Generalized Family of Fractional-Order Oscillators Based on Single CFOA and RC Network

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Abstract—**This paper presents a generalized family of fractional-order oscillators based on single CFOA and RC network. Five RC networks are investigated with their general state matrix, and design equations. The general oscillation frequency, condition and the phase difference between the oscillatory outputs are introduced in terms of the fractional order parameters. They add extra degrees of freedom which in turn increase the design flexibility and controllability that is proved numerically. Spice simulations are introduced to validate the theoretical findings.**

Keywords— Fractional calculus; oscillators; CFOA; RC network

I. INTRODUCTION

The current feedback operational amplifier (CFOA) is a four ports network as depicted in Fig.1 with terminal characteristics described by [1]:

$$\begin{bmatrix} I_Y \\ V_X \\ I_Z \\ V_O \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} V_Y \\ I_X \\ V_Z \\ I_O \end{bmatrix}, \qquad (1)$$

where V_X, V_Y ,V_Z , V_O , I_X , I_Y , I_Z and I_O are the voltages and the currents of X-, Y-, Z- and O- terminals respectively. It was originally introduced to replace the voltage mode Op-Amp. It is a very powerful building block in analog current-mode signal processing. The CFOA has been employed in several applications including oscillators and filters [2-5].

Fractional calculus is the branch of mathematics concerning differentiation and integration, of non-integer orders. The conventional calculus is now considered a tiny subset from the larger fractional domain. Fractional order circuits and systems are the result of integrating the new fundamentals added from fractional calculus into the theory and design of different applications [6-13].

The objective of this paper is to generalize the design of a fractional order oscillators family based on single CFOA. The family employs resistors and fractional-order capacitors in the form of RC networks. Five different RC networks are discussed with their general state matrix, design equations. The extra degree of freedom provided by the fractional order parameters conquers the restrictions of integer order designs.

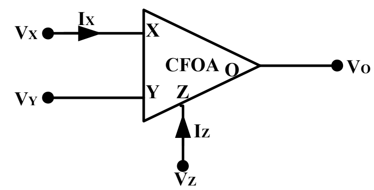

Fig. 1. CFOA symbol diagram.

This paper is organized as follows; section II presents the theory of fractional order oscillators. Section III discusses the topology of the presented family of oscillators. Five RC networks are investigated with their fundamentals. Section IV illustrates Spice simulations for different cases and finally section V concludes the work.

II. OSCILLATION THEORY

The newly formed theory of fractional order oscillators was introduced in [10-11]. It states that any linear fractional order system of the form described by:

$$\begin{bmatrix} D^{\alpha} v_1 \\ D^{\beta} v_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = [A] \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}, \qquad (2)$$

oscillates if and only if the poles exist on the $j\omega$ axis in the s domain, where $s = s_1\, e^{\pm j\frac{\pi}{2}}$ is the solution. The two equations satisfy this formula are described by [10-11]:

$$\omega^{\alpha+\beta} \cos\left(\frac{(\beta+\alpha)\pi}{2}\right) - a_{11}\, \omega^{\beta} \cos\left(\frac{\beta\pi}{2}\right) - a_{22}\, \omega^{\alpha} \cos\left(\frac{\alpha\pi}{2}\right) + |A| = 0, \qquad (3a)$$

$$\omega^{\beta} \sin\left(\frac{(\beta+\alpha)\pi}{2}\right) - a_{11}\, \omega^{\beta-\alpha} \sin\left(\frac{\beta\pi}{2}\right) - a_{22} \sin\left(\frac{\alpha\pi}{2}\right) = 0, \qquad (3b)$$

where $|A| = a_{11}a_{22} - a_{12}a_{21}$, is the determinant of the system coefficient matrix and α, β are the orders of the fractional-order system. The phase difference between the generated signals is calculated as follows [10-11]:

$$\varphi = \begin{cases} \tan^{-1}\left(\dfrac{\omega^{\alpha}\sin\left(\frac{\alpha\pi}{2}\right)}{\omega^{\alpha}\cos\left(\frac{\alpha\pi}{2}\right) - a_{11}}\right) & a_{12} > 0 \\ \tan^{-1}\left(\dfrac{\omega^{\alpha}\sin\left(\frac{\alpha\pi}{2}\right)}{\omega^{\alpha}\cos\left(\frac{\alpha\pi}{2}\right) - a_{11}}\right) - \pi & a_{12} < 0 \end{cases} \qquad (4)$$

III. Oscillators Family

The general topology of the presented family of oscillators is shown in Fig. 2. It was introduced in [3] and consists of a single CFOA together with a general RC network. It employs a voltage feedback such that R_3 and R_4 act as a voltage attenuator to provide a voltage kv_o to terminal 1 of the network, where k is given by:

$$k = \frac{R_3}{R_3 + R_4}. \tag{5}$$

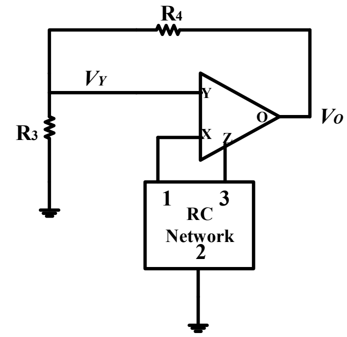

Fig. 2. Family of oscillators general topology

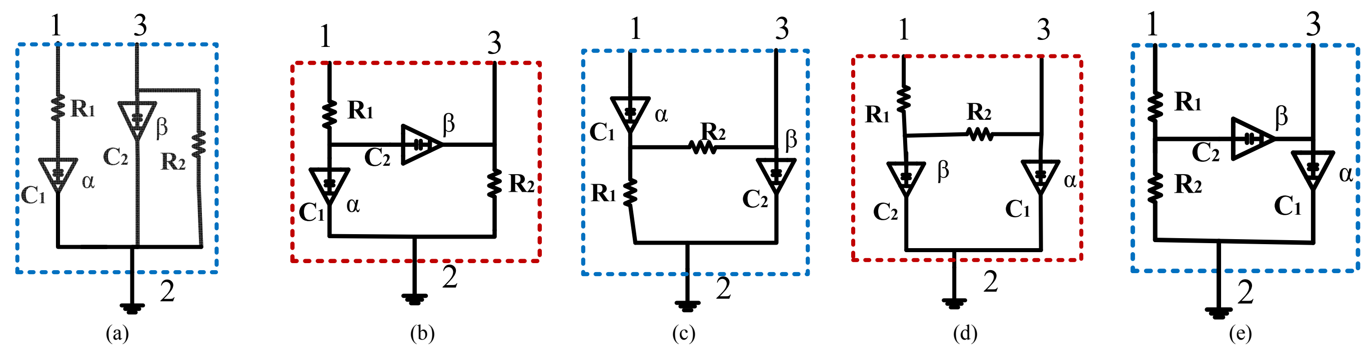

Fig. 3. Different RC networks (a) Network A,(b)Network B, (c)Network C,(d)Network D,and(e)Network E

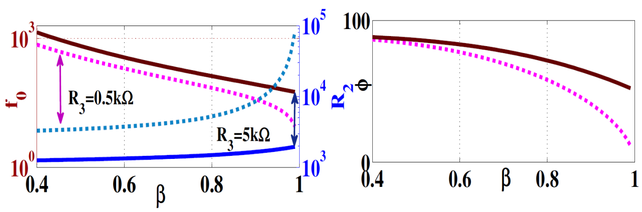

Fig. 4. Oscillation frequency , condition and phase for Network A oscillator

Figure 3 shows five possible RC networks belongs to the presented family with different RC connections (Network A, Network B, Network C, Network D, and Network E). The oscillator based on Network A shown in Fig. 3(a) is the generalization of the integer-order oscillator presented in [3]. The state matrix describes this oscillator could be written as follows:

$$\begin{bmatrix} D^{\alpha} v_{C1} \\ D^{\beta} v_{C2} \end{bmatrix} = \begin{bmatrix} \frac{-1}{C_1 R_1} & \frac{k}{C_1 R_1} \\ \frac{-1}{C_2 R_1} & \frac{k}{C_2 R_1} - \frac{1}{C_2 R_2} \end{bmatrix} \begin{bmatrix} v_{C1} \\ v_{C2} \end{bmatrix}. \tag{6}$$

According to the theorem discussed in section II; for this system to oscillate there must be a value of ω satisfies the following two equations:

$$\omega^{\alpha+\beta} \cos\left(\frac{(\beta+\alpha)\pi}{2}\right) + \left(\frac{1}{C_2 R_2} - \frac{k}{C_2 R_1}\right) \omega^{\alpha} \cos\left(\frac{\alpha\pi}{2}\right) + \frac{1}{C_1 R_1} \omega^{\beta} \cos\left(\frac{\beta\pi}{2}\right) + \frac{1}{C_1 C_2 R_1 R_2} = 0, \tag{7a}$$

$$\omega^{\alpha+\beta} \sin\left(\frac{(\beta+\alpha)\pi}{2}\right) + \left(\frac{1}{C_2 R_2} - \frac{k}{C_2 R_1}\right) \omega^{\alpha} \sin\left(\frac{\alpha\pi}{2}\right) + \frac{1}{C_1 R_1} \omega^{\beta} \sin\left(\frac{\beta\pi}{2}\right) = 0. \tag{7b}$$

Choosing a parameter from the above equations to control condition of oscillations such as R_2 and it can be represented as follows:

$$R_2 = -\frac{\frac{1}{C_2}\omega^{\alpha} \cos\left(\frac{\alpha\pi}{2}\right) + \frac{1}{C_1 C_2 R_1}}{\omega^{\alpha+\beta} \cos\left(\frac{(\beta+\alpha)\pi}{2}\right) - \frac{k}{C_2 R_1}\omega^{\alpha} \cos\left(\frac{\alpha\pi}{2}\right) + \frac{1}{C_1 R_1}\omega^{\beta} \cos\left(\frac{\beta\pi}{2}\right)}, \tag{8a}$$

$$R_2 = -\frac{\frac{1}{C_2}\omega^{\alpha} \sin\left(\frac{\alpha\pi}{2}\right)}{\omega^{\alpha+\beta} \sin\left(\frac{(\beta+\alpha)\pi}{2}\right) - \frac{k}{C_2 R_1}\omega^{\alpha} \sin\left(\frac{\alpha\pi}{2}\right) + \frac{1}{C_1 R_1}\omega^{\beta} \sin\left(\frac{\beta\pi}{2}\right)}. \tag{8b}$$

By eliminating R_2, the equation that governs the oscillation frequency can be written as follows:

$$\omega^{2\alpha+\beta} \sin\left(\frac{\beta\pi}{2}\right) + \frac{\omega^{\beta+\alpha}}{C_1 R_1}\left(\sin\left(\frac{(\beta+\alpha)\pi}{2}\right) + \sin\left(\frac{(\beta-\alpha)\pi}{2}\right)\right) - \frac{k}{C_1 C_2 R_1^2}\omega^{\alpha} \sin\left(\frac{\alpha\pi}{2}\right) + \frac{1}{C_1^2 R_1^2}\omega^{\beta} \sin\left(\frac{\beta\pi}{2}\right) = 0. \tag{9}$$

The phase difference can be calculated according to (4). Multiple configurations could be obtained with changing the fractional order parameters. For example, let $\alpha = 1, C_1 = 3C_2$ with different values of R_3 to control k; the relations between the oscillation frequency, condition and phase versus the fractional order parameter β are shown in Fig.4. The frequency and phase decreases with the increase of β.

Oscillators based on Networks B and C depicted in Figs. 3(b) and 3(c) are also generalization to their integer order counterparts introduced in [3]. The oscillation parameters and state matrix of these oscillators are summarized in Table I. One of the advantages provided by the fractional order parameters is the design flexibility and controllability as shown in Fig.5. It shows oscillation frequency versus phase for both oscillators for different values of α with $0 \leq \beta \leq 1, C_1 = 3C_2$.

TABLE I. OSCILLATION PARAMETERS

Network B	$\begin{bmatrix} D^{\alpha}v_{C1} \\ D^{\beta}v_{C2} \end{bmatrix} = \begin{bmatrix} \frac{2(k-1)}{C_1 R_1} - \frac{1}{C_1 R_2} & \frac{2k}{C_1 R_1} - \frac{1}{C_1 R_2} \\ \frac{(k-1)}{C_2 R_1} - \frac{1}{C_2 R_2} & \frac{k}{C_2 R_1} - \frac{1}{C_2 R_2} \end{bmatrix} \begin{bmatrix} v_{C1} \\ v_{C2} \end{bmatrix}$ $R_2 = -\frac{\frac{1}{C_2}\omega^{\alpha}\cos\left(\frac{\alpha\pi}{2}\right) + \frac{1}{C_1}\omega^{\beta}\cos\left(\frac{\beta\pi}{2}\right) + \frac{1}{C_1 C_2 R_1}}{\omega^{\alpha+\beta}\cos\left(\frac{(\beta+\alpha)\pi}{2}\right) - \frac{k}{C_2 R_1}\omega^{\alpha}\cos\left(\frac{\alpha\pi}{2}\right) - \frac{2(k-1)}{C_1 R_1}\omega^{\beta}\cos\left(\frac{\beta\pi}{2}\right)}, R_2 = -\frac{\frac{1}{C_2}\omega^{\alpha}\sin\left(\frac{\alpha\pi}{2}\right) + \frac{1}{C_1}\omega^{\beta}\sin\left(\frac{\beta\pi}{2}\right)}{\omega^{\alpha+\beta}\sin\left(\frac{(\beta+\alpha)\pi}{2}\right) - \frac{k}{C_2 R_1}\omega^{\alpha}\sin\left(\frac{\alpha\pi}{2}\right) - \frac{2(k-1)}{C_1 R_1}\omega^{\beta}\sin\left(\frac{\beta\pi}{2}\right)}$ $\frac{\omega^{2\alpha+\beta}}{C_2}\sin\left(\frac{\beta\pi}{2}\right) + \frac{\omega^{\alpha+2\beta}}{C_1}\sin\left(\frac{\alpha\pi}{2}\right) + \frac{\omega^{\beta+\alpha}}{C_1 C_2 R_1}\left(\sin\left(\frac{(\beta+\alpha)\pi}{2}\right) - k\sin\left(\frac{(\alpha-\beta)\pi}{2}\right) - 2(k-1)\sin\left(\frac{(\beta-\alpha)\pi}{2}\right)\right) - \frac{k}{C_1 C_2^2 R_1^2}\omega^{\alpha}\sin\left(\frac{\alpha\pi}{2}\right) - \frac{2(k-1)}{C_1^2 C_2 R_1^2}\omega^{\beta}\sin\left(\frac{\beta\pi}{2}\right) = 0.$
Network C	$\begin{bmatrix} D^{\alpha}v_{C1} \\ D^{\beta}v_{C2} \end{bmatrix} = \begin{bmatrix} \frac{-1}{C_1 R_1} - \frac{1}{C_1 R_2} & \frac{k}{C_1 R_1} + \frac{(k-1)}{C_1 R_2} \\ \frac{-1}{C_2 R_1} - \frac{2}{C_2 R_2} & \frac{k}{C_2 R_1} + \frac{2(k-1)}{C_2 R_2} \end{bmatrix} \begin{bmatrix} v_{C1} \\ v_{C2} \end{bmatrix}$ $R_2 = -\frac{\frac{1}{C_1}\omega^{\beta}\cos\left(\frac{\beta\pi}{2}\right) - \frac{2(k-1)}{C_2}\omega^{\alpha}\cos\left(\frac{\alpha\pi}{2}\right) + \frac{1}{C_1 C_2 R_1}}{\omega^{\alpha+\beta}\cos\left(\frac{(\beta+\alpha)\pi}{2}\right) - \frac{k}{C_2 R_1}\omega^{\alpha}\cos\left(\frac{\alpha\pi}{2}\right) + \frac{1}{C_1 R_1}\omega^{\beta}\cos\left(\frac{\beta\pi}{2}\right)}, R_2 = -\frac{\frac{1}{C_1}\omega^{\beta}\sin\left(\frac{\beta\pi}{2}\right) - \frac{2(k-1)}{C_2}\omega^{\alpha}\sin\left(\frac{\alpha\pi}{2}\right)}{\omega^{\alpha+\beta}\sin\left(\frac{(\beta+\alpha)\pi}{2}\right) - \frac{k}{C_2 R_1}\omega^{\alpha}\sin\left(\frac{\alpha\pi}{2}\right) + \frac{1}{C_1 R_1}\omega^{\beta}\sin\left(\frac{\beta\pi}{2}\right)}$ $\frac{\omega^{\alpha+2\beta}}{C_1}\sin\left(\frac{\alpha\pi}{2}\right) - \frac{2(k-1)}{C_2}\omega^{2\alpha+\beta}\sin\left(\frac{\beta\pi}{2}\right) + \frac{\omega^{\beta+\alpha}}{C_1 C_2 R_1}\left(\sin\left(\frac{(\beta+\alpha)\pi}{2}\right) - k\sin\left(\frac{(\alpha-\beta)\pi}{2}\right) - 2(k-1)\sin\left(\frac{(\beta-\alpha)\pi}{2}\right)\right) - \frac{k}{C_1 C_2^2 R_1^2}\omega^{\alpha}\sin\left(\frac{\alpha\pi}{2}\right) + \frac{\omega^{\beta}}{C_1^2 C_2 R_1^2}\sin\left(\frac{\beta\pi}{2}\right) = 0$
Network D	$\begin{bmatrix} D^{\alpha}v_{C1} \\ D^{\beta}v_{C2} \end{bmatrix} = \begin{bmatrix} \frac{k}{C_1 R_1} - \frac{1}{C_1 R_2} & \frac{1}{C_1 R_2} - \frac{1}{C_1 R_1} \\ \frac{k}{C_2 R_1} + \frac{1}{C_2 R_2} & -\frac{1}{C_2 R_1} - \frac{1}{C_2 R_2} \end{bmatrix} \begin{bmatrix} v_{C1} \\ v_{C2} \end{bmatrix}$ $R_2 = -\frac{\frac{1}{C_1}\omega^{\beta}\cos\left(\frac{\beta\pi}{2}\right) + \frac{1}{C_2}\omega^{\alpha}\cos\left(\frac{\alpha\pi}{2}\right) - \frac{2(k-1)}{C_1 C_2 R_1}}{\omega^{\alpha+\beta}\cos\left(\frac{(\beta+\alpha)\pi}{2}\right) + \frac{1}{C_2 R_1}\omega^{\alpha}\cos\left(\frac{\alpha\pi}{2}\right) - \frac{k}{C_1 R_1}\omega^{\beta}\cos\left(\frac{\beta\pi}{2}\right)}, R_2 = -\frac{\frac{1}{C_1}\omega^{\beta}\sin\left(\frac{\beta\pi}{2}\right) + \frac{1}{C_2}\omega^{\alpha}\sin\left(\frac{\alpha\pi}{2}\right)}{\omega^{\alpha+\beta}\sin\left(\frac{(\beta+\alpha)\pi}{2}\right) + \frac{1}{C_2 R_1}\omega^{\alpha}\sin\left(\frac{\alpha\pi}{2}\right) - \frac{k}{C_1 R_1}\omega^{\beta}\sin\left(\frac{\beta\pi}{2}\right)}.$ $\frac{\omega^{\alpha+2\beta}}{C_1}\sin\left(\frac{\alpha\pi}{2}\right) + \frac{1}{C_2}\omega^{2\alpha+\beta}\sin\left(\frac{\beta\pi}{2}\right) + \frac{\omega^{\beta+\alpha}}{C_1 C_2 R_1}\left(-2(k-1)\sin\left(\frac{(\beta+\alpha)\pi}{2}\right) + \sin\left(\frac{(\alpha-\beta)\pi}{2}\right) - k\sin\left(\frac{(\beta-\alpha)\pi}{2}\right)\right) - \frac{2(k-1)}{C_1 C_2^2 R_1^2}\omega^{\alpha}\sin\left(\frac{\alpha\pi}{2}\right) + \frac{2k(k-1)\omega^{\beta}}{C_1^2 C_2 R_1^2}\sin\left(\frac{\beta\pi}{2}\right) = 0.$
Network E	$\begin{bmatrix} D^{\alpha}v_{C1} \\ D^{\beta}v_{C2} \end{bmatrix} = \begin{bmatrix} \frac{2(k-1)}{C_1 R_1} - \frac{1}{C_1 R_2} & \frac{2}{C_1 R_1} + \frac{1}{C_1 R_2} \\ \frac{1}{C_2 R_2} - \frac{(k-1)}{C_2 R_1} & -\frac{1}{C_2 R_1} - \frac{1}{C_2 R_2} \end{bmatrix} \begin{bmatrix} v_{C1} \\ v_{C2} \end{bmatrix}$ $R_2 = -\frac{\frac{1}{C_1}\omega^{\beta}\cos\left(\frac{\beta\pi}{2}\right) + \frac{1}{C_2}\omega^{\alpha}\cos\left(\frac{\alpha\pi}{2}\right) - \frac{k}{C_1 C_2 R_1}}{\omega^{\alpha+\beta}\cos\left(\frac{(\beta+\alpha)\pi}{2}\right) + \frac{1}{C_2 R_1}\omega^{\alpha}\cos\left(\frac{\alpha\pi}{2}\right) - \frac{2(k-1)}{C_1 R_1}\omega^{\beta}\cos\left(\frac{\beta\pi}{2}\right)}, R_2 = -\frac{\frac{1}{C_1}\omega^{\beta}\sin\left(\frac{\beta\pi}{2}\right) + \frac{1}{C_2}\omega^{\alpha}\sin\left(\frac{\alpha\pi}{2}\right)}{\omega^{\alpha+\beta}\sin\left(\frac{(\beta+\alpha)\pi}{2}\right) + \frac{1}{C_2 R_1}\omega^{\alpha}\sin\left(\frac{\alpha\pi}{2}\right) - \frac{2(k-1)}{C_1 R_1}\omega^{\beta}\sin\left(\frac{\beta\pi}{2}\right)}$ $\frac{\omega^{\alpha+2\beta}}{C_1}\sin\left(\frac{\alpha\pi}{2}\right) + \frac{1}{C_2}\omega^{2\alpha+\beta}\sin\left(\frac{\beta\pi}{2}\right) + \frac{\omega^{\beta+\alpha}}{C_1 C_2 R_1}\left(-k\sin\left(\frac{(\beta+\alpha)\pi}{2}\right) + \sin\left(\frac{(\alpha-\beta)\pi}{2}\right) - 2(k-1)\sin\left(\frac{(\beta-\alpha)\pi}{2}\right)\right) - \frac{k}{C_1 C_2^2 R_1^2}\omega^{\alpha}\sin\left(\frac{\alpha\pi}{2}\right) + \frac{2k(k-1)\omega^{\beta}}{C_1^2 C_2 R_1^2}\sin\left(\frac{\beta\pi}{2}\right) = 0$

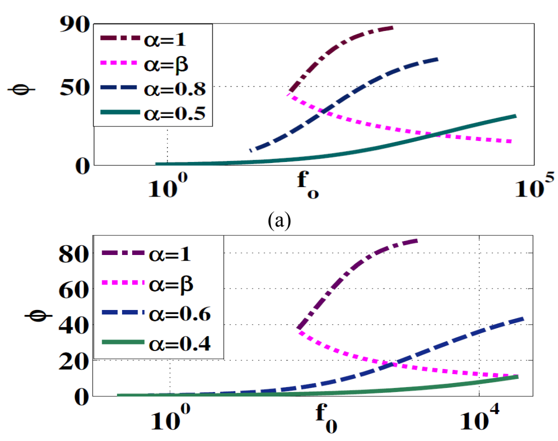

Fig. 5. Oscillation frequency versus phase (a) Network B,and (b) Network C.

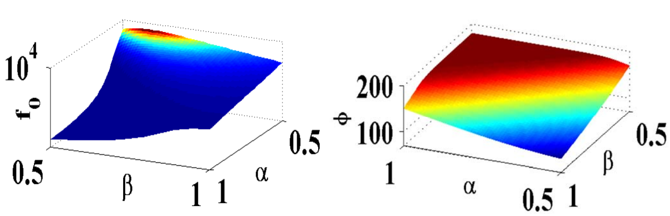

Fig. 6. Oscillation frequncy and phase surfaces versus $\alpha-\beta$ plane for Network D.

Therefore, designing an oscillator for a specific phase and frequency is now possible and it is done by only choosing the suitable fractional orders. Figures 3(d) and 3(e) propose new networks (Networks D and E) for oscillator realization. Network D has the advantage that it depends on two grounded fractional order capacitors. Figure 6 shows the oscillation frequency and phase surfaces versus $\alpha-\beta$ plane for this oscillator. The presented oscillators won't work in the integer case in case of equal C design. This consolidates the idea that integer order designs force limitations. The fractional-order designs are more flexible with wider capabilities. For Network E to oscillate; R_2 must be negative. The negative resistance could be implemented using op-amps. Figure 7 shows a comparison between oscillation frequency for the four working networks versus β, where Network A and B have identical frequency range.

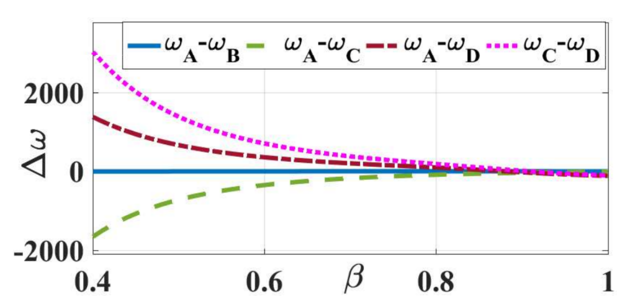

Fig. 7. $\Delta\omega$ versus β for all networks when $\alpha = 1$.

IV. SIMULATION RESULTS

In this section, Spice simulations of some cases are presented to verify the theoretical findings. The fractional order capacitor is simulated using the ladder structure depicted in Fig.8 where the values of the resistances, the capacitors and the number of branches depend on the order of the capacitor as discussed in [12-13]. The CFOA is implemented with AD844 spice model.

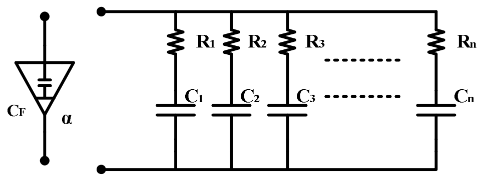

Fig. 8. Approximation the fractional order capacitor with general order.

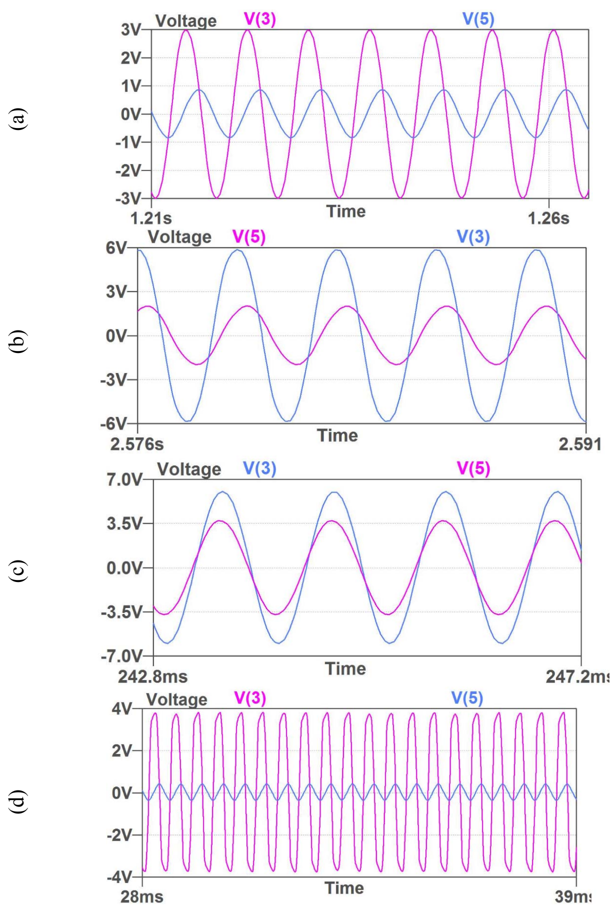

Fig. 9. Spice simulation output waveforms for the oscillator based on (a)Network A, (b) Network B, (c)Network C and (d) Network D.

For Network A based oscillators, the simulation parameters are selected to be $C_1 = 3C_2 = 3.6x10^{-6}$, $R_1 = 1k\Omega$, $k = (5/6)$, fractional orders, $\alpha = 1$ & $\beta = 0.8$, and the oscillation condition R_2 is calculated according to the theoretical analysis to be $1.49k\Omega$. The output waveforms are depicted in Fig. 9(a) with oscillation frequency equals 133.33Hz.

For Networks B and C oscillators, the simulation parameters are selected to be $C_1 = 3C_2 = 3.6x10^{-6}$, $R_1 = 1k\Omega$, $k = (2/3)$. The simulated fractional orders are $\alpha = 0.7$ & $\beta = 0.8$, (Network B) and $\alpha = 0.8$ & $\beta = 0.6$ (Network C). The oscillation condition R_2 is calculated according to the theoretical analysis to be $2.98k\Omega$ and $1.62k\Omega$, respectively. The output waveforms are depicted in Figs. 9(b) and 9(c) with oscillation frequency equals 326.5Hz and 952.5Hz, respectively.

For Network D oscillator, the simulation parameters are selected to be equal C design with $C_1 = C_2 = 1.2x10^{-6}$, $R_1 = 1k\Omega$, $k = (2/3)$, $\alpha = 0.4$ & $\beta = 1$. The oscillation condition R_2 is calculated according to Table I to be $1.61k\Omega$. The output waveforms are depicted in Fig. 9(d) with oscillation frequency equals 2kHz.

V. CONCLUSION

In this paper, a generalized family of fractional-order oscillators based on single CFOA and RC networks was introduced. Five different networks were introduced with derivations of their general oscillation frequency; condition and the phase difference. The extra degree of freedom provided by the fractional order parameters proved to add more control on oscillator parameters. Finally, Spice simulations results were presented to show the reliability of the design.

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