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Canonic OTA-C Sinusoidal Oscillators: Generation of New Grounded-Capacitor Versions

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Abstract OTA-C Sinusoidal oscillators are useful for implementation in both bipolar and CMOS technologies due to the complete absence of passive resistors, requirements of only OTAs and integratable MOS capacitors in their design with the advantageous feature of providing electronic tunability of the oscillation frequency through external current/voltage signal. In particular, the oscillator circuit topologies which employ a minimum number of OTAs (no more than three) along with a minimum number of capacitors (no more than two), along with both capacitors being grounded, are particularly attractive from the view point of IC implementation. This article shows how, starting from various known three-OTA-C oscillators, even if this may not be employing both grounded capacitors, new three-OTA-grounded-capacitor (TOGC) versions can be derived systematically using a theoretical framework based upon nullors. The workability of the new TOGC oscillator configurations has been confirmed by SPICE simulations based upon CMOS OTAs using 0.18 μm CMOS technology process parameters and some sample results have been presented.

Keywords: *sinusoidal oscillators, operational transconductance amplifiers, nullors, analog integrated circuits*

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1. Introduction

After the advent of the operational transconductance amplifier (OTA) as a versatile electronically-controllable analog circuit building block [1,2], sinusoidal oscillators realized with the circuits containing OTAs and capacitors (OTA-C) have been widely investigated during the last three decades because of their potential suitability for integrated circuit (IC) implementation. This feature stems from the complete elimination of passive resistors in the internal circuit architecture of OTAs (since both bipolar and CMOS OTAs can be realized exclusively using transistors only) and requiring only OTAs and capacitors to form a circuit configuration exhibiting a second order characteristic equation suitable for oscillator realization. Another significant advantageous feature of OTA-C oscillators is the availability of the electronic control of the oscillation frequency through an external current or voltage signal.

As a consequence, a variety of OTA-based oscillator topologies using, two, three and four or more OTAs have been reported in technical literature earlier [3-70]. Out of these, the oscillator configurations, which can provide non-interacting controls of the condition of oscillation (CO) and frequency of oscillation (FO) and which employ both grounded capacitors, are particularly attractive from the view point of integrated circuit (IC) implementation [7,8,9,10], [12-19], [28,32,33,37,40,50,52,53,59,60,62,63], [68,69,60,61,71].

This article shows how, starting from known three-OTA-C oscillators [12,13,15,17,18], even if they may not be employing both grounded capacitors, *new* three-OTA-grounded-capacitor (TOGC) oscillators can be derived systematically using a theoretical framework in terms of nullors.

However, before proceeding further, it appears useful to briefly outline the previously known methodologies of generating equivalent op-amp-RC and OTA-C oscillator circuits, to put the contents of this paper in the right perspective.

In [64], it was shown that corresponding to any given single-OTA-RC sinusoidal oscillator, there are three other structurally distinct equivalent forms having the same characteristic equation (CE)] one of which employs both grounded capacitors (GC) as preferred for IC implementation [71]. Similarly, in [72] it was demonstrated, through five theorems that, each of the two dual-OTA-RC oscillators considered therein has three other equivalent forms having the same CE one of which employs both GCs.

During the past three decades, there has been a lot of interest in the literature in current-mode (CM) circuits and techniques because of their potential advantages. There have also been many methods of transforming the voltage-mode circuits to CM circuits many of which employed the notion of *adjoint networks*. However, it was somehow overlooked that the concept of deriving the current-mode structures from a voltage-mode (VM) structure goes back to 1971 when Bhattacharyya and Swamy in [73] introduced the concept of *network transposition*. It was shown that through the network transposition, a given network N could be easily converted to another network N^T whose admittance matrix is the transpose of that of N. It was demonstrated in [73] that the concept of *network transposition* facilitates the realization of a current transfer function which is identical to the voltage transfer function of a given VM network. This method was also shown to be useful to derive alternative equivalent structures of one port networks. In retrospection, it is found that for linear networks, the *transpose* is essentially the same as *adjoint*.

Recently, Swamy, Raut and Tang in [74] demonstrated that the operation of *network transposition* can also be applied to known OTA-C oscillators to derive new OTA-C oscillators. The methodology is based upon the notion that for a given linear network N, its transposed network N^T can be obtained simply by replacing the nonreciprocal elements by their respective *transposes* while leaving reciprocal elements as it is. This is demonstrated in Figure 1a. By doing this, voltage transfer function of N in the forward direction would be the same as the corresponding transfer function of N^T in the reverse direction and vice versa. Thus, a current-mode OTA-C circuit can be obtained, in a straight forward manner, by simply changing the input and output terminals of each OTA and reversing the input and output ports. Obviously, both the circuits would have the same transfer function. If the given circuit is an oscillator, the transposed circuit would also be an oscillator; both having the same CE (see Figure 1b).

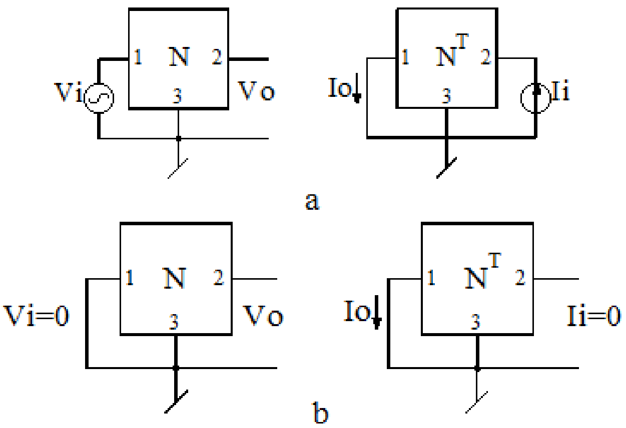


Figure 1. Application of the concept of network transposition

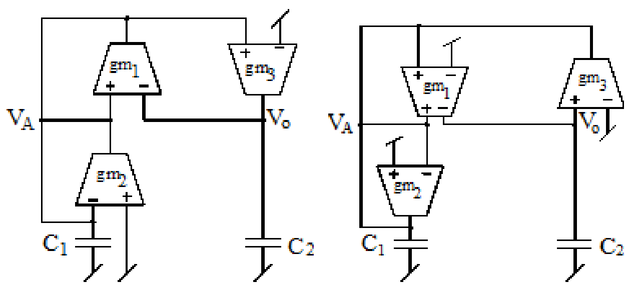


Figure 2. Derivation of the equivalent OTA-C oscillator using network transposition

Using this methodology, Swamy-Raut-Tang in [74] derived a number of *transposed* OTA-C oscillators corresponding to the OTA-C oscillators known earlier in [15] and other works. An exemplary derived oscillator, corresponding to a known OTA-C oscillator from [15], is shown in Figure 2.

Some time back, it was shown in [75,76] that every oscillator N realized with *m*-nullors along with an arbitrary number of resistors and capacitors (and/or inductors), has an equivalent companion oscillator N^* which is distinctly different than N but employs exactly the same number of active and passive components and has the same characteristic equation (CE) and hence, the same CO and FO.

The following theorems were presented in [75,76]:

Theorem 1: *Suppose there is a sinusoidal oscillator circuit N which employs m-nullators, m-norators and an arbitrary number of RC elements. If N is transformed into* N^* *by interchanging all nullators by all norators and vice-versa, then* N^* *will have the same CE as that of N.*

Theorem 2: *Corresponding to any RC-nullor oscillator having n nodes (excluding the ground node which is taken "external" to the circuit) and consisting of m nullors along with an arbitrary number of passive resistor and capacitors, there are 2n grounded nullor-RC equivalent oscillator circuits having the same CE since in an oscillator, because there is no external input, the ground node can be chosen arbitrarily without affecting the CE.*

In [75], the above theorems were shown to be useful artifices for generating equivalent op-amp-RC oscillators many of which were shown to possess interesting properties not present in the corresponding *parent* oscillator circuits.

Although not demonstrated therein, it was envisaged in [75] that the theory could also be applied to oscillators using any other active building blocks which can be modelled by nullors. In view of this, since an OTA can be represented by a pair of nullors and a single resistor R = $1/g_m$ (see Figure 3), the theory was shown [78] to be applicable to OTA-RC oscillators of [51,56,64,72] as well.

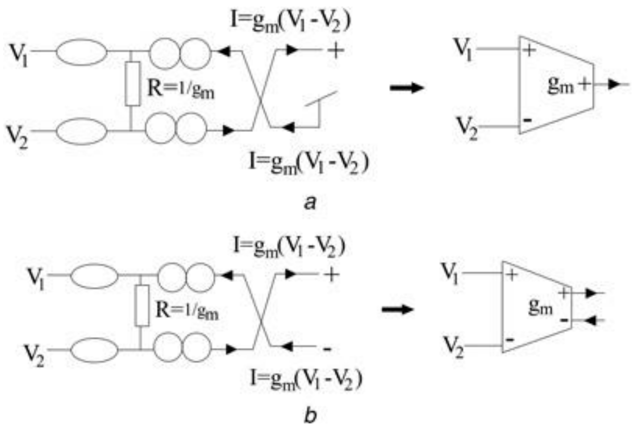


Figure 3. Nullor representations of OTAs (a) Differential-input single-output (b) Differential-input dual- output

By doing so, a much larger number of equivalent OTA-RC oscillators having the same CE were derived in [78] than possible with the theories presented in quoted works [64,72,73]. The methodology presented in [78], thus, lead to several other important consequences thereby considerably extending the utility of the generated additional OTA-RC oscillator equivalents.

It may however be noted that OTA-RC oscillators have the drawback of requiring resistors. In principle, all the resistors encountered can be replaced by OTAs thereby leading to entirely OTA-C oscillators however, such circuit will not be considered as efficient because of the employment of an excessive number of OTAs. By contrast, it has been amply demonstrated by a number of researchers that three OTAs and two capacitors are the minimum number of active and passive components required to devise a linearly controllable sinusoidal oscillator with independent control of both CO and FO. In view of this, therefore, the main focus of this paper is only on such canonic *three- OTA- two capacitor oscillators*.

In the next section, we demonstrate that the application of the Theorems 1 and 2 outlined above to the class of three-OTA-C oscillators known earlier leads to a large number of equivalent oscillators many of which are found to possess properties not available in the previously known OTA-C oscillators. In particular, we show that even if the chosen three-OTA-two capacitor oscillator may not have any of the capacitors grounded, the presented theory yields equivalent grounded-capacitor versions of such oscillators, which are preferable (than the original circuits) from the view point of IC implementation.

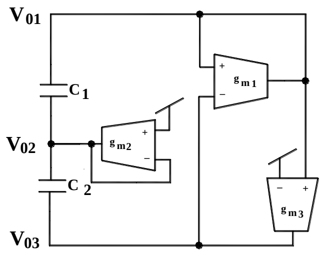
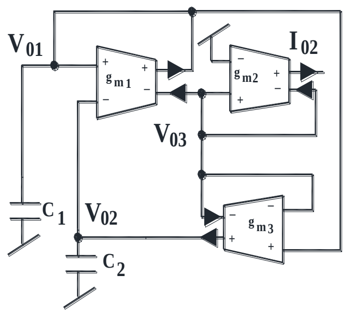
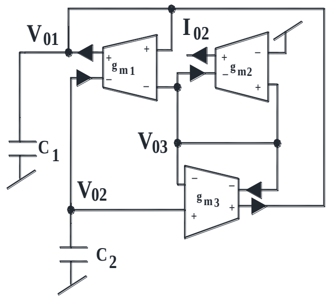
2. Derivation of Equivalents of a Class of Three-OTA-C Oscillators with particular Emphasis on Grounded Capacitor Versions

We would demonstrate the proposed methodology of generating equivalent OTA-C oscillators through an illustrative example for the sake of clarity. It must be clarified that the theory is sufficiently general but we will show its application only on the class of three-OTA-C oscillators as presented in [12,13,15,17,18].

Consider now an exemplary oscillator from [18] (oscillator number 3 of Table 1 therein) which is reproduced here in Figure 4a. Note that although this oscillator employs two capacitors but both are floating. In the following, we will show how two GC- oscillators can be derived by applying theorems 1 and 2 on the considered circuit of Figure 4a. First we make a differential-input-dual-output (DIDO) OTA-based version of this circuit which is shown here in Fig. 4b. Now we make a nullor model of this circuit using the nullor model shown in Figure 3b which is shown in Fig.4c. Now if we apply Theorem 1 on this circuit, we obtain the nullor model of Figure 4d. From this nullor model, we can construct an alternative DIDO based oscillator which would be as shown in Figure 4e. It is not difficult to verify that this alternative circuit too is characterized by the same CE as that of the circuit of Fig. 4a and Fig. 4b. Furthermore, it is interesting to observe that by applying the notion of *network transposition* also the transposed version of the oscillator of Figure 4b would turn out to be exactly the same as the circuit of Figure 4e due to the reason that the *transposed* element of a DIDO is the DIDO itself, with its input and output ports interchanged. In that sense, the generation of equivalent of the chosen oscillator of Figure 4a as that of Figure 4e as obtained by applying Theorem 1 is exactly same as would be obtained from the application of the method of *network transposition* on the oscillator of Fig. 4b and the two methods would, thus, appear to be similar so far. However, the apparent similarity stops here.

Now, we invoke Theorem 2 and apply it on the DIDO OTA-based oscillator of Fig. 4b as well that of Fig.4e. In the first case, since the ground node can be selected in four different ways without altering the CE, this results in four new three-OTA-two-capacitor oscillators shown in Fig.4f-i, whereas applying Theorem2 on the oscillator of Fig.4e also results in four additional new three-OTA-two-capacitor oscillators (Figure 4 j-m). It is, thus, seen that among the eight generated equivalent (all having the same CE as the parent circuit of Figure 4a), the presented theory generates two new three-OTA-two-GC oscillators as in Figure 4h and Figure 4l.

Table 1. Generation of new canonic OTA-C grounded-capacitor oscillators

S. No.	Original circuit and its reference	Grounded Capacitors oscillator obtained by making a DIDO version of the parent circuit and then applying Theorem-2 and choosing an appropriate node as ground	Grounded Capacitors oscillator obtained by making a DIDO version of the parent circuit and then applying Theorem-1 and subsequently Theorem-2 and choosing an appropriate node as ground
1	 a Circuit 3 of Table- I of [18] $C_1 = C_2 = C$ $2g_{m3} - g_{m2} = 0$ $f_o = \frac{1}{2\pi C}\sqrt{g_{m1} g_{m2}}$	 b	 c

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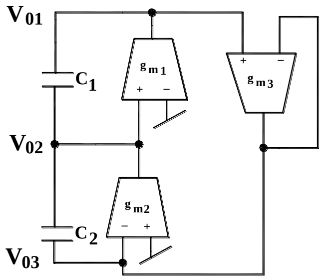
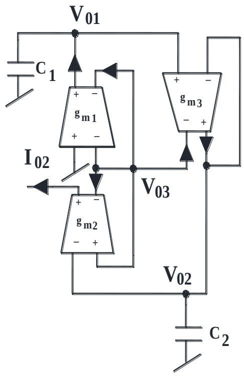
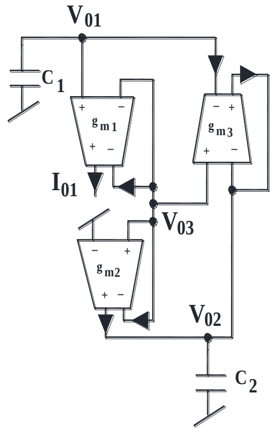
<td>

a
Circuit 4 of Table- I of [18]
$C_1 = C_2 = C$
$g_{m2} - 2g_{m1} = 0$
$f_o = \frac{1}{2\pi C}\sqrt{g_{m3}g_{m2}}$</td>
<td>

b
$\frac{V_{01}(s)}{V_{03}(s)} = -\frac{g_{m1}}{sC_1}$</td>
<td>

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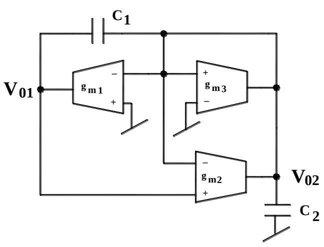
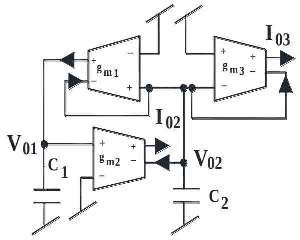
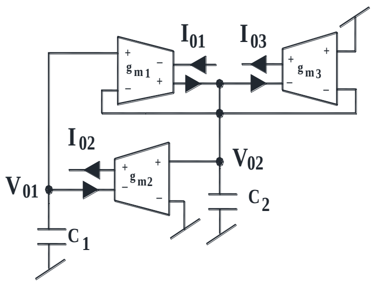
<td>

a
Circuit 1 of Table- III of [18]
$C_1 = C_2 = C$
$g_{m1} - g_{m3} = 0$
$f_o = \frac{1}{2\pi C}\sqrt{g_{m1}g_{m2}}$</td>
<td>

b
$\frac{V_{01}(s)}{V_{02}(s)} = \frac{g_{m1}}{sC_1}$
$\frac{I_{02}(s)}{I_{03}(s)} = -\frac{g_{m1}g_{m2}}{g_{m3}sC_1}$</td>
<td>

C*
$\frac{V_{01}(s)}{V_{02}(s)} = -\frac{g_{m2}}{sC_1}$</td>
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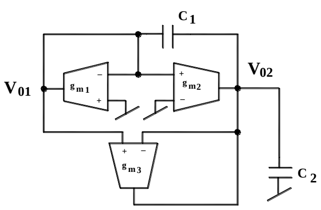
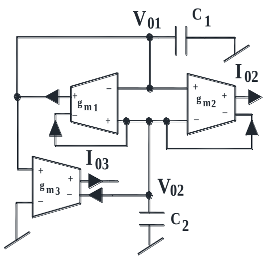
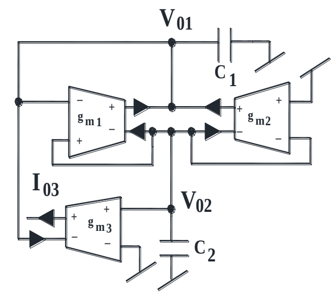
<td>

a
Circuit 4 of Table-III of [18]
$C_1 = C_2 = C$
$2g_{m1} - g_{m2} = 0$
$f_o = \frac{1}{2\pi C}\sqrt{g_{m1}g_{m3}}$</td>
<td>

b
$\frac{I_{03}(s)}{I_{02}(s)} = -\frac{g_{m1}g_{m3}}{g_{m2}sC_1}$</td>
<td>

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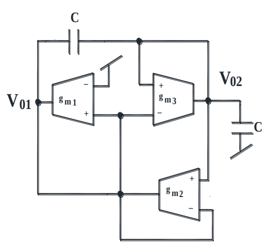
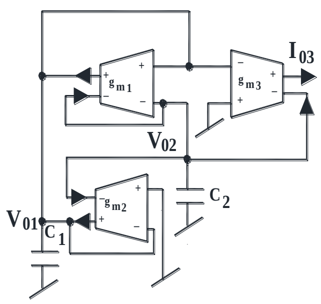
<td>

a
Circuit 5 of Table-III of [18]
$C_1 = C_2 = C$
$-2g_{m1} + g_{m2} = 0$
$f_o = \frac{1}{2\pi C}\sqrt{g_{m1}g_{m3}}$</td>
<td>

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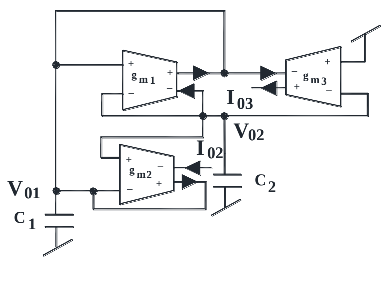
<td>

c
$\frac{I_{03}(s)}{I_{02}(s)} = \frac{g_{m1}g_{m3}}{g_{m2}sC_2}$</td>
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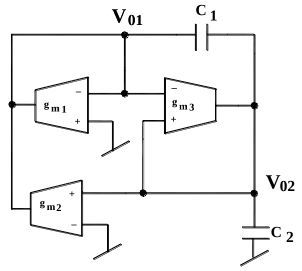
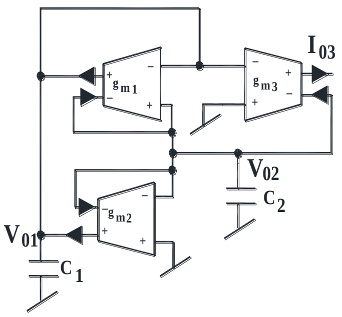
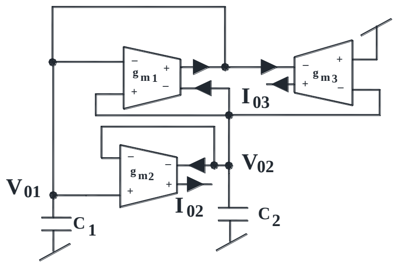
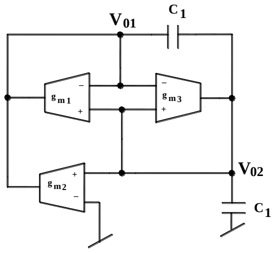
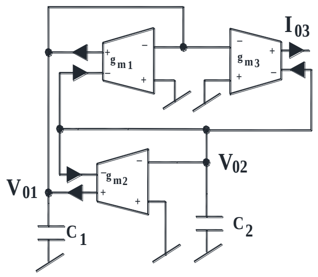
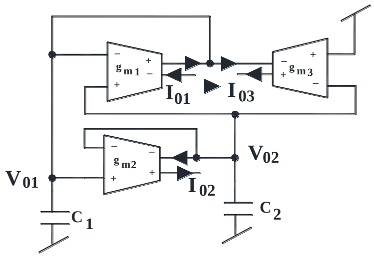
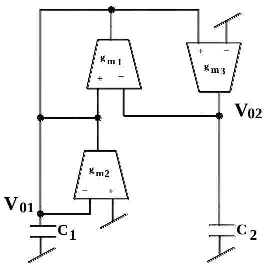
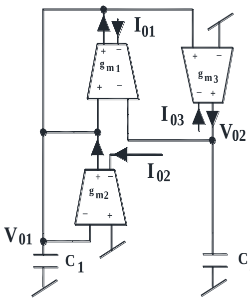
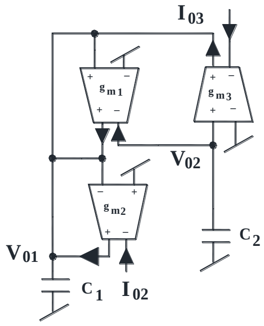
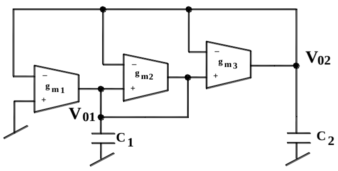
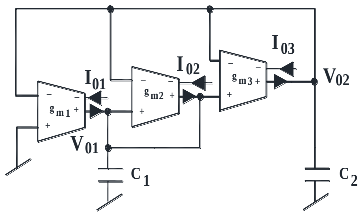
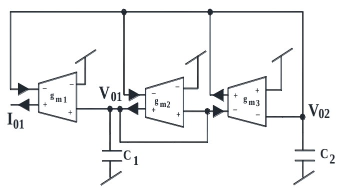
6	 a Circuit 6 of Table-III of [18] $C_1 = C_2 = C$ $2g_{m1} - g_{m2} = 0$ $f_o = \frac{1}{2\pi C}\sqrt{g_{m1}g_{m3}}$	 b	 c
7	 a Circuit 7 of Table-III of [18] $C_1 = C_2 = C$ $g_{m1} - g_{m2} = 0$ $f_o = \frac{1}{2\pi C}\sqrt{g_{m2}g_{m3}}$	 b	 c $\frac{I_{03}(s)}{I_{02}(s)} = \frac{g_{m3}}{sC_2}$ $\frac{I_{03}(s)}{I_{01}(s)} = -\frac{g_{m2}g_{m3}}{g_{m1}sC_2}$
8	 a Circuit 1 of Table-IV of [18] $C_1 = C_2 = C$ $g_{m2} - g_{m1} = 0$ $f_o = \frac{1}{2\pi C}\sqrt{g_{m1}g_{m3}}$	 b $\frac{V_{02}(s)}{V_{01}(s)} = \frac{g_{m3}}{sC_2}$	 c $\frac{V_{02}(s)}{V_{01}(s)} = -\frac{g_{m1}}{sC_2}$ $\frac{I_{03}(s)}{I_{02}(s)} = \frac{g_{m1}g_{m3}}{g_{m2}sC_2}$
9	 a Circuit 2 of Table-IV of [18] $C_1 = C_2 = C$ $g_{m3} - g_{m2} = 0$ $f_o = \frac{1}{2\pi C}\sqrt{g_{m1}g_{m3}}$	 b $\frac{I_{01}(s)}{I_{03}(s)} = -\frac{g_{m1}}{sC_2}$ $\frac{I_{01}(s)}{I_{02}(s)} = -\frac{g_{m1}g_{m3}}{g_{m2}sC_2}$	 c

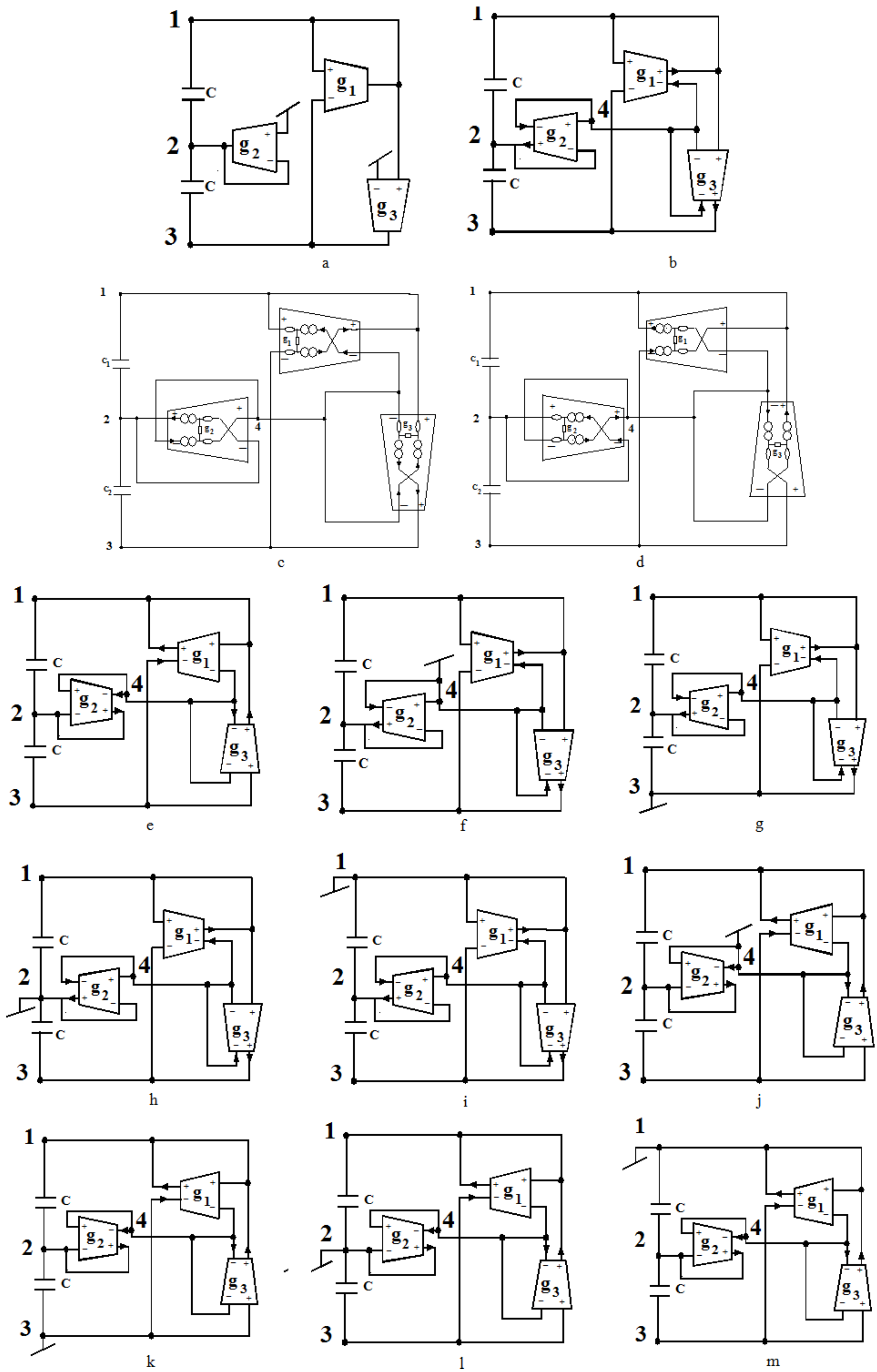


Figure 4. Derivation of new equivalent OTA-C oscillators from a known oscillator using Theorem-1 and Theorem-2

Applying the same method (as explained above) eight new OTA oscillators are derivable corresponding to every three-OTA-C oscillator known earlier in [18]. However, GC–based equivalent structures will evolve from only those circuits in which the two capacitors share a common node. Since the major intention of this paper was to present only new canonic three-OTA-GC oscillators, we omit the further details of the derivation of this large number of equivalent circuits and to conserve space, we present here only the resulting *both-GC* oscillators which are shown in Table 1 which also shows their CO and FO. In doing so also, for brevity (The complete catalogue of such circuits is described elsewhere [79]) we have included here only those circuits the CO and FO of which are distinctly and independently controllable through two separate transconductances.

3. Discussion

We now show that, apart from generating new three OTA-two GC oscillators, the various steps of the methodology of transformations presented here offers a number of interesting results.

(i) First of all, it may be seen that even the first step of formulating a DIDO-based oscillator from the considered DISO-type of parent oscillator offers a number of significant advantages. By looking at the circuit of Figure 4, it may be seen that if the grounded current output terminals in oscillators (f, g, h, i, j, k, l, m) of Figure 4 are ungrounded it immediately becomes possible in these oscillators to provide *explicit current outputs*. Such CM oscillators would be of interest due to potential applications as test signal generation for a wide variety of CM signal processing circuits which have come up during the past three decades such as CM filters, CM precision rectifiers, CM square rooters and squarers etc.

(ii) As the analysis of the new generated structures shows, there are a number of circuits which offer quadrature current outputs such as those (circuit 2-4, circuit 6-8) of Table 1, there are a number of them which offer quadrature VM outputs and finally there are two (circuit 2 and circuit 7 of Table 1) more interesting circuits which offer quadrature VM outputs as well as quadrature CM outputs. Since quadrature oscillators find numerous applications in instrumentation and communication systems, the quoted oscillators appear to be excellent candidates for such applications.

(iii) It must be pointed out that out of the numerous equivalent OTA-C grounded-capacitor oscillators generated through the use of methodology presented here, only the circuits 7and 8 of Table-1 are somewhat similar to the circuits of Figure 5(b) and Figure 6(b) of [74] and circuit 4 of [33], the remaining 15 circuits are completely new.

(iv) If instead of DIDO-OTAs, multiple output OTAs are employed then all the circuits of Figure 4 as well as of Table 1 can be equipped with three explicit current outputs thereby increasing the possibility of finding additional CM quadrature oscillators (see [33]).

4. SPICE Simulation Results

The workability of all the circuits shown in Figure 4 and Table 1 has been verified through SPICE simulations and they have been found to work satisfactorily within admissible errors between the theoretical and simulated oscillation frequencies. Such errors/deviations are different for different circuits because of the effect of parasitic capacitances of the OTAs on the CE which obviously is not same in all the cases.

In the simulations, a DIDO-OTA structure was employed which has been reproduced here in Figure 5. The aspect ratios for various MOSFETs were chosen as shown in Table 2 whereas 0.18 µm CMOS technology parameters obtained from TSMC were used.

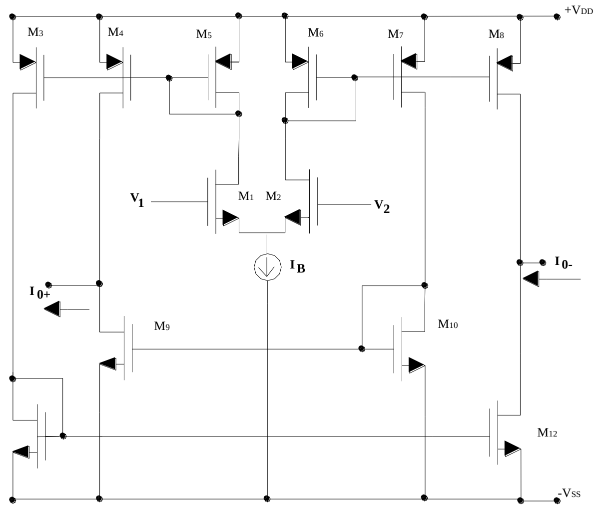


Figure 5. An exemplary DIDO CMOS OTA structure [33]

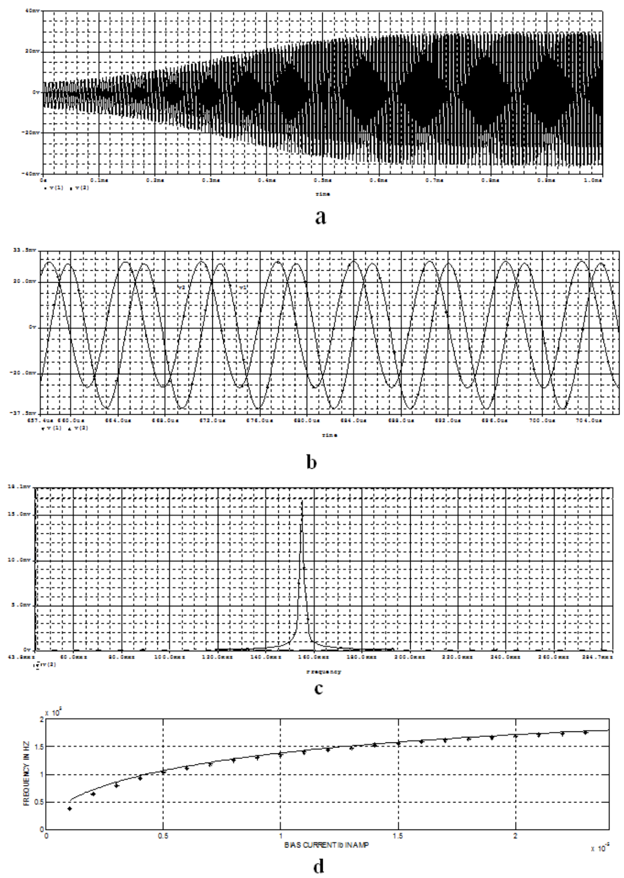


Figure 6. Results of SPICE simulation of the oscillator 3c of Table-1 (a) Transient response (b) Steady state response of two voltage outputs (c) Frequency spectrum (d) The variation of oscillation frequency with the external bias current of OTA2

Table 2. Aspect ratios of MOSFETs used in the DIDO CMOS OTA structure

MOSFETS	W, μM	L, μM
M1, M2	5.76	0.72
M3, M4, M5, M6, M7, M8	2.16	0.72
M9, M10, M11, M12	1.44	0.72

To conserve space, instead of giving results of all the generated equivalent circuits, we present here some representative results of oscillators of circuit 3, circuit 4 and circuit 5 of Table 1 only. Figure 6 shows the transient response, steady state waveforms of two quadrature outputs, the frequency spectrum and the variation of oscillation frequency with external DC bias current of OTA2 for the oscillator circuit of Figure 3c. With both capacitors taken as 100pF, the circuit generated oscillation frequencies from 38 kHz to 179 kHz. The SPICE-measured phase angle between the two output voltages at a frequency of 154 kHz was found to be 88.91^0, as against the ideal value of 90^0.

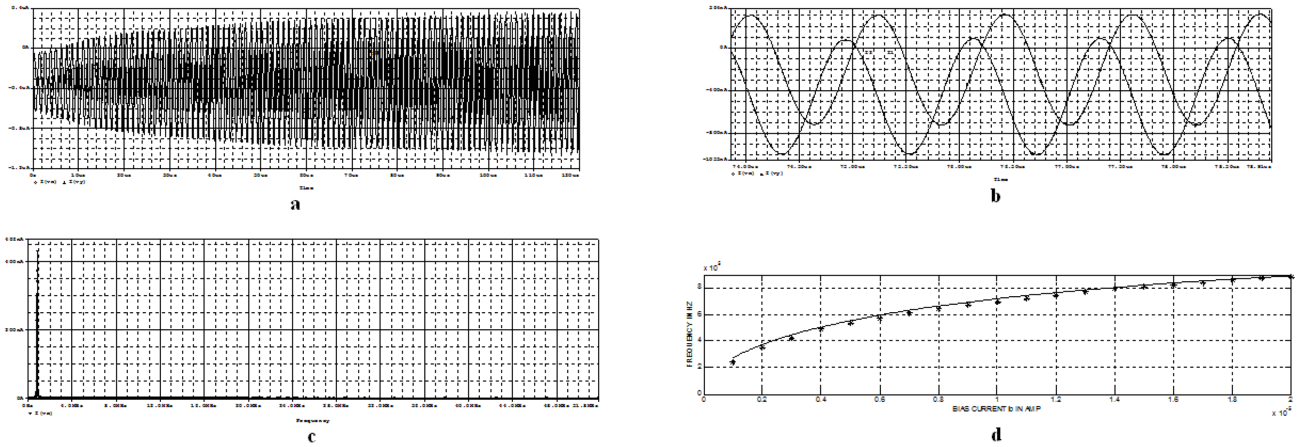


Figure 7. Results of SPICE simulation of the oscillator 4b of Table-1 (a) Transient response (b) Steady state response of two voltage outputs (c) Frequency spectrum (d) The variation of oscillation frequency with the external bias current of OTA3

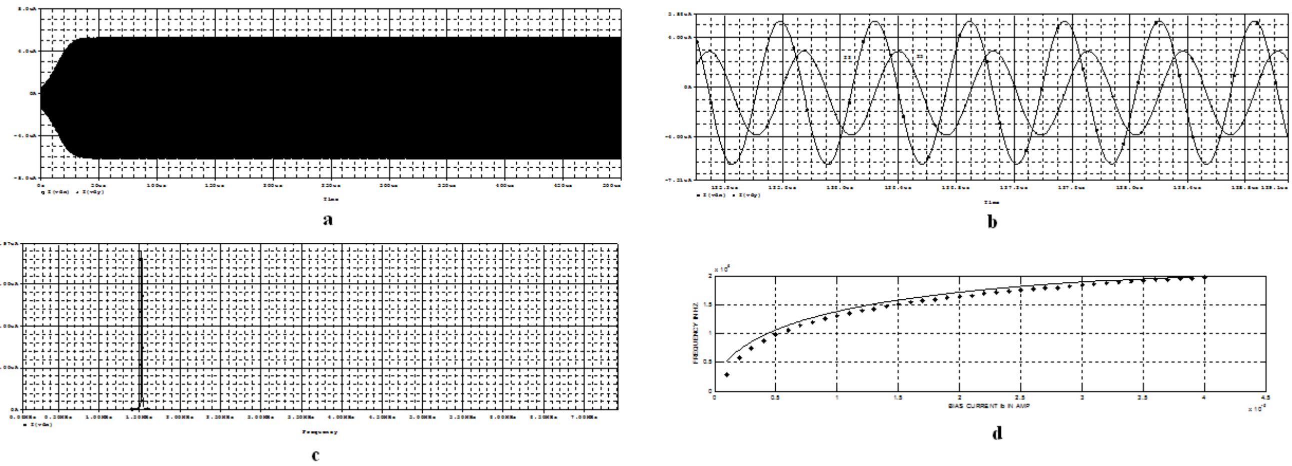


Figure 8. Results of SPICE simulation of the oscillator 5c of Table 1 (a) Transient response (b) Steady state response of two voltage outputs (c) Frequency spectrum (d) The variation of oscillation frequency with the external bias current of OTA3

Similar results for the oscillators of circuit 4b and circuit 5c of Table 1 have been shown in Figure 7 and Figure 8 respectively. The circuit 4b and circuit 5c of Table 1 had the two capacitors of 10 pF each and generated oscillation frequencies in the ranges of 289 kHz to 941 kHz and 346 kHz to 1752 kHz respectively when the external DC bias current of OTA 3 were varied from 1 μA to 25 μA in both the cases. The phase angles between the current output waveforms for these two circuits were found to be 88.23^{0}and 88.61^0 at the oscillation frequencies of 810 kHz and 1.520 MHz respectively.

The SPICE simulation results have, thus, established the practical viability of the generated new three-OTA-two-GC circuits of Table 1.

5. Concluding Remarks

It was demonstrated how starting from canonic three-OTA-two capacitor oscillators which do not have both grounded capacitors, a number of equivalent circuits having the same CE can be derived systematically out of which two new three OTA-C oscillators having both GCs also emerge. Thus, starting from nine previously known three-OTA-C oscillators from [18] none of which have both GCs, *eighteen new* TOGC oscillators were derived. The derived GC circuits are attractive from the view point of IC implementation as compared to the original circuits which did not have both GCs. Out of the eighteen generated equivalent circuits, only three have been known earlier; all the remaining *fifteen* TOGC oscillator circuits are completely new. The workability of all the new TOGC oscillator configurations has been confirmed by SPICE simulations based upon CMOS OTAs using 0.18 μm CMOS technology process parameters and some sample results have been presented which establish the viability of the new derived structures.

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