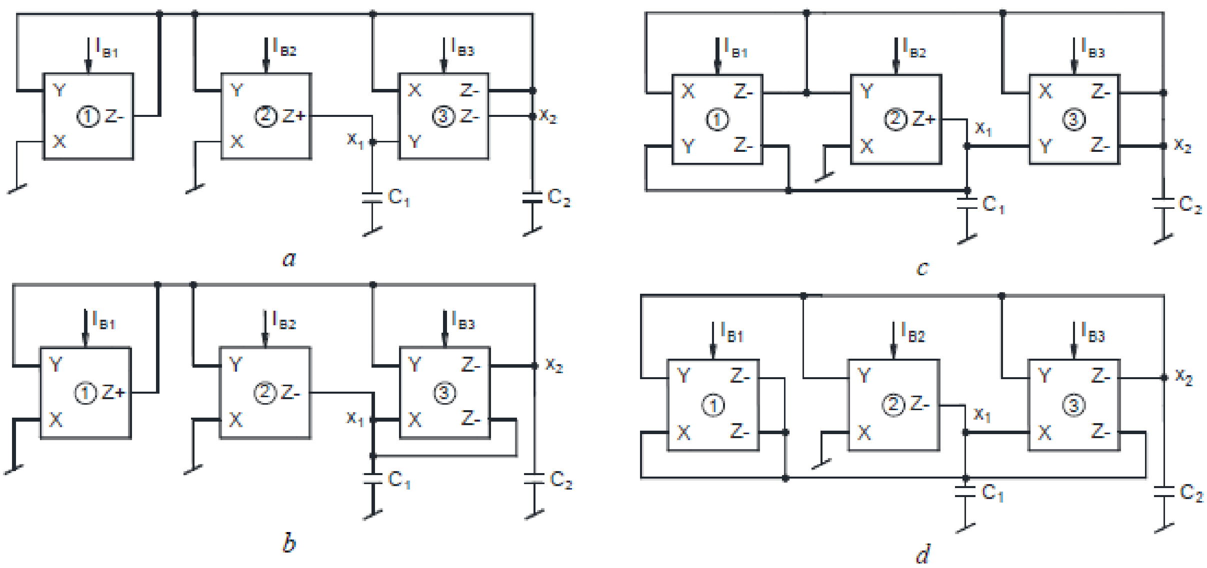

Figure 4. New oscillator circuits synthesized from the NEs (19) to (22)

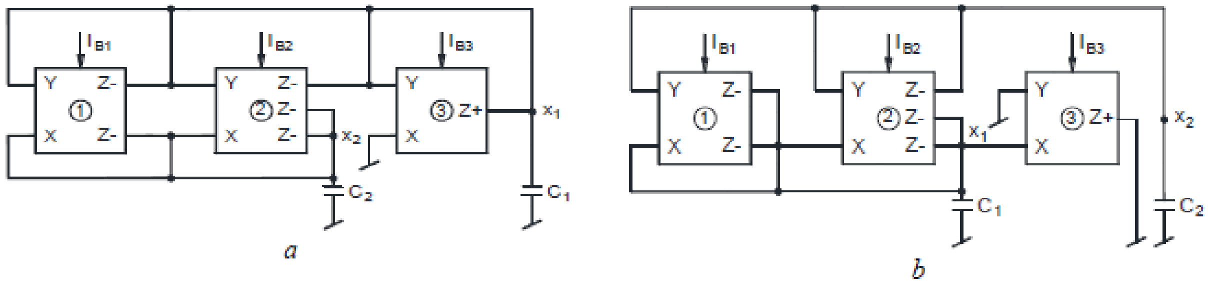

Figure 5. New oscillator circuits synthesized from the NEs (23) and (24)

It may be mentioned that although *three-CCCII-based* oscillators possessing the intended properties mentioned in the Introduction, have been reported earlier also in references [24,25,27,37] none of the fourteen topologies presented here have been known earlier and hence, are completely new.

3. Frequency Stability and Sensitivities

Frequency stability is an important figure of merit on the basis of which different sinusoidal oscillators can be compared. We use the definition of frequency stability factor as $S^F = \left.\frac{d\varphi(u)}{du}\right|_{u=1}$, where $u=\frac{\omega}{\omega_0}$ is the normalized frequency and $\varphi(u)$ represents the phase of the open loop transfer function of the oscillator circuit.

Here we show the derivation of S^F for the circuit of Figure 1. The open loop transfer function (with the link broken at point 'P' as shown in Figure 1) is found to be:

$$T(s)=\frac{I_{out}}{I_{in}} = \frac{\frac{s}{C_1R_{x1}}}{s^2+\frac{s}{C_1R_{x3}}+\frac{s}{C_2R_{x3}}+\frac{1}{C_1C_2R_{x2}R_{x3}}}. \qquad (25)$$

Thus, from Eqn. (25), the phase of the T(s) with the selection of component values as $C_1=C_2=C$, $2R_{x1}=R_{x3}=R_x$ and $R_{x2}=R_x/n$, is given by:

$$\varphi(u)=\tan^{-1}\frac{\left(u/\sqrt{n}\right)}{0}-\tan^{-1}\left(\frac{2u\sqrt{n}}{\left(1-u^2\right)n}\right). \qquad (26)$$

Now, differentiating Eqn. (26) with respect to u, we get

$$\frac{d}{du}\varphi(u)=\frac{2\sqrt{n}\left(1+u^2\right)}{n\left(1-u^2\right)^2+4u^2}. \qquad (27)$$

From (27) the value of S^F for this particular oscillator with u=1, is obtained to be

$$S^F=\sqrt{n}. \qquad (28)$$

Thus, the current-controlled oscillator of Figure 1 offers very good frequency stability factor for large values of n. By a similar analysis, it is found that the magnitude of S^F is $\sqrt{n}$ for oscillator 7 also whereas for all the remaining oscillators, S^F is found to be $2\sqrt{n}$. Thus, all the new oscillators enjoy excellent frequency stability properties.

On the other hand, the sensitivity of ω_0 with respect to R_{xi}; i=1-3 and the capacitances are found to be $S^{\omega 0}_{C_1}=S^{\omega 0}_{C_2}=S^{\omega 0}_{R_{x2}}=S^{\omega 0}_{R_{x3}}=-½$ and $S^{\omega 0}_{R_{x1}}=0$, which shows that all the oscillator circuits of Figure 2 to Figure 5 also enjoy very low sensitivity properties.

4. SPICE Simulation Results

To check the workability of the synthesized new current-controlled oscillator circuits, SPICE simulations have been performed using the bipolar transistor parameters of PR100N (PNP) and NR100N (NPN) transistors [41]. All the circuits realized using MO-CCCII have been simulated in SPICE using the structure of the MO-CCCII shown in Figure 6, which is obtained by suitably augmenting the architecture proposed by Yuce, Kircay and Toker in [42]. The capacitor values used were $C_1=C_2=100nF$ and the CO was adjusted through the variation of R_{x1} which is a function of the bias current I_{B1}. The FO was varied through the change of R_{x2} which is a function of the bias current I_{B2} and the value of R_{x3} was fixed through I_{B3}. The three MO-CCCIIs were biased with ±2.5V DC power supplies.

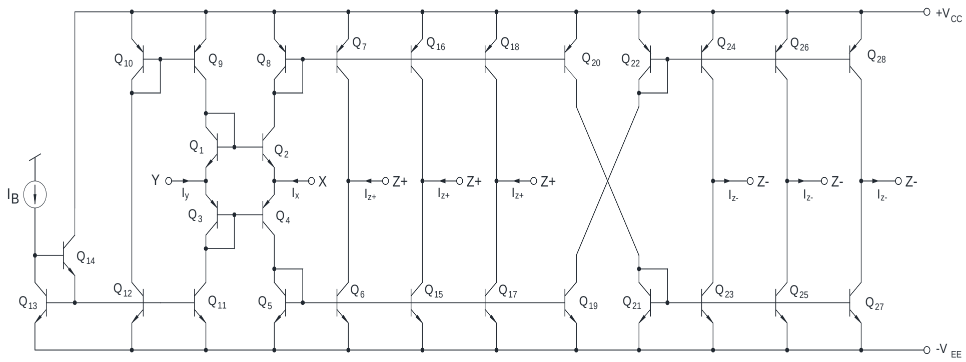

Figure 6. MO-CCCII internal structure obtained by suitable augmentation of the circuit of [42]

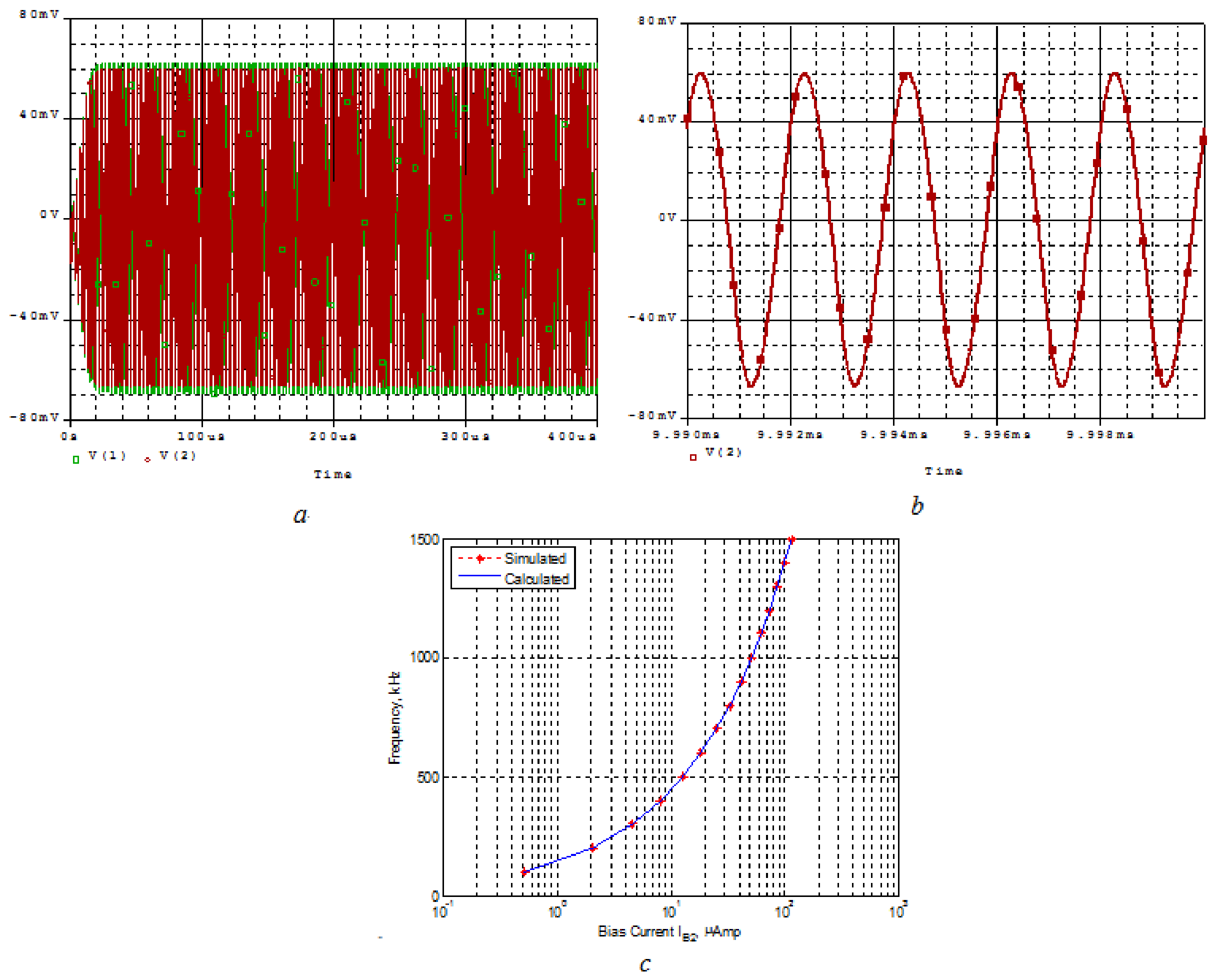

Figure 7. The variation of oscillation frequency with respect to bias current for the oscillator circuit of Figure 5(b) **(a)** Transient response **(b)** Steady state response ($C_1=C_2=100pF$, $I_{B1}=2.086\mu A$, $I_{B2}=12.83\mu A$ and $I_{B3}=1.3\mu A$) and **(c)** variation of FO w.r.t. I_{B2}

The SPICE generated transient and steady state waveforms and the variation of FO w.r.t. I_{B2} were studied for all the fourteen oscillator circuits. With the exception of the circuit of Figure 4a which was found to be in *latch-up*[1], all other circuits behaved as predicted by the theory.

To conserve space, we show here the simulation results only for the oscillator circuit of Figure 5(b). The output waveforms are shown in Figure 7(a) and Figure 7(b) whereas the variation of oscillation frequency w.r.t. I_{B2} is shown in Figure 7(c) by varying I_{B2} from 0.513μA to 115.47μA corresponding to which f_0 was found to vary from 99.965 kHz to 1500.00 kHz. The circuit exhibited excellent correspondence between I_{B2} and f_0. The % total harmonic distortion (THD) in the generated waveform, at the frequency of 499.95 kHz, was found to be 3.55%. The workability of the oscillator circuit of Figure 5(b) is, thus, established by these simulation results.

5. Comparison with Earlier Known CCCII-based Oscillators

A comparison of the generated new oscillator circuits with those previously reported in [23-39] is shown in Table 2 from where it is revealed that oscillators of [23,29] suffer from the drawback of employing dissimilar type of active elements; those in [34,36,39] use more than three active elements; those in [28,30,31,32,35,38] employ less than three CCCIIs but do not possess independent controls of both CO and FO. It turns out that only the earlier circuits of [24,25,27,37] use only three CCCIIs and two grounded capacitors, however, none of the 14 oscillators presented here are found to exist in any of these earlier works [24,25,27,37] and hence, are completely new.

From the data given in seventh column of Table 2, it is revealed that the new circuits appear to have an edge over the quoted ones in terms of their comparatively larger frequency range of operation 100 kHz-1.5 MHz.

Table 3 shows the operating frequency ranges and the % THD for all the fourteen synthesized oscillator circuits. From the data of all the 14 new circuits, it is found that comparatively, the circuit of Figure 5(b) appears to be the best in terms of largest possible tuning range, low THD and high S^F.

It may be mentioned that like the three CCCII-based oscillators of [37] which are realised by using a CMOS CCCII architecture implementable in 0.35μm CMOS technology, the circuits of this paper can also be implemented with any chosen CMOS CCCII structure since the *kernel* of the work reported here is not dependent on the technology used.

[1] The study of *latch-up* behavior in CCCII-based oscillators is, as yet, unstudied phenomenon and constitutes an interesting problem for further research.

Table 2. Comparison of the synthesized new oscillators with the previously published CCCII-based Oscillators

Ref. No.	Number and type of building blocks used	Whether same type of building blocks used?	Does the circuit employ two grounded capacitors?	Whether the circuit is external resistor-less?	Whether CO and FO are independently adjustable?	Frequency range	Power supply used	Technology used
[23]	2 CCCII, 1 Current Mirror	No	Yes	Yes	No	1 kHz-3000 kHz	±2.5V	Bipolar
[24]	3 CCCII	Yes	Yes	Yes	Yes	-	±2.5V	Bipolar
[25]	1 MOCCCII, 2 CCCII+	Yes	Yes	Yes	Yes	25 kHz-900 kHz	±2.5V	Bipolar
[26]	2 CCCII+, 1 CCCII-	Yes	Yes	No (1 grounded)	Yes	3 kHz-1000 kHz	±2.5V	Bipolar
[27]	2 CCCII+, 1 CCCII-	Yes	Yes	Yes	Yes	37 kHz-375 kHz	±2.5V	Bipolar
[28]	1 CCCII+, 1 CCCII-	Yes	Yes	Yes	No	1 kHz-100 kHz	±5V	Bipolar
[29]	1 MOCCCII, 1 CCCII+, 1 CCII±	No	No (1 Floating)	Yes	No	-	±2.5V	Bipolar
[30]	1 MOCCCII, 1 CCCII	Yes	Yes	Yes	No	212 kHz	±2.5V	Bipolar
[31]	1 MOCCCII, 1 CCCII	Yes	Yes	Yes	No	212 kHz	±2.5V	Bipolar
[32]	2 MOCCCII	Yes	Yes	Yes	No	-	±2.5V	Bipolar
[33]	2 CCCII(-IR)	Yes	Yes	Yes	No	80 kHz-120 kHz	±2.5V	Bipolar
	1 CCCII+, 1 CCCII-	Yes	Yes	Yes	No	90 kHz-110 kHz	±2.5V	Bipolar
[34]	1 OTA, 4 MOCCCII	No	Yes	Yes	Yes	200 kHz-1000 kHz	±2.5V	Bipolar
[35]	1 CCCII+	Yes	No (1 Floating)	No,(1 grounded)	No	-	±1.0V	45nm CMOS
[36]	5 CCCII+	Yes	No (1 Floating)	No (1 grounded and 1 floating)	No	358 MHz-572 MHz	±1.0V	0.18µm CMOS
	3 CCCII+, 2 CCCII-	Yes	No (1 Floating)	No (1 grounded and 1 floating)	No	470 MHz-694 MHz	±1.0V	0.18µm CMOS
[37]	3 MOCCCII	Yes	Yes	Yes	Yes	420 kHz-660 kHz	±2.5V	0.35µm CMOS
[38]	1 CCCII+, 1 CCCII-	Yes	Yes	Yes	No	-	±1.25V	0.35µm CMOS
[39]	3 CCCII+, 1 CCCII-	Yes	Yes	Yes	Yes	-	±2.5V	Bipolar
Proposed	3 MOCCCII	Yes	Yes	Yes	Yes	100 kHz-1500 kHz	±2.5V	Bipolar

'-': means the relevant information is not available, CCII: Second generation current conveyor, CCCII: Second generation current controlled conveyor, CCCII (-IR): negative intrinsic resistance CCCII, MOCCCII: Multiple output second generation controlled current conveyor, OTA: operational trans-conductance amplifier.

Table 3. Comparison of operating frequency range and % THD for the fourteen synthesized oscillators

S. No.	Frequency Range (kHz)	THD (%)
1.	100 – 900	3.972 (500.05kHz)
2.	200 – 900	4.11 (500.00kHz)
3.	100 – 800	3.374 (499.95kHz)
4.	74 – 390*	5.576 (357.3kHz)
5.	400 – 600	1.713 (500.05kHz)
6.	300 – 500	2.186 (504.9kHz)
7.	300 – 800	3.843 (500.00kHz)
8.	400 – 1400	4.802 (499.85kHz)
9.	-	-
10.	200 – 500	3.119 (527.6kHz)
11.	69 – 374*	4.856 (327kHz)
12.	300 – 500	2.046 (500kHz)
13.	138 – 209*	6.82 (209.9kHz)
14.	100 – 1500	3.55 (499.95kHz)

`-': the circuit exhibited latch-up.

Thus, the CCCII-based new oscillator circuits synthesized and reported in this paper compare well with the CCCII-based oscillators previously reported in [23-40].

6. Concluding Remarks

Fourteen new electronically-controllable sinusoidal oscillator circuits have been synthesized by using the state-variable approach of [5,6,7]. All the fourteen circuits have employed only three MO-CCCIIs and two grounded capacitors. The derived oscillator circuits provide the following desirable properties *simultaneously:* (i) employment of similar types of building blocks (ii) use of only three active elements (iii) availability of independent electronic controls of the FO and CO *both* (iv) complete elimination of *external* passive resistors and (v) the use of both grounded capacitor, as preferred for IC implementation. The workability of the proposed circuits has been verified by PSPICE simulations and some sample simulation results were presented. This paper has, thus, added 14 new oscillator structures to the existing repertoire of three CCCII-based electronically-controllable oscillators of [24,25,27,37].

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