Catalogue of Variable Frequency and Single-Resistance-Controlled Oscillators Employing A Single Differential Difference Complementary Current Conveyor

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Abstract –A set of fourteen current-mode sinusoidal oscillators employing a single differential difference complementary current conveyor (DDCCC) is proposed. This is the largest catalogue of sinusoidal oscillators with single resistor frequency control, that use only a single active building block (ABB) and minimum number of passive components. The proposed topologies were automatically designed by a genetic algorithm rather than by a human designer. Some of the synthesized networks have very attractive topological features. PSPICE simulation results and non-ideal analysis of the oscillators has been included.

Index Terms – sinusoidal oscillators, current conveyors, genetic algorithms

1. Introduction

The generation of sinusoidal waveform is an important task for electronics engineering. Oscillators are widely used in signal processing circuits, communication, control and measurement systems, etc. Many sinusoidal oscillators employing operational amplifier (opamp) have been reported in literature [1-3]. However, the classical opamp suffers from limited gain-bandwidth product affecting both the condition of oscillation (CO) and the oscillation frequency of the oscillators designed using opamp. Therefore, they remain unsatisfactory at higher frequencies [4]. In recent times, current mode circuits have been receiving considerable attention due to their potential advantages such as inherently wide bandwidth, higher slew-rate, greater linearity, wider dynamic range, simple circuitry and low power consumption [5]. Several sinusoidal oscillators have been introduced which use operational transconductance amplifier (OTA), current conveyor (CCII), current feedback operational amplifier (CFOA) or four terminal floating nullor (FTFN), as the active element [6-14]. Many of these oscillators are current mode oscillators having an explicit current output.

Recently, a new current-mode (CM) active building block (ABB) called differential difference current conveyor (DDCC) was introduced [15]. In [16], Gupta and Senani extend this building block to differential difference complementary current conveyor (DDCCC), where two complementary current outputs are present to combine the effect of both DDCC+ and DDCC- in a single ABB. A very similar active element called differential voltage current conveyor (DVCC) was proposed in [17], which can be implemented using a DDCCC (grounding terminal Y3 of a DDCCC results in a DVCC). Oscillators using DVCC and DDCCC have been proposed earlier [16, 18-21].

With every new ABB appearing in literature, analog design researchers start questioning its versatility to synthesize a sine wave oscillator. Authors propose oscillators using the ABB which have some desirable property like minimum components, canonicity, use of a single ABB, single resistance frequency control, explicit current mode output, etc. [6, 13, 18, 20]. Bhattacharya et. al. set the tradition in the 1980's to bring out a catalogue of oscillators in his classic paper [2] which covered all single opamp based Single Frequency and Variable Frequency Oscillators. His methodology to synthesize the oscillators was used by other researchers in bring out oscillator catalogues [7]. Also, there were other catalogues of oscillators based on some specific design approach, such as the state variable approach of Senani, et. al. [22, 23].

These methods were based on rigorous mathematical analysis, circuit design ideas and require lot of manual work from the analog designer. In the present paper, we use Aggarwal's methodology [24] for oscillator synthesis using genetic algorithms (GAs) to generate a catalogue of DDCCC based oscillators. The biggest advantage of the method is automated synthesis of oscillators using any linear ABB without much work from the analog designer. It automatically generates oscillator topologies once the definition of the ABB has been fed to it.

There has been a catalogue of oscillator using DDCCC/DVCC before. In [19], a catalogue of oscillators containing multiple DDCCCs and grounded passive elements was published. A catalogue of oscillators using a new building block DDCCFA and grounded capacitors was also recently published. Since a DDCCFA can implement a DDCC, some of the oscillators published in this catalogue can be implemented using a DDCCC [21]. [1]

In the present paper, we present a catalogue of fourteen current mode oscillators using a single DDCCC with minimum passive components and control of frequency using a single resistor. This is the largest catalogue of single ABB based minimum-component Single Resistance Controlled Oscillators (SRCOs) and Variable Frequency Oscillators (VFOs). No oscillator topology presented in this paper is a repetition of topologies already published. A DDCCC can implement many of the existing ABBs, such as opamp, FTFN, and CCII [21]. We have avoided reporting oscillators which can be synthesized using these ABBs in the present catalogue.

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1 This catalogue [21] was published after we had completed the current work. No oscillator reported in [21] has been included in this catalogue.

Through this paper, we demonstrate the following: a. Versatility of DDCCC to implement single ABB based SRCOs and VFOs with minimum components, b. Usefulness of Aggarwal's genetic algorithm [24] as an automated methodology to generate sine-wave oscillator topologies, c. Fourteen new SRCO and VFO topologies using DDCCC with different interesting architectural, electronic properties, d. A SPICE verification of these oscillators and an inspection of their non-ideal behavior.

The paper has been organized as follows. Section 2 compares the genetic algorithm approach to synthesize oscillators with other approaches in literature. Section 3 contains the proposed catalogue of oscillators and compares it with other oscillator catalogues. Section 4 and 5 look into the non-ideal behavior and SPICE simulation results of these topologies. Finally, Section 6 concludes the study.

2. Genetic algorithms and other approaches to oscillator design

Sinusoidal oscillators using different ABBs have been synthesized using adhoc methods, intuition and some analysis for a long time [12, 13, 18]. There have been methods to systematically generate a catalogue of canonic oscillators using a given ABB [2, 3, 7, 14, 21, 25]. Some of these methods [2, 3, 7, 14] essentially consider all possible networks for a given number of (minimum) passive elements to synthesize an oscillator. Thus, they are able to find all possible minimal oscillators and prove analytically (using network theory and mathematics) that no other oscillator using the ABB and given number of elements exist.

These studies are mathematically rigorous and use a lot of time of the analog designer. On increasing the number of passive or active elements (for instance, to synthesize desirable topological features), these studies become excessively tough due to the larger search space and may become completely infeasible. Generally this approach has not been used for oscillator synthesis using multiple ABBs or high number of passive components. A few studies where this was done are the following: Opamp based grounded capacitor oscillators (passive component count increases to eight) [3]; oscillator synthesis using multiple OTAs [14]. Even when this approach was used in these cases, the mathematical rigor and (assumedly) the time spent was enormous.

Other than this approach, there have been approaches where the topology of the oscillator was fixed and different oscillators were synthesized by the choice of the element (capacitor or resistor) [12, 26, 27]. This approach limits the search space (fixed topology) and many innovative designs cannot be found. There have been other methods using some specific design principle (integral loop biquads [9], state-variable analysis [21-23], etc.), which once again explore only a small important part of the search space. These methods don't claim to find the exhaustive set of oscillators using the ABB. Undoubtedly, they also require a good amount of analysis and time of the analog designer.

Genetic algorithms are a class of algorithms inspired by natural evolution [28]. In the past, they have been used to design various analog circuits such as filters and opamps [24, 29 and reference therein]. An innovative genetic algorithm for generating oscillator topologies automatically has been developed. The algorithm has been discussed in detail in [24]. It can synthesize topologies of sinusoidal oscillators using any given linear ABB and looks for oscillator in the complete search space with no restriction on topology (by default). Topological restrictions such as use of only grounded capacitors, etc. may be imposed according to the choice of the designer, if only a class of oscillators is required. The algorithm only takes the defining equations of the ABB as the input. The oscillators are generated automatically without any added effort or time of the designer. As a case study, the complete set of opamp based SFOs [24] were rediscovered by the algorithm and oscillators using OTRA [24] and DDCC [20] were also synthesized. The algorithm is unable to determine whether the complete set of oscillators using a given ABB has been found (which is true for other approaches discussed above), but is able to synthesize a considerably large set of oscillator as shall become evident also in the present paper.

The advantages of the genetic algorithm over conventional methods are the following, a. Quick (say a week) and automated design of oscillators using a new ABB, b. By default, it doesn’t impose any topological restriction on the oscillator circuit and explores the whole search space, c. The algorithm can be modified to synthesize oscillators with desired topological features. In the present paper, we used the algorithm to synthesize DDCCC based oscillators and synthesis of fourteen new oscillators not only shows the versatility of DDCCC, but the efficiency of the genetic algorithm to synthesize new oscillator topologies.

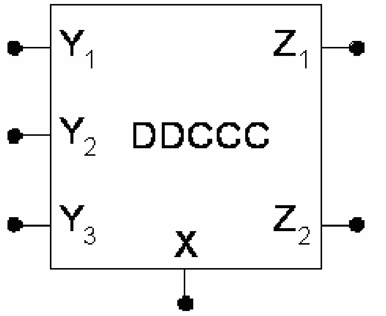


Figure 1. Circuit symbol of DDCCC

3. Proposed oscillators and their relevance

DDCCC, whose circuit symbol shown in Fig. 1, has the following characterizing equations

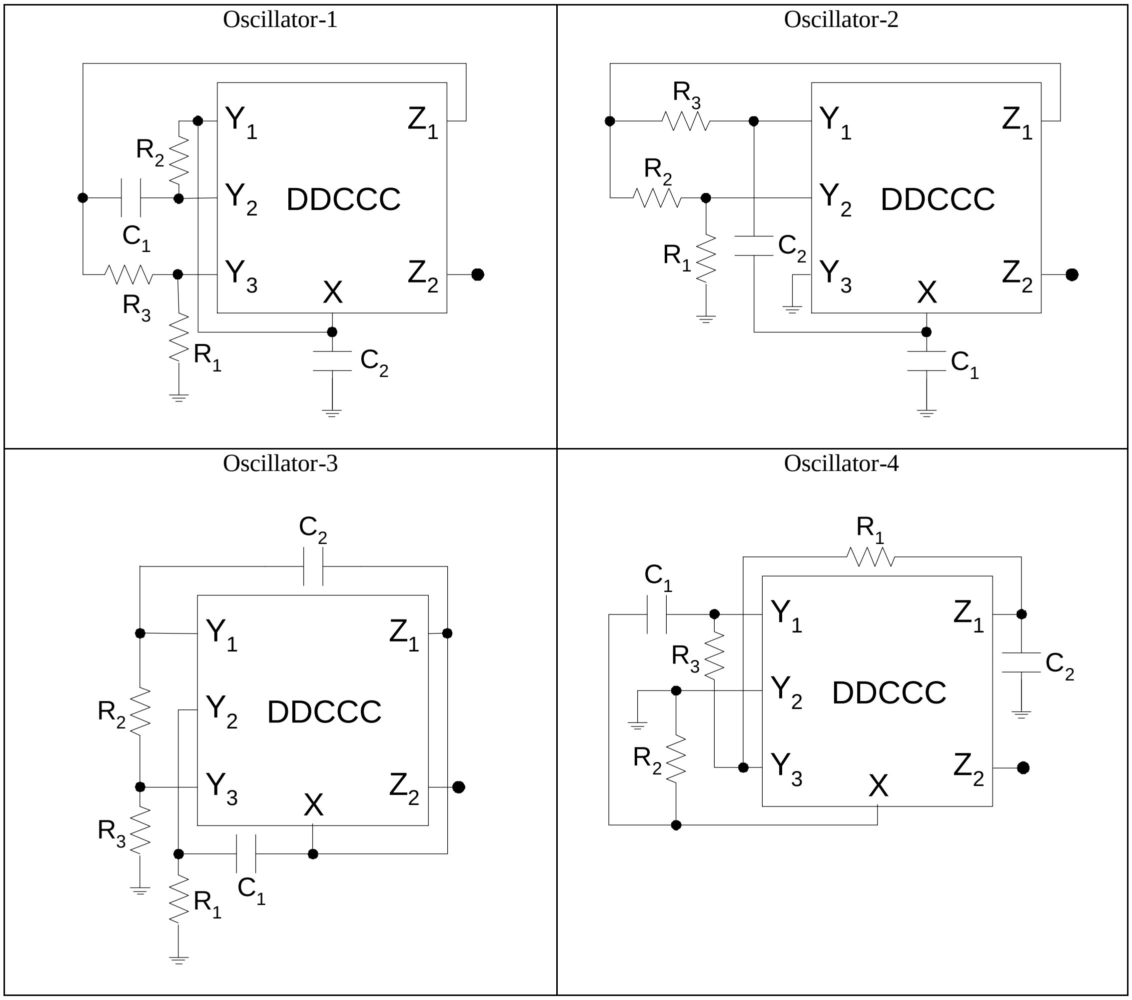
$$I_{y1} = I_{y2} = I_{y3} = 0 \tag{1a}$$

$$V_x = V_{y1} - V_{y2} + V_{y3} \tag{1b}$$

$$I_{z1} = -I_{z2} = I_x \tag{1c}$$

The proposed current mode sinusoidal oscillator circuits are shown in Fig. 2. Routine analysis yields the oscillation conditions and frequencies as given in Table 1. As it is seen from Fig. 2, the realizations are canonic as the circuits contain two capacitors and are minimal as they have at most three resistors. For the first five topologies, both CO and FO can be controlled using a single resistance. The sixth topology has resistance independent control that means the FO can be controlled by single resistance without bothering about CO. For the remaining topologies, only the FO can be controlled using a single resistance.

Figure 2. Proposed current mode sinusoidal oscillator circuits



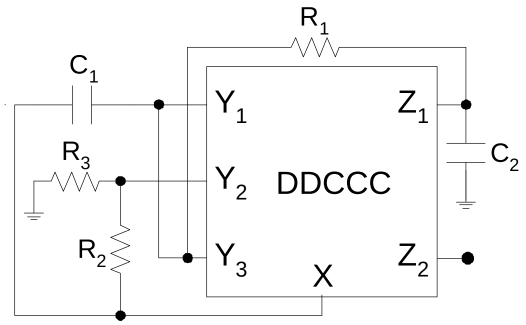
Oscillator-1

Oscillator-2

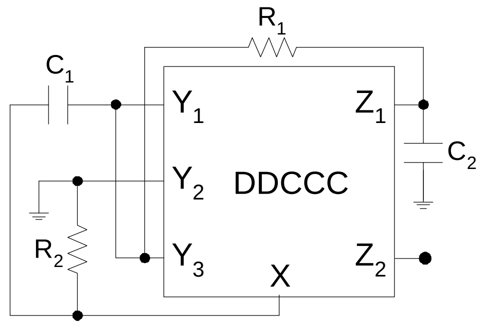
Oscillator-3

Oscillator-4

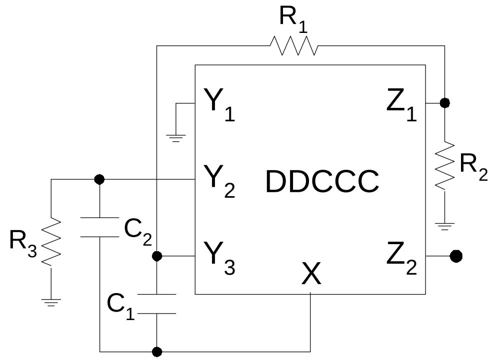
Oscillator-5



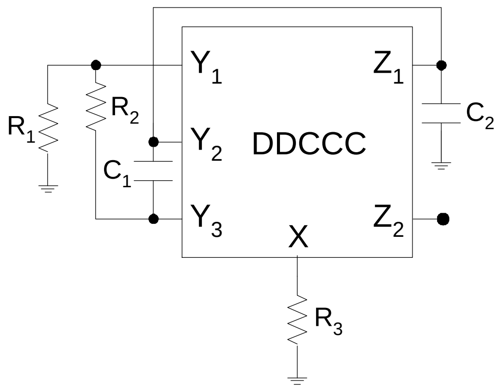
Oscillator-6



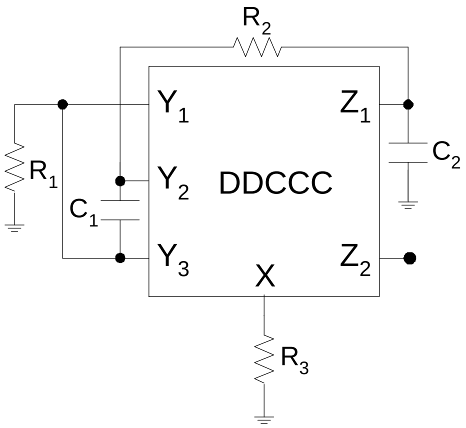
Oscillator-7



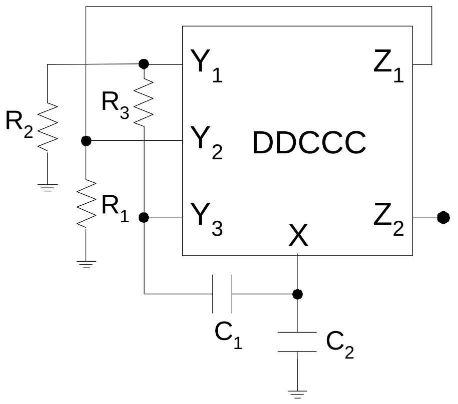
Oscillator-8



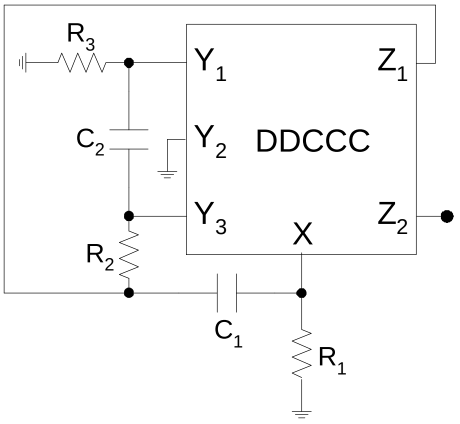
Oscillator-9



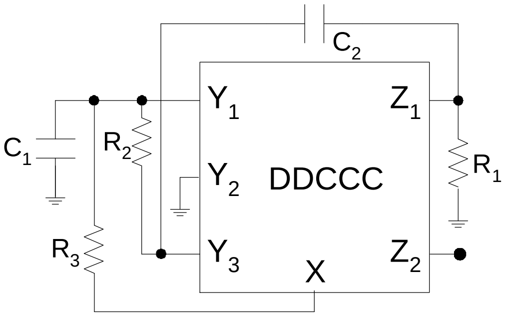
Oscillator-10



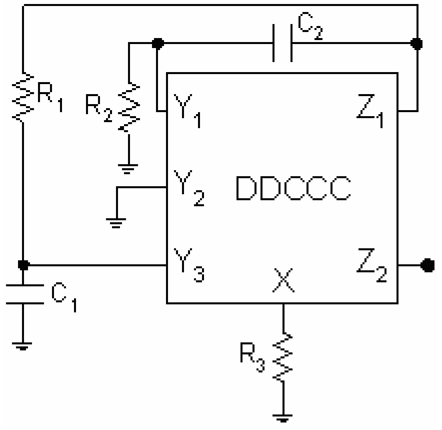
Oscillator-11



Oscillator-12



Oscillator-13



Oscillator-14

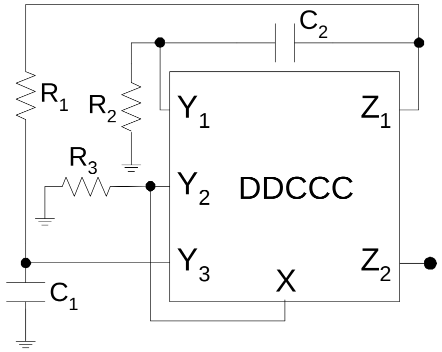


Table 1. Oscillation conditions and frequencies for the proposed circuits

Oscillator no	Condition of Oscillation	Frequency of Oscillation
1	$2R_3C_1 = R_1C_2$	$\sqrt{\frac{1}{R_2R_3C_1C_2}}$
2	$2R_1C_2 = R_2C_1$	$\sqrt{\frac{1}{R_1R_3C_1C_2}}$
3	$2R_1C_1 = R_3C_2$	$\sqrt{\frac{1}{R_1R_2C_1C_2}}$
4	$(2R_2 + R_3)C_1 = R_2C_2$	$\sqrt{\frac{2}{R_1R_2C_1C_2}}$
5	$2R_2C_1 = (R_2 + 2R_3)C_2$	$\sqrt{\frac{2}{R_1R_2C_1C_2}}$
6	$2C_1 = C_2$	$\sqrt{\frac{2}{R_1R_2C_1C_2}}$
7	$2R_3 = R_2$	$\sqrt{\frac{1}{R_3(R_1 + 2R_2)C_1C_2}}$
8	$R_3(C_1 + C_2) = R_1C_1$	$\sqrt{\frac{1}{R_3(R_1 + R_2)C_1C_2}}$
9	$R_3(C_1 + C_2) = R_1C_1$	$\sqrt{\frac{1}{R_3(R_1 + R_2)C_1C_2}}$
10	$R_1(C_1 + C_2) = R_2C_1$	$\sqrt{\frac{1}{R_1(R_2 + R_3)C_1C_2}}$
11	$R_1 = 2R_3$	$\sqrt{\frac{1}{2R_1(R_3 - R_2)C_1C_2}}$
12	$R_3(C_1 + C_2) = 2R_1C_2$	$\sqrt{\frac{1}{[R_1R_2 - R_3(R_1 + R_2)]C_1C_2}}$
13	$R_3(C_1 + C_2) = 2R_2C_2$	$\sqrt{\frac{1}{[R_1R_2 - R_3(R_1 + R_2)]C_1C_2}}$
14	$R_3(C_1 + C_2) = R_2C_2$	$\sqrt{\frac{1}{[R_1R_2 - 2R_3(R_1 + R_2)]C_1C_2}}$

Table 2. Effects of tracking errors on oscillation conditions and frequencies

Oscillator no	Condition of Oscillation	Frequency of Oscillation
1	$a_3b_1R_1C_2 + R_1C_1(1 + B_1)(a_1 + a_3 - a_2 - 1) = (1 - a_1)R_2C_1 + R_3C_1(1 + b_1)(a_2 + 1 - a_1)$	$\sqrt{\frac{1+a_2-a_1}{C_1R_2b_1C_2(a_2R_3+R_1(a_2-a_3))}}$
2	$a_1b_1R_2C_1 + (a_1 - 1)C_2(R_3 + R_2(1 + b_1)) = R_1C_2((1 + a_2)(1 + b_1) - a_1(1 + b_1)) + R_1C_1b_1(a_2 - a_1)$	$\sqrt{\frac{1}{a_2b_1R_1R_3C_1C_2}}$
3	$R_1C_1(1 + a_2)(1 + b_1) + R_2C_2(1 + b_1)(1 - a_1) = R_3C_2((1 + b_1)(a_1 + a_3 - 1)$	$\sqrt{\frac{1}{R_1R_2C_1C_2(1+a_2-a_1)+R_1R_3C_1C_2(1+a_2-a_1-a_3)}}$
4	$(R_2(1 + b_1)(a_1 + a_3 - 1) + a_3b_1R_3)C_1 = R_2C_2$	$\sqrt{\frac{b_1(a_1+a_3)}{R_1R_2C_1C_2(a_1+a_3-1)+R_2R_3C_1C_2(a_1-1)}}$
5	$C_1(1 + b_1)(R_3(a_1 + a_3 - a_2 - 1) + R_2(a_1 + a_3 - 1)) = (R_2 + R_3(1 + a_2))C_2$	$\sqrt{\frac{b_1(a_1+a_3)}{R_1R_2C_1C_2(a_1+a_3-1)+R_1R_3C_1C_2(a_1+a_3-a_2-1)}}$
6	$C_1(1 + b_1)(a_1 + a_3 - 1) = C_2$	$\sqrt{\frac{b_1(a_1+a_3)}{R_1R_2C_1C_2(a_1+a_3-1)}}$
7	$R_3C_2(1 + a_2) = (a_3 - 1)(R_2C_1(1 + b_1) + R_1C_1) + a_3b_1R_2C_2$	$\sqrt{\frac{1}{R_2R_3C_1C_2(1+b_1)(1+a_2-a_3)+R_1R_3C_1C_2(1+a_2-a_3)}}$
8	$R_3(C_1 + C_2) = b_1((a_1 + a_3 - a_2)R_1C_1 + R_2C_1(a_3 - a_2))$	$\sqrt{\frac{a_2b_1}{R_3(R_1+R_2)C_1C_2}}$
9	$R_3(C_1 + C_2) + R_1C_1a_2b_1 = R_1C_1b_1(a_1 + a_3)$	$\sqrt{\frac{a_2b_1}{R_3(R_1+R_2)C_1C_2}}$
10	$a_2b_1R_1(C_1 + C_2) = R_2C_1(a_1 + a_3 - 1) + R_3C_1(a_3 - 1)$	$\sqrt{\frac{1}{a_2b_1R_1(R_2+R_3)C_1C_2}}$
11	$R_1(C_2 + C_1(1 + b_1)(1 - a_3)) = b_1R_3C_2(a_1 + a_3)$	$\sqrt{\frac{a_3b_1}{R_1C_1C_2(1+b_1)((a_1+a_3-1)R_3-R_2)}}$
12	$R_3(C_1 + C_2) = R_1C_2(1 + b_1)(a_1 + a_3 - 1) + R_2C_2(a_1 - 1)$	$\sqrt{\frac{a_1+a_3-1}{\left[R_1R_2a_3b_1-R_3(R_1+R_2)\right]C_1C_2}}$
13	$R_3(C_1 + C_2) = R_2C_2b_1(a_1 + a_3)$	$\sqrt{\frac{a_3b_1}{\left[R_1R_2a_1b_1-R_3(R_1+R_2)\right]C_1C_2}}$
14	$R_3(C_1 + C_2)(1 + a_2) = R_2C_2b_1(a_1 + a_3)$	$\sqrt{\frac{a_3b_1}{\left[a_1b_1R_1R_2-R_3(R_1+R_2)(1+a_2)\right]C_1C_2}}$

The family of oscillators reported have the following desirable features, a. Minimum component count to implement a SRCO/VFO, i.e. five, b. Canonicity, only two capacitors used, c. A single ABB, d. Control of frequency using a single resistor, e. Explicit current mode output. The independent control of CO may be useful, but is not limiting since once the CO is set, the FO can be varied using a single resistor. Thus the frequency of the oscillator can be easily tuned using a single resistor. Most of the oscillators proposed here don't use a grounded resistor frequency control. However, grounded resistance control is not really very advantageous (as believed earlier), since many recently proposed floating VCRs (Voltage Controlled Resistance) [30-33] use the same number of MOSFETs as grounded VCRs.

Oscillator-6 is specifically interesting due to the following reason. It contains only four passive elements, namely two capacitors and two resistors. To the best knowledge of the authors, this is the only VFO synthesized using a single ABB and four passive elements. All other such oscillators required five passive elements. Also, the FO of oscillator-6 is controllable by a grounded resistor, which shall reduce effect of parasitics.

Such a large catalogue of Single-ABB based minimum-component SRCOs and VFOs doesn't exist according to the best knowledge of the authors. Opamp based SRCOs/VFOs require seven passive components, where the minimum required is just five. In case of CCII based oscillators, only two minimum-component single-ABB based oscillators with single resistance control exist [7]. Using a single CFOA, there are eight known oscillators with single resistance frequency control [34]. These oscillators don't provide an explicit current output. Thus, the present catalogue of oscillators is the largest set of current mode SRCOs and VFOs using a single ABB.

4. Non-ideal analysis

Considering the voltage and current tracking errors, the characterizing equations of DDCCC may be modified as follows.

$$V_x = a_1 V_{y1} - a_2 V_{y2} + a_3 V_{y3} \tag{2a}$$

$$I_{z1} = b_1 I_x \tag{2b}$$

$$I_{z2} = -b_2 I_x \tag{2c}$$

We have examined the effects of these tracking errors on the performance of the new SRCOs in Table 2. This table shows the modified FO and the CO of the oscillators after tracking errors are considered. It may appear from the table that FO and CO are interdependent in case tracking errors are considered. However, if $\alpha_{1,}$ is assumed to be unity, the FO and CO become independent for some of the oscillators irrespective of the value of α_2 and $\beta_{1, 2.}$ Most of the circuits enjoy low sensitivity of frequency with respect to $\alpha_{1, 2, 3}$ and $\beta_{1, 2}$. From the non-ideal expressions of ω_0 in Table 2, it is found that most of the active and passive sensitivities remain less than 1 for all of the oscillators. There shall be non-ideal effects also due to the internal pole and the port impedances of the building block. A quantitative estimation of all these effects has been provided in the simulation results, where theoretical and simulated frequency is plotted over a range of resistors.

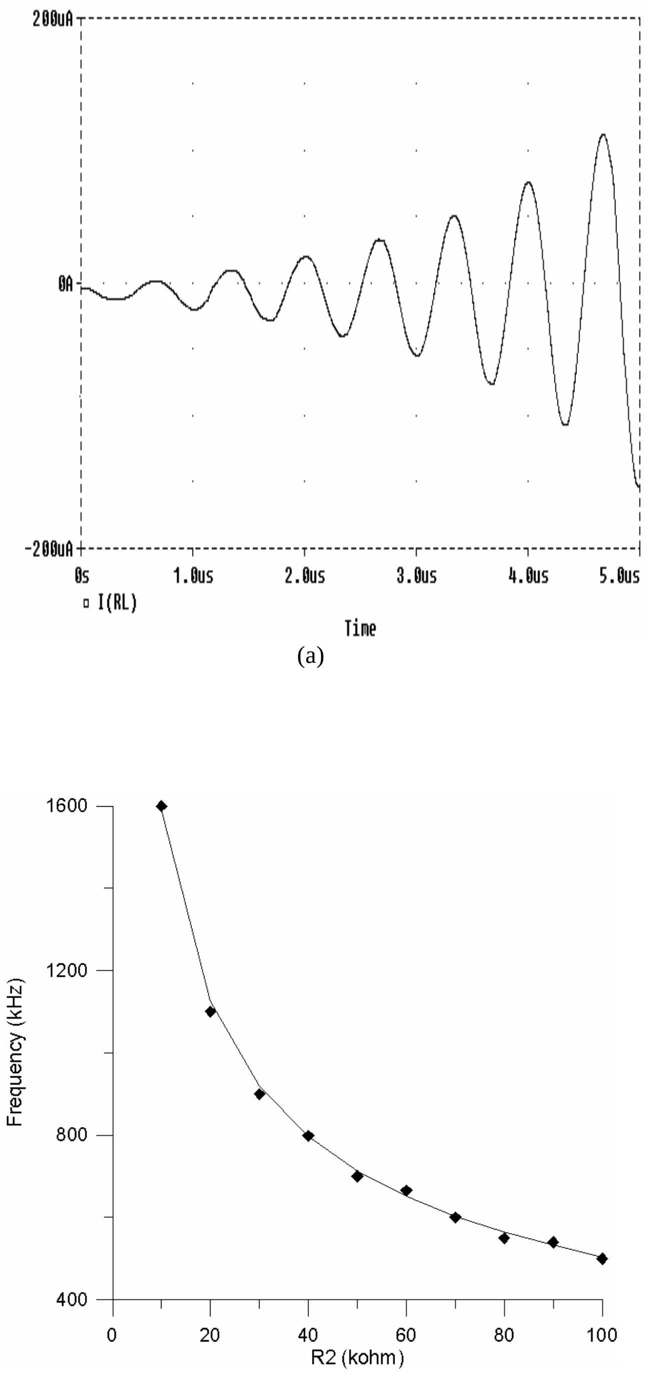
5. Simulation results

The PSPICE simulations were performed using a CMOS realization of DDCCC proposed in [16] using 1.2µm, level 3 MOSFET parameters obtained through MOSIS. The aspect ratios, biasing current and supply voltages were chosen as in [16]. As an example, simulation results of oscillator-1 are given in Fig. 3, which are obtained by using the following set of passive element values: R_1=20kO, R_2=10kO, R_3=10kO, C_1=10pF, C_2=10pF. Fig. 3(a) depicts a typical current output waveform of the oscillator. The variation of FO with R_2, obtained by changing its value from 10kO to 100kO, is shown in Fig. 3(b). In this figure, solid line shows the theoretical results whereas dots show the simulated frequencies. As it can be seen the results are very close to each other. According to the simulation results, oscillators 1, 2, 3, 7, 8, 9, 10 are stable; whereas oscillators 4, 5, 6, 11, 12, 13, 14 are unstable with the CMOS implementation of DDCCC in [16].

All the unstable circuits give oscillations if an ideal DDCCC model is employed in SPICE. This indicates that using a better implementation of DDCCC (or a different Silicon technology), these circuits may give stable oscillations.

6. Conclusion

Current mode single DDCCC based sinusoidal oscillators synthesized using an innovative genetic algorithm are presented. A family of 14 oscillators has been presented, which is the largest family of canonic single ABB-based minimum component SRCOs/VFOs. The paper also showcases the successful application of a new automated methodology of oscillator design [24] to a recent ABB, i.e. DDCCC. Specific features of interest relating to the different oscillator topologies have been discussed in the paper. The stability analysis, non-ideal performance of the circuits and SPICE simulations are included.



(a)

(b)

Figure 3. PSPICE simulation results for the oscillator

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