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GENERATION OF THE MINIMUM COMPONENT OSCILLATORS FROM SALLEN KEY FILTERS*

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Two new minimum passive component oscillators using inverting current conveyor (ICCII−) acting as a voltage negative impedance converter are generated from the Sallen Key low-pass and high-pass filters. It is also shown that the Sallen Key low-pass, high-pass, and band-pass filters are the origin of the three minimum component oscillators using the current conveyor acting as a current negative impedance converter. In addition, it is also shown that the Sallen Key high-pass and band-pass filters are the origin of the two minimum component oscillators using single input single output transconductance amplifier as the active element. Although this paper is considered partially a review paper it includes new generation methods and new minimum component oscillator circuit realizations. Simulation results for the new oscillators using ICCII− are included.

Keywords: Minimum component oscillators; Op Amp; CCII; ICCII; VNIC; CNIC.

1. Introduction

Several oscillators are available in the literature using the operational amplifier (Op Amp), current conveyor (CCII), inverting current conveyor (ICCII), current feedback operational amplifier (CFOA), and the transconductance amplifier (TA) as the basic building block. Most recently there has been interest in finding the source circuit employing the Op Amp that can be transformed to generate the newly reported oscillators using other active elements.[1,2] It is proved in this paper that the Sallen Key low-pass, high-pass, and band-pass filters[3–9] are very powerful circuits and are the origin of many oscillators that are available in the literature[10] as well as to new oscillators.

Although minimum passive component oscillators using two resistors and two capacitors cannot be realized using a single Op Amp, they can be realized using a single CFOA[11] or a single ICCII−[12] or a single CCII+[13–15] or a single input single output TA also known as the voltage controlled current source (VCCS).[10]

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It is shown in this paper that the Sallen Key low-pass, high-pass, and band-pass filters are the origin of the three minimum component oscillators using the CCII+ acting as a current negative impedence converter (CNIC). It is also shown that the Sallen Key low-pass, high-pass, and band-pass filters are the origin of three minimum component oscillators using the ICCII− acting as a VNIC. Two of the three generated circuits using ICCII− are new. In addition it is also shown that the Sallen Key high-pass and band-pass filters are the origin of the two minimum component oscillators using the single input single output TA reported in Ref. 10.

2. Sallen Key Filters

The second-order Sallen Key low-pass, high-pass, and band-pass filter circuits employing a single noninverting amplifier also known as voltage controlled voltage source (VCVS) of gain K are shown in Fig. 1.[3] Electronics textbooks that have included this family of the Sallen Key filters are many and only few of them are referenced here as in Refs. 4–9. The VCVS of gain K larger than one is realized using an Op Amp and two resistors.

The transfer functions of the three filter circuits shown in Fig. 1 are given by

$$T_{\mathrm{LP}}(\mathrm{s}) = \frac{\dfrac{K}{R_1 R_2 C_1 C_2}}{s^2 + s\left[\dfrac{1}{R_1 C_1} + \dfrac{1}{R_2 C_1} + \dfrac{1-K}{R_2 C_2}\right] + \dfrac{1}{R_1 R_2 C_1 C_2}}, \tag{1}$$

$$T_{\mathrm{HP}}(\mathrm{s}) = \frac{s^2 K}{s^2 + s\left[\dfrac{1}{R_2 C_2} + \dfrac{1}{R_2 C_1} + \dfrac{1-K}{R_1 C_1}\right] + \dfrac{1}{R_1 R_2 C_1 C_2}}, \tag{2}$$

$$T_{\mathrm{BP}}(\mathrm{s}) = \frac{\dfrac{sK}{R_3 C_1}}{s^2 + s\left[\dfrac{1}{R_1 C_1} + \dfrac{1}{R_2 C_2} + \dfrac{1}{R_3 C_1} + \dfrac{1}{R_3 C_2} + \dfrac{1-K}{R_2 C_1}\right] + \dfrac{1}{R_1 R_2 C_1 C_2}\left[1 + \dfrac{R_2}{R_3}\right]}. \tag{3}$$

These three circuits, although introduced long time ago,[3] have remain as very powerful source circuits as will be demonstrated next.

3. KRC Oscillators

The first generation method of minimum passive component active RC oscillators namely two resistors and two capacitors and using a single controlled source was introduced in Ref. 10. It is proved in Ref. 10 that there are a total of 16 oscillators using two resistors, two capacitors, and a single controlled source. The generation method is based on taking all possible second-order two resistor and two capacitor

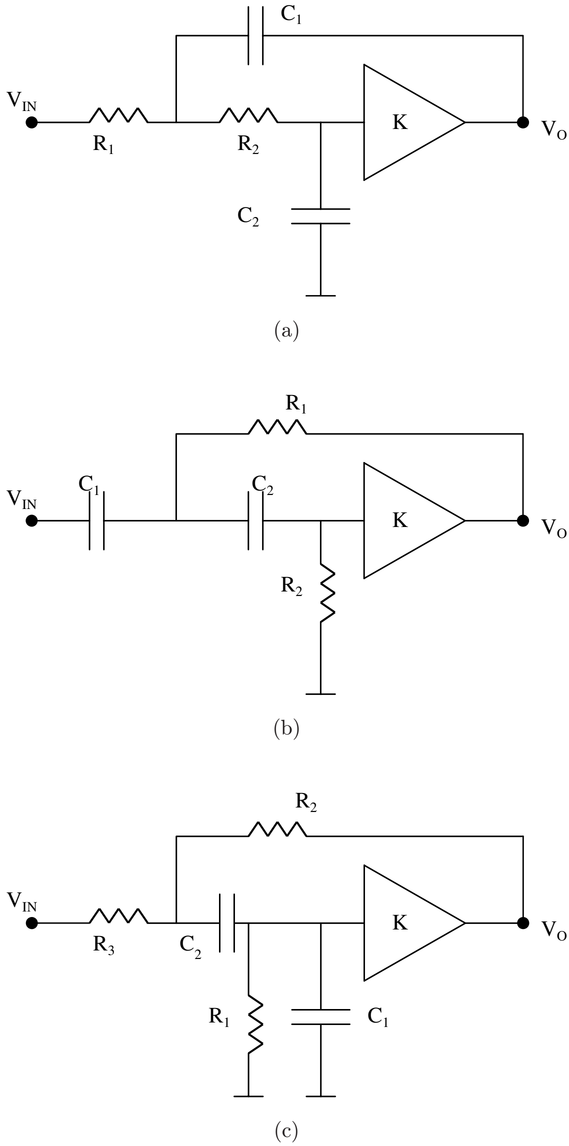


Fig. 1. (a) Sallen Key low-pass filter. (b) Sallen Key high-pass filter. (c) Sallen Key band-pass filter.

circuits in a closed loop with the controlled source and derive the practical oscillator circuits using the Op Amp as the active element. It is found that among the 16 canonic oscillator circuits given in Ref. 10, there are only three oscillator circuits using the VCVS of gain K as shown in Fig. 2.

It is interesting to report here that these three oscillators can also be generated from the Sallen Key filters by setting $V_{\rm IN}$ equal to zero that is ground the input node

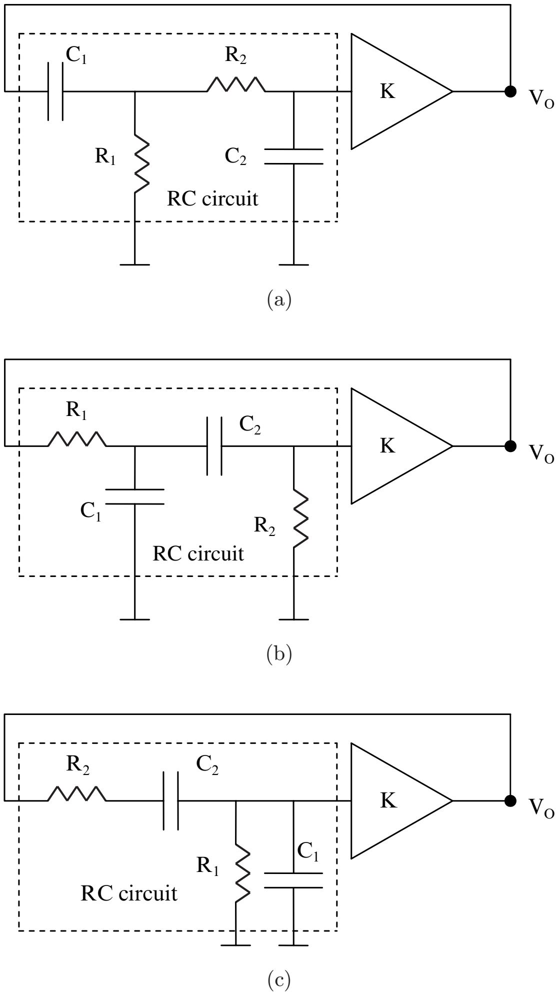


Fig. 2. Three well-known oscillators using VCVS of gain K.[9,10]

and set R_3 equal to infinity in the circuit of Fig. 1(c) resulting in the oscillator circuits of Fig. 2.

The characteristic equations for these three oscillators are obtained from Eqs. (1)–(3) by setting the denominator equal to zero and set R_3 equal to infinity in Eq. (3) and are given by

$$s^2 + s\left[\frac{1}{R_1C_1} + \frac{1}{R_2C_1} + \frac{1-K}{R_2C_2}\right] + \frac{1}{R_1R_2C_1C_2} = 0\,, \tag{4}$$

$$s^2 + s\left[\frac{1}{R_2C_2} + \frac{1}{R_2C_1} + \frac{1-K}{R_1C_1}\right] + \frac{1}{R_1R_2C_1C_2} = 0\,, \tag{5}$$

$$s^2 + s\left[\frac{1}{R_1C_1} + \frac{1}{R_2C_2} + \frac{1-K}{R_2C_1}\right] + \frac{1}{R_1R_2C_1C_2} = 0\,. \tag{6}$$

From the above three equations the necessary condition of oscillation for each of the three circuits is given respectively as follows:

For the oscillator circuit of Fig. 2(a):

$$K = 1 + \frac{C_2}{C_1}\left[1 + \frac{R_2}{R_1}\right]. \tag{7}$$

For the oscillator circuit of Fig. 2(b):

$$K = 1 + \frac{R_1}{R_2}\left[1 + \frac{C_1}{C_2}\right]. \tag{8}$$

For the oscillator circuit of Fig. 2(c):

$$K = 1 + \frac{R_2}{R_1} + \frac{C_1}{C_2}\,. \tag{9}$$

The radian frequency of oscillation is the same for each of the three oscillator circuits and is given by

$$\omega_o = \sqrt{\frac{1}{R_1R_2C_1C_2}}\,. \tag{10}$$

It should be noted that real world oscillators are nonlinear circuits. The above analysis is based on assuming linear oscillators and is used as a starting point for oscillator design. The steady-state oscillations, however, are achieved by varying R_1 or R_2 controlling the s term in Eqs. (4)–(6).

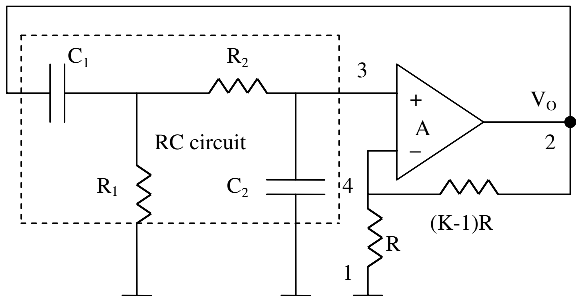
It is worth noting that in the oscillator of Fig. 2(c) by replacing the VCVS by an Op Amp and two resistors results in the well-known Wien bridge oscillator.[4–8] The effect of the finite and frequency dependent gain of the Op Amp in the Wien bridge oscillator has been studied in Ref. 16. Additionally, detailed study of the finite and frequency dependent gain of the Op Amp in the three oscillator circuits together with active compensation methods was given in Ref. 17.

4. Minimum Component NIC Oscillators

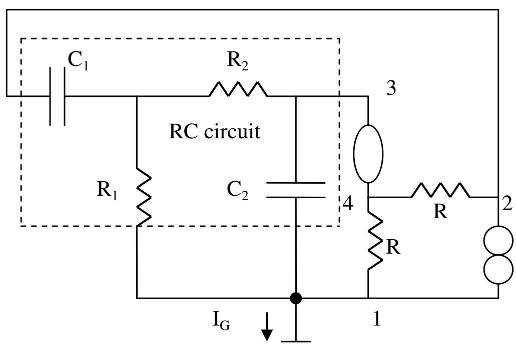
There are two types of the two resistor plus two capacitor NIC oscillators, one is the VNIC oscillator circuits and the second is the CNIC oscillators using CCII+ and already known in the literature.[14,15] The generation of the three VNIC oscillator circuits from the circuits of Fig. 2 is given in detail in the following section.

4.1. *VNIC oscillators using ICCII−*

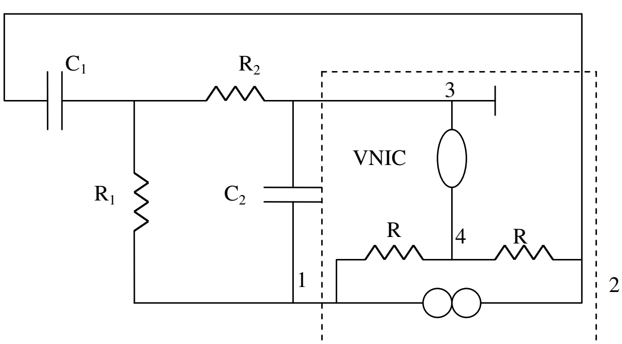
From Fig. 2(a) and realizing the VCVS of gain K by an Op Amp and two resistors results in Fig. 3(a). Replacing the Op Amp in Fig. 3(a) by its nullator norator[18]



(a)



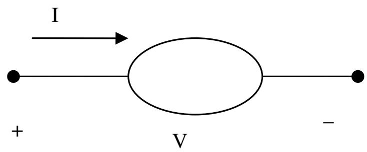
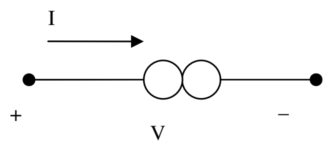
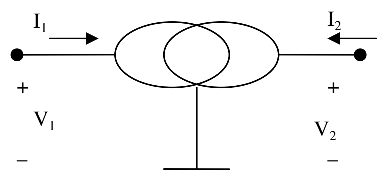
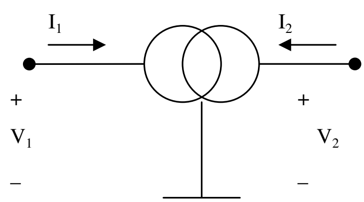
(b)



(c)

Fig. 3. (a) Oscillator of Fig. 2(a) realized using an Op Amp. (b) Pathological realization of (a) for $K = 2$. (c) Realization of (b) after interchanging ground terminal.

Table 1. Summary of the definitions and symbols of the pathological elements.

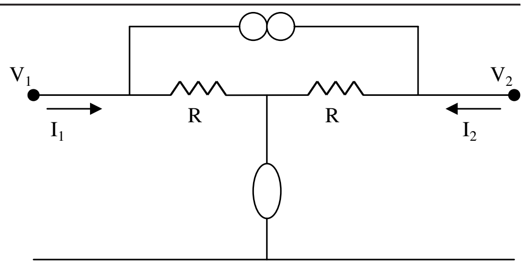
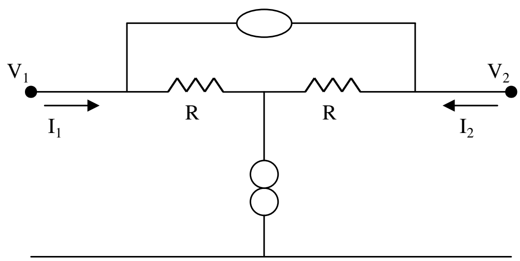
Pathological element	Definition	Symbol
Nullator[18]	$V = I = 0$	
Norator[18]	V and I are arbitrary	
Voltage mirror (VM)[19,20]	$V_1 = -V_2$ $I_1 = I_2 = 0$	
Current mirror (CM)[19,20]	V_1 and V_2 are arbitrary $I_1 = I_2$, and they are also arbitrary	

model, for convenience to the reader Table 1 is included summarizing the definition of the four pathological elements namely nullator and norator,[18] voltage mirror (VM), and current mirror (CM)[19] to be used in this paper.

Setting $K = 2$ in the circuit of Fig. 3(a) results in the oscillator circuit of Fig. 3(b) in which the grounded current I_G equal to zero. Interchanging the ground terminal from node 1 to node 3, the circuit shown in Fig. 3(c) is obtained. Examining the pathological circuit in the dotted box, it is seen that it realizes a VNIC as given in Table 2.

It is worth noting in an earlier work in Ref. 13 this pathological circuit appeared in setting the VCVS equivalent nullor circuit and it was stated that: this network

Table 2. Summary of the definitions and pathological realizations of the VNIC and CNIC.

Active element	Definition	Pathological realization
VNIC[9]	$V_2 = -V_1 \; I_2 = -I_1$	
CNIC[5,9]	$V_2 = V_1 \; I_2 = I_1$	

cannot be implemented using current conveyors.[13] It is a correct statement at the time of publication of Ref. 13, but now after the ICCII− was introduced in Ref. 20, it is the VNIC circuit realizable by ICCII− as given in Table 3.

Figure 4(a) represents the equivalent oscillator circuit to Fig. 3(c) using the ICCII− as a VNIC. From Eq. (7) and setting $K = 2$ results in the following condition of oscillation for the circuit of Fig. 4(a).

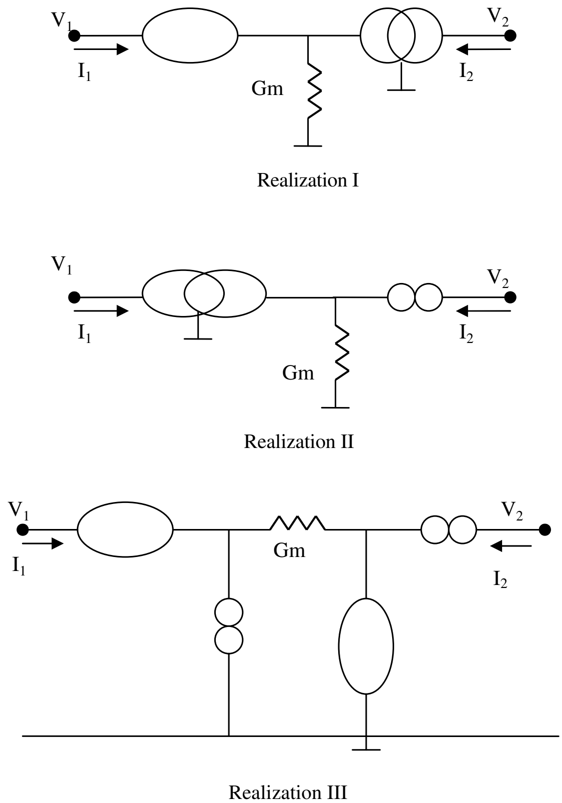
$$\frac{C_1}{C_2} = 1 + \frac{R_2}{R_1}. \tag{11}$$

Following similar steps, the circuits of Figs. 2(b) and 2(c) can be transformed to obtain the oscillator circuits of Figs. 4(b) and 4(c), respectively. The conditions of oscillation are obtained from Eqs. (8) and (9) by setting $K = 2$ resulting in the following conditions:

$$\frac{R_2}{R_1} = 1 + \frac{C_1}{C_2}, \tag{12}$$

$$1 = \frac{R_2}{R_1} + \frac{C_1}{C_2}, \tag{13}$$

Table 3. Summary of the definitions and pathological realizations of the TA.

Active element	Definition	Pathological realization
TA or VCCS	$I_1 = 0$ $I_2 = -\mathrm{Gm}V_1$ V_2 arbitrary	

The radian frequency of oscillation for each of the three circuits of Fig. 4 is the same as given by Eq. (10). It should be noted that the two circuits of Figs. 4(a) and 4(b) are new. The circuit of Fig. 4(c) was reported before in Ref. 12.

It is worth noting that the parasitic element affecting the circuit of Fig. 4(a) is R_X; on the other hand C_Z can be absorbed in C_2.

The parasitic element affecting the circuit of Fig. 4(b) is C_Z; on the other hand R_X can be absorbed in R_1.

The circuit of Fig. 4(c), however, is not affected by parasitic R_X and C_Z and can absorb the effect of R_X in R_2 and C_Z in C_1.

4.2. *CNIC oscillators using CCII+*

It can also be shown that the oscillators of Fig. 2 can be transformed to realize the minimum passive component oscillators using CCII+ acting as CNIC. Consider the

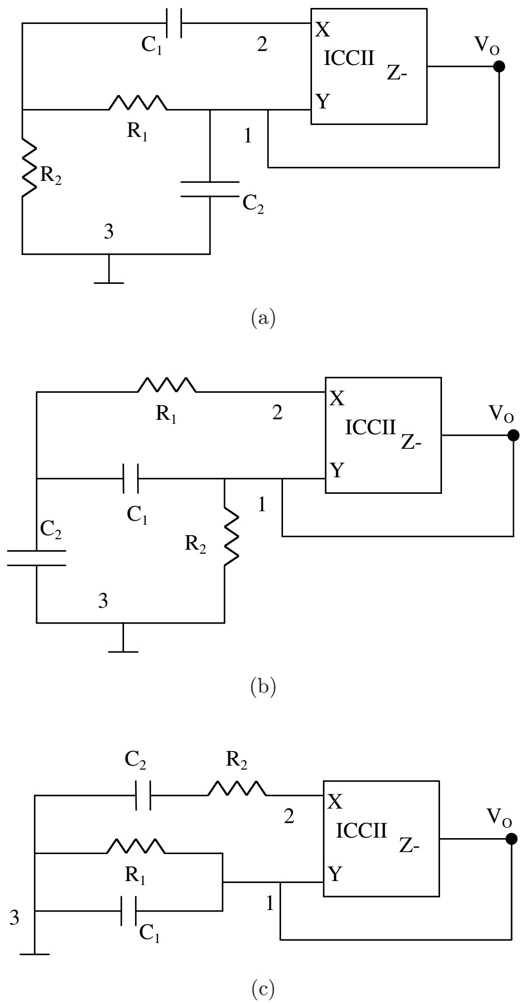


Fig. 4. Three oscillators using ICCII− as a VNIC.

circuit of Fig. 3(c) and apply the adjoint circuit theorem[21−23] to it by replacing nullator by norator and vice versa results in the circuit of Fig. 5.

Figure 6(a) represents the equivalent oscillator circuit to Fig. 5 using the CCII+ as a CNIC as given in Table 2. It should be noted that the VNIC and the CNIC are adjoint to each other.[21−23] Similarly the circuits of Figs. 2(b) and 2(c) can be transformed to obtain the oscillator circuits of Figs. 6(b) and 6(c), respectively. The conditions of oscillation for the three circuits of Fig. 6 are given by Eqs. (11)−(13), respectively, with the radian frequency of oscillation as given by Eq. (10). The parasitic element effects are the same as the adjoint circuits of Fig. 4 and the circuit of Fig. 6(c) can absorb the effects of R_X and C_Z.

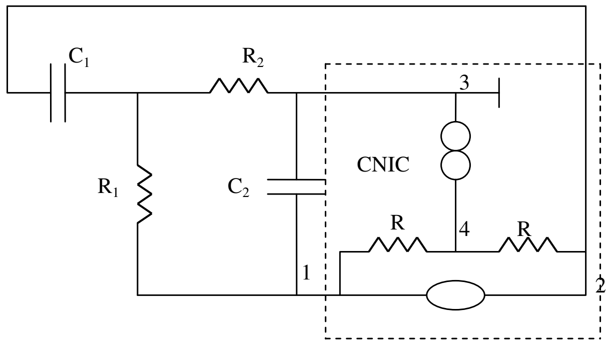


Fig. 5. Adjoint circuit to Fig. 3(c).

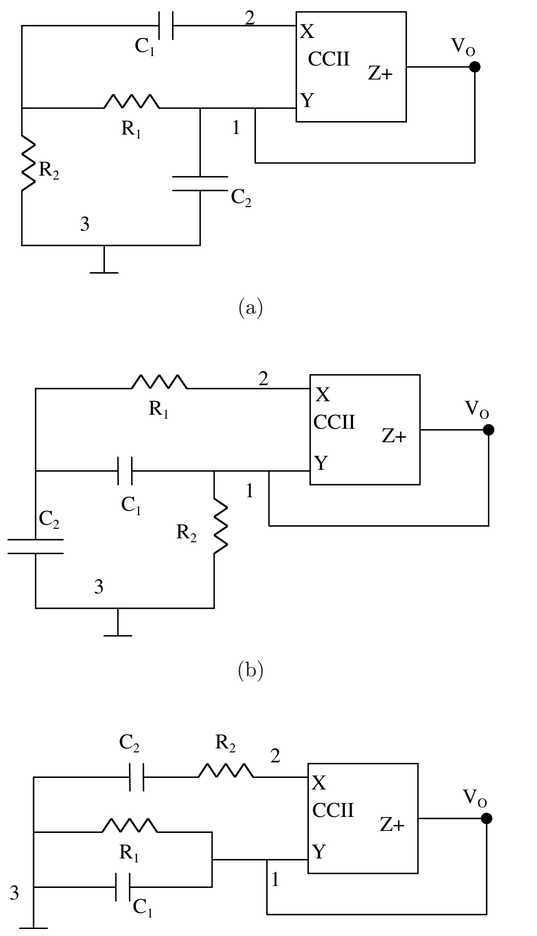


Fig. 6. Three known oscillators using CCII+ as a CNIC.[13–15]

5. TA or VCCS Oscillators

The generation method introduced in Ref. 10 resulted in two minimum component oscillators using a single VCCS and shown in Fig. 7 of Ref. 10. It is proved in this section that these two oscillators can be generated from the Sallen Key high-pass and band-pass filters, respectively.

Consider the oscillator circuit of Fig. 2(b) and take R_1 to be the output resistance of the VCVS of gain K as shown in Fig. 7(a). Realizing the VCVS by a CCII+ of gain

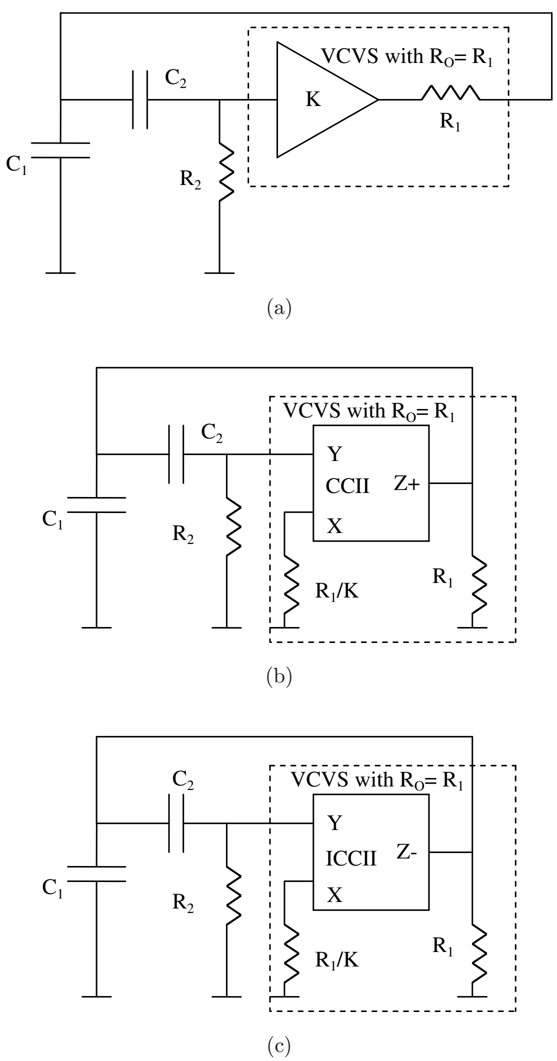
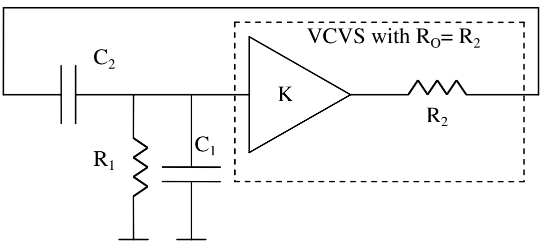


Fig. 7. (a) Oscillator circuit of Fig. 2(b); (b) Equivalent circuit to (a) using CCII+; (c) Equivalent circuit to (a) using ICCII−.

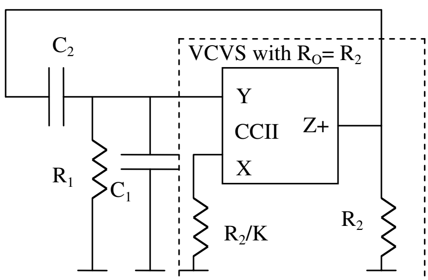
K results in the circuit shown in Fig. 7(b); similarly the VCVS can be realized by an ICCII− of gain K which results in the circuit shown in Fig. 7(c).

Similarly from the oscillator circuit of Fig. 2(c), the circuits shown in Fig. 8 can be obtained. It should be noted that the circuit of Fig. 8(b) has been reported before in Ref. 24.

From Table 4, the two equivalent circuits of Figs. 7(b) and 7(c) are realizable by a TA having Gm equal to K/R_1 resulting in the well-known circuit shown in Fig. 9(a).[10]



(a)



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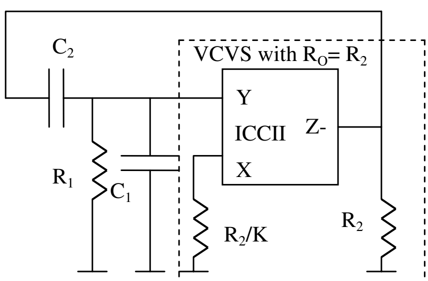
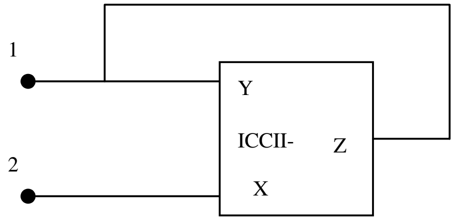


(c)

Fig. 8. (a) Oscillator circuit of Fig. 2(c); (b) Equivalent circuit to (a) using CCII+; (c) Equivalent circuit to (a) using ICCII.

Table 4. ICCII− or CCII+ realizations of VNIC, CNIC, and TA.

<table>
<tr><th>Active element</th><th>ICCII or CCII realization</th></tr>
<tr><td>VNIC</td><td>
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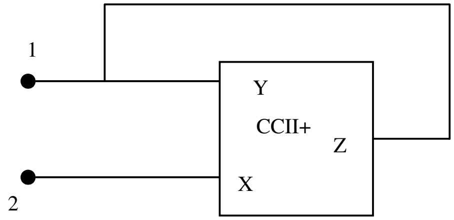
<tr><td>CNIC</td><td>
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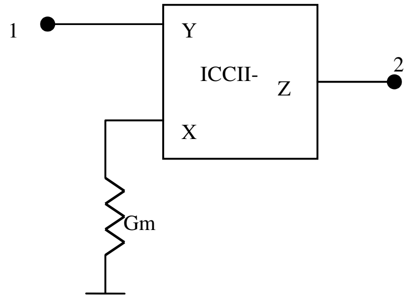
<tr><td></td><td>
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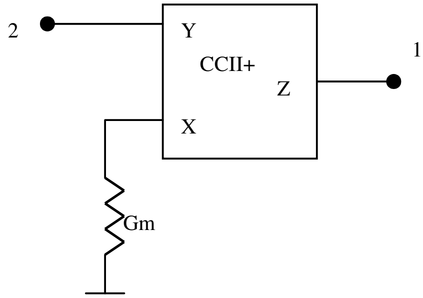
<tr><td>TA or VCCS</td><td>
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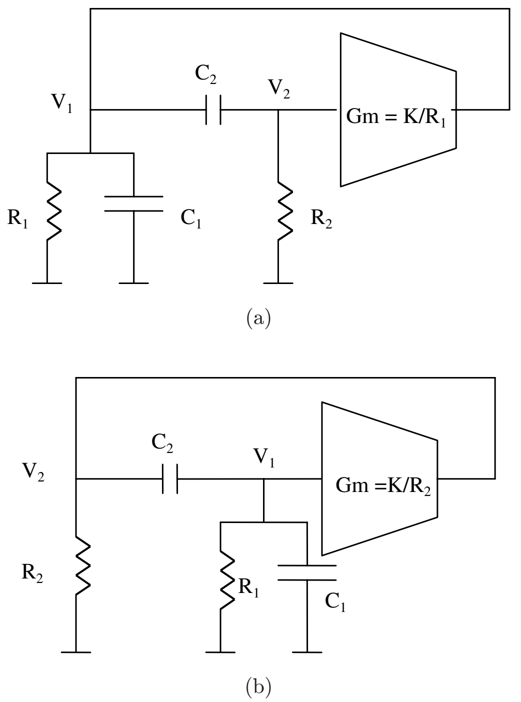


Fig. 9. Two minimum component oscillators using TA.[10]

It should be noted that realizations I and II in Table 3 uses grounded conductance and are adjoint to each other. Realizations III in Table 3 uses floating conductance and is self adjoint.

The condition of oscillation is derived from Eq. (8) by setting $K = \mathrm{Gm}\ R_1$ resulting in

$$\mathrm{Gm} = G_1 + G_2\left(1 + \frac{C_1}{C_2}\right). \tag{14}$$

The radian frequency of oscillation is given by Eq. (10).

It is seen the Gm controls the condition of oscillation without affecting the frequency of oscillation.

Similarly, the two equivalent oscillator circuits of Figs. 8(b) and 8(c) are realizable by a TA having Gm equal to K/R_2 resulting in the well-known circuit shown in Fig. 9(b). This circuit was first generated in Ref. 10 by a systematic method of using minimum passive components RC circuits with the VCCS as the active element.

The condition of oscillation is derived from Eq. (9) by setting $K = \mathrm{Gm}\ R_1$ resulting in Eq. (14). Of course since the two circuits of Fig. 9 are adjoint to each other they must have the same condition of oscillation and the same expression for the radian frequency of oscillation given by Eq. (10).

Due to the attractive features of the oscillator of Fig. 9(a),[10] it has been most recently generalized to a fully differential version and used in the generation of a new RF oscillator.[25]

6. Simulation Results

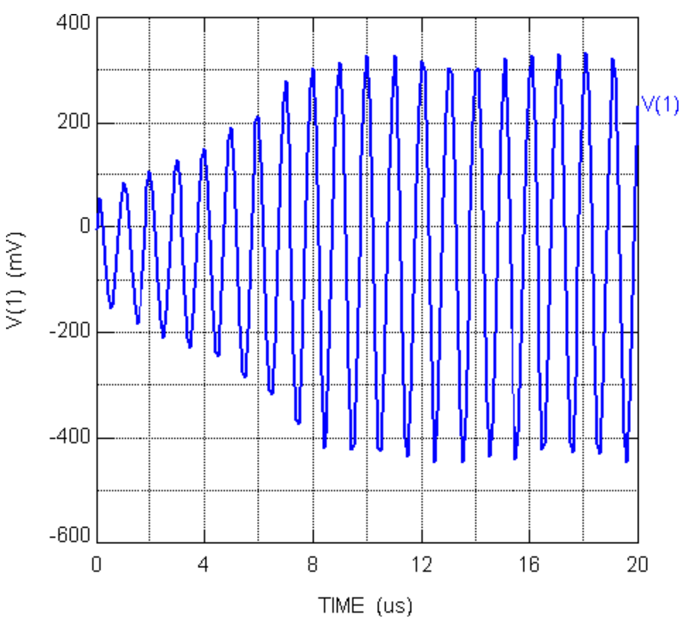
The oscillator circuit shown in Fig. 4(a) is simulated using the differential voltage current conveyor (DVCC)[26] which realizes the ICCII− as special case; the DVCCS is biased with ±1.5 V. The oscillator is designed for oscillation frequency equal to 1.126 MHz by taking $C_1 = 2C_2 = 20\,\text{pF}$, $R_1 = R_2 = 10\,\text{k}\Omega$.

Figure 10(a) represents the output voltage waveform.

Figure 10(b) represents the output voltage waveform of the oscillator circuit 2 of Fig. 4(b) using $C_1 = C_2 = 20\,\text{pF}$ and $R_2 = 2R_1 = 20\,\text{k}\Omega$ to realize an oscillation frequency equal to 563 kHz.

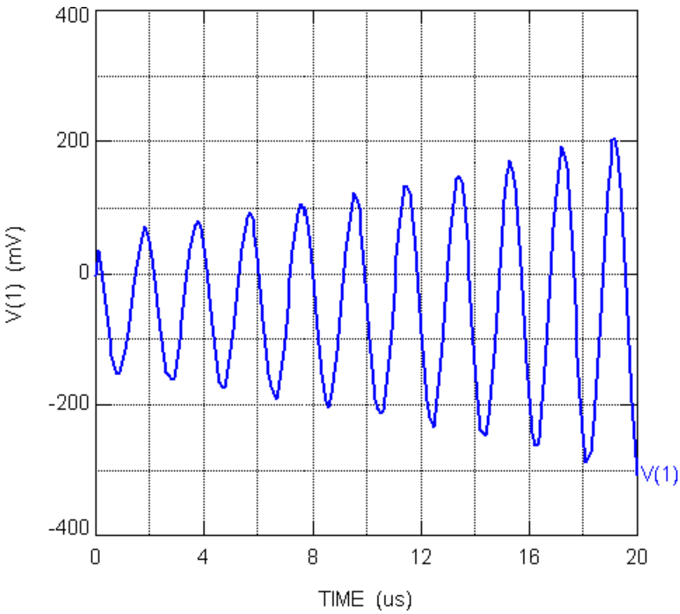
Figure 10(c) represents the output voltage waveform of the oscillator circuit 3 of Fig. 4(c) using $C_2 = 2C_1 = 20\,\text{pF}$ and $R_1 = 2R_2 = 20\,\text{k}\Omega$ to realize an oscillation frequency equal to 796 kHz.

The total power dissipation for each of circuits 1, 2 and 3 in Fig. 4 is given by 0.984 mW.



(a)

Fig. 10. (a) Simulation results for the circuit of Fig. 4(a); (b) Simulation results for the circuit of Fig. 4(b); (c) Simulation results for the circuit of Fig. 4(c).



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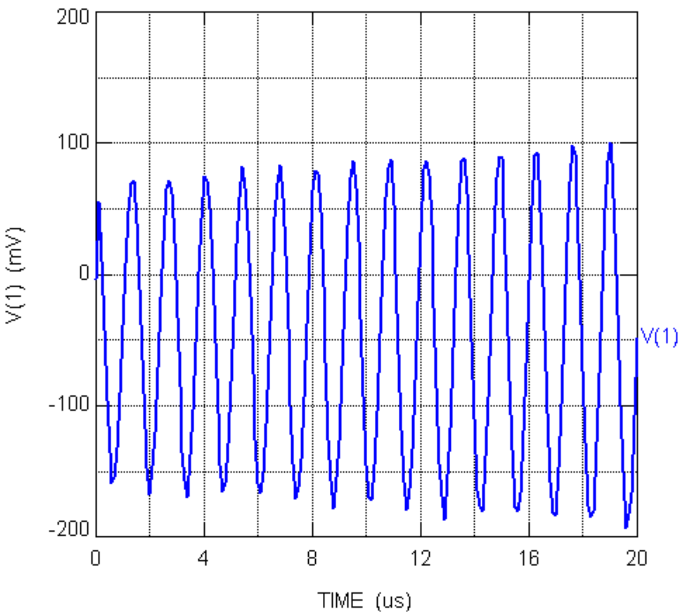

(c)

Fig. 10. (*Continued*)

7. Conclusion

It is shown that the Sallen Key low-pass, high-pass, and band-pass filters are the source circuits of the three minimum component oscillators using CCII+ acting as a CNIC. Three minimum passive component oscillators using ICCII− acting as VNIC are also generated from the Sallen Key low-pass, high-pass, and band-pass filters, two of them are new. In addition, it is also shown that the Sallen Key high-pass and band-pass filters are the origin of the two minimum component oscillators using single input single output TA as the active element. Although this paper is considered partially as a review paper it includes new generation methods and new minimum component oscillator realizations using ICCII−. The three ICCII− minimum component oscillators are the adjoint of the three well-known minimum components CCII+ oscillators.[13,14] Simulation results for the new oscillators using ICCII− are included.

The intention of this paper is not only to generate some new ICCII− minimum component oscillators but also to review many of the valuable work in Refs. 3 and 10 and to show the link between the circuits known since long time and the new CCII+ and ICCII− oscillators based on new approaches of current mode circuits.[27]

It is worth noting that the oscillators reported in Ref. 28 do not belong to the single input single output TA reported in this paper and shown in Fig. 9 and they employ a two input TA with positive feedback to realize a negative resistor in series with a buffer at the inverting TA input.

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