General View on Fractional-Order All-Pass Filters Using Generalized Current Conveyors

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Abstract—**The paper presents a general structure for realizing current-mode (CM) fractional-order all-pass filters (FOAPFs) using generalized first-kind five-port current conveyors (GCC5s). The proposed circuit topology employs two GCC5s and minimum number of passive components, i.e.. one resistor and one fractional-order capacitor, both in grounded form. A total of eight CM FOAPFs using second-generation current conveyor are derived, which are capable of providing simultaneously both inverting and non-inverting current-outputs from high impedance terminals. A theoretical study of a variant created using universal current conveyor is provided, which verify the concept of the proposed circuit topology.**

Index Terms—**all-pass filter; APF; current-mode; fractional-order filter; generalized first-kind five-port current conveyor; GCC5; universal current conveyor; UCC**

I. Introduction

Current conveyors (CCs) have proved to be one of the most versatile active building blocks (ABBs) in circuit theory and have received considerable attention in realizing wide variety of circuit solutions [1], [2]. These include first-order filters, biquadratic filters, impedance simulators (including inductor simulators and capacitance multipliers), chaotic circuits, proportional-integral-derivative controllers, sinusoidal oscillators, precision rectifiers and non-linear circuits for squaring, square-rooting and vector summation. The motivation of this paper is to extend the knowledge about current-mode (CM) fractional-order all-pass filters (FOAPFs) and propose a new general topology using a generalized first-kind five-port current conveyor (GCC5) [3] and minimum passive components. All-pass filters are very important circuits for many analog signal processing applications. These are generally used in phase equalization and for introducing a frequency dependent delay while keeping the amplitude of the input signal constant over the desired frequency range [4]–[51]. The proposed circuit topology employs two GCC5s and only two passive components, namely one virtually grounded resistor and one virtually grounded capacitor. Both the passive components are grounded and the use of grounded capacitor makes the circuit suitable for monolithic integration. Limiting our study to second-generation current conveyor designs only, a total of eight FOAPFs have been derived from the topology. All variants are capable of simultaneously providing two explicit

current outputs from high impedance terminals and thus can realize both inverting and non-inverting APFs without any change of the circuit configuration. A theoretical study of the selected variant created using universal current conveyor (UCC) [52] has been included to verify the concept of the proposed circuit.

II. Circuit Description

A. The Generalized Current Conveyor (GCC)

In the general design of frequency filters and oscillators with CCs it is of advantage to use the classical generalized current conveyor (GCC). Using the GCC, authors in [3] introduced new classification for CCs. In their viewpoint, the classification of CCs by generations is not suitable. For example, the third-generation CC differs from the first-generation CC by the sign of one port current only and the term 'second-generation' does not in fact denotes a development stage but a certain property. According to this classification, the number of input ports X specifies the conveyor *order*, the number of all auxiliary ports Y determines the conveyor *kind*, and the number of output ports Z to which an independent current i_X is conveyed classifies the conveyor *class*. This classification has not undertaken yet, however, some of defined novel types of GCCs could be still expanded in the future. One of them is the generalized first-kind five-port current conveyor (GCC5) [3], which schematic symbol is shown in Fig. 1.

Relations between the individual terminals of the GCC5 can be described by the following matrix equation:

$$
\begin{bmatrix} v_X \\ i_Y \\ i_{Z1} \\ i_{Z2} \\ i_{Z3} \end{bmatrix} = \begin{bmatrix} 0 & a & 0 & 0 & 0 \\ b & 0 & 0 & 0 & 0 \\ d_1 & 0 & 0 & 0 & 0 \\ d_2 & 0 & 0 & 0 & 0 \\ d_3 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_X \\ v_Y \\ v_{Z1} \\ v_{Z2} \\ v_{Z3} \end{bmatrix}, \qquad (1)
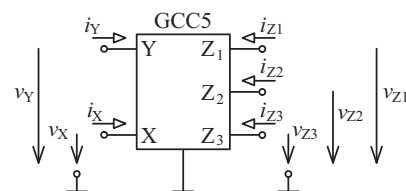$$

Fig. 1. Generalized first-kind five-port current conveyor

where a, b, d_1, d_2, d_3 are the conveyance coefficients of the GCC5 that can be substituted by the values: $a \in \{-1, +1\}$, $b \in \{-1, 0, +1\}$, and $d_i \in \{-1, +1\}$ for $i = 1, 2, 3$. If in (1) $a = +1$, we consider a conventional (non-inverting) CC, while $a = -1$ characterizes an inverting current conveyor (ICC) [2]. With $b = +1$ the first-generation current conveyor (CCI or ICCI) [2] can be realized. Similarly, the second-generation CC (CCII or ICCII) [2] can be realized, if the $b = 0$ and the third-generation CC (CCIII or ICCIII) [2], when $b = -1$. Eventually, when $d_i = +1$ we speak about a positive current conveyor, which is denoted by the "+" sign following the schematic symbol (e.g. ICCIII+), when $d_i = -1$, we consider the negative current conveyor, which is denoted by the "–" sign (e.g. CCI–). In general, the GCC5 represents 24 different types of multiple-output CCs of different generations.

B. The Universal Current Conveyor (UCC)

As it was mentioned above, the GCC5 is just a general tool for the initial filter design. For further implementation and simulation of the selected filter topology proposed in the first step using GCC5s, the universal current conveyor (UCC) [52] can be used. In 2000, the UCC was designed and developed using the CMOS 0.35 μm technology under the designation UCC-N1B 0520 and produced in cooperation with ON Semiconductor Czech Republic, Ltd. It is an eight-port active element that schematic symbol is shown in Fig. 2. Analogous to differential difference current conveyor (DDCC) [2] or to differential difference complementary current conveyor (DDCCC) [2], the UCC has three high-impedance voltage inputs Y (one differencing - Y_2, and two additive - Y_1, and Y_3), one low impedance input X, and four current outputs (Z_{1+}, Z_{1-}, Z_{2+}, Z_{2-}). Outputs Z_{1-}, Z_{2-} are inverse to outputs Z_{1+} and Z_{2+}.

Relations between the individual terminals of UCC can be described by the following hybrid matrix:

$$
\begin{bmatrix}
i_{Y1} \\
i_{Y2} \\
i_{Y3} \\
v_X \\
i_{Z1+} \\
i_{Z1-} \\
i_{Z2+} \\
i_{Z2-}
\end{bmatrix}
=
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\beta_1 & -\beta_2 & \beta_3 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \alpha_1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -\alpha_2 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \alpha_3 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -\alpha_4 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
v_{Y1} \\
v_{Y2} \\
v_{Y3} \\
i_X \\
v_{Z1+} \\
v_{Z1-} \\
v_{Z2+} \\
v_{Z2-}
\end{bmatrix},
\tag{2}
$$

where $\beta_k = 1 - \varepsilon_{vk}$ and $\alpha_j = 1 - \varepsilon_{ij}$ ($k = 1, 2, 3$ and $j = 1, 2, 3, 4$) are the non-ideal voltage and current gains, respectively, and ε_{vk} ($|\var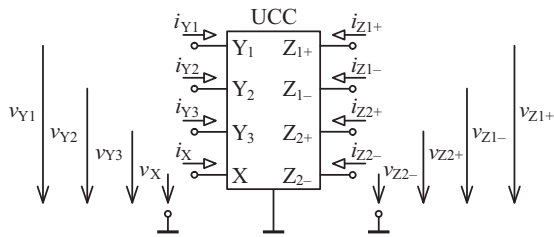epsilon_{vk}| \ll 1$) denote voltage tracking errors and ε_{ij} ($|\varepsilon_{ij}| \ll 1$) denote current tracking errors of the UCC, respectively.

By connecting or grounding suitable terminals of the UCC, it helps to realize different generations and types of current conveyors with single low impedance current input X [52]. Moreover, as it is mentioned above, the UCC can be also used for realization of 24 different types of multiple-output CCs of different generations, defined by the GCC5 (excluding those 12 that have three plus or three minus outputs Z). The multiple-output current follower (MO-CF) [53] can be also realized by the UCC when only current input X and all four current outputs Z are used, while voltage inputs are connected to the ground. Implementation of the balanced-output operational transconductance amplifier (BOTA) using UCC is another option [54]. In this case, voltage inputs Y_1 and Y_2) are used and admittance G_K is connected to current input X in order to represent transconductance g_m. Terminals Z_{1+} and Z_{1-} are used as current outputs.

III. GENERAL VIEW ON CM FOAPFS AND DERIVED CIRCUITS

The proposed general CM FOAPF using two GCC5s, grounded resistor, and grounded fractional-order capacitor (FoC) [5], [12], [55] with pseudo-capacitance C_α ($0 < \alpha < 1$) of impedance $Z_{C_\alpha}(s) = 1/C_\alpha s^\alpha$ is shown in Fig. 3.

Routine analysis yields to current transfer functions (TFs) that can be expressed in following general forms:

$$
T_1(s) = \frac{I_{o1}}{I_{in}} = \frac{a_2 d_{23} s^\alpha C_\alpha + a_1 d_{12} G}{a_2 s^\alpha C_\alpha (b_2 + d_{21}) + a_1 G (b_1 + d_{11})} =
$$
$$
= \frac{a_2 d_{23} s^\alpha C_\alpha R + a_1 d_{12}}{a_2 s^\alpha C_\alpha R (b_2 + d_{21}) + a_1 (b_1 + d_{11})}, \tag{3}
$$

$$
T_2(s) = \frac{I_{o2}}{I_{in}} = \frac{a_2 d_{22} s^\alpha C_\alpha + a_1 d_{13} G}{a_2 s^\alpha C_\alpha (b_2 + d_{21}) + a_1 G (b_1 + d_{11})} =
$$
$$
= \frac{a_2 d_{22} s^\alpha C_\alpha R + a_1 d_{13}}{a_2 s^\alpha C_\alpha R (b_2 + d_{21}) + a_1 (b_1 + d_{11})}. \tag{4}
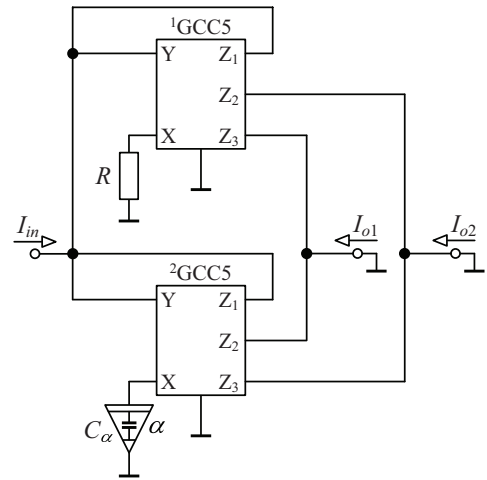$$

Fig. 3. Proposed general current-mode all-pass filter

Fig. 2. Schematic symbol of universal current conveyor

TABLE I
CONVEYANCE COEFFICIENTS OF GCC5s

Variant no.	^{1}GCC5				^{2}GCC5			
	a_1	d_{11}	d_{12}	d_{13}	a_2	d_{21}	d_{22}	d_{23}
#1	1	1	1	–1	1	1	1	–1
#2	1	1	1	–1	–1	–1	–1	1
#3	1	–1	–1	1	1	–1	–1	1
#4	1	–1	–1	1	–1	1	1	–1
#5	–1	1	1	–1	1	–1	–1	1
#6	–1	1	1	–1	–1	1	1	–1
#7	–1	–1	–1	1	1	1	1	–1
#8	–1	–1	–1	1	–1	–1	–1	1

To obtain an inverting and a non-inverting all-pass filter in the same configuration the following conditions must be fulfilled in (3) and (4):

$$b_1 = b_2 = 0, \tag{5}$$

$$a_1 a_2 d_{11} d_{21} = 1, \qquad d_{21} d_{22} = 1, \qquad d_{21} d_{23} = -1, \tag{6}$$

$$d_{11} d_{12} = 1, \qquad d_{11} d_{13} = -1. \tag{7}$$

From (5) it is evident that in this work only the second-generation CCs are considered. Eight different variants satisfy conditions (5)–(7) and conveyance coefficients of GCC5s are given in Table III. In all eight cases both inverting (3) and non-inverting (4) CM APFs can be realized with the same circuit topology.

IV. THE DESIGN EXAMPLE AND ITS CONCEPTUAL VERIFICATION

The variant #7 using ideal UCCs ($\beta_k = 1$ and $\alpha_j = 1$ for $k = 1, 2, 3$ and $j = 1, 2, 3, 4$) is shown in Fig. 4. Current TFs of the circuit are given as follows:

$$T_1(s) = \frac{I_{o1}}{I_{in}} = -\frac{s^\alpha C_\alpha - G}{s^\alpha C_\alpha + G} = -\frac{s^\alpha C_\alpha R - 1}{s^\alpha C_\alpha R + 1}, \tag{8}$$

$$T_2(s) = \frac{I_{o2}}{I_{in}} = \frac{s^\alpha C_\alpha - G}{s^\alpha C_\alpha + G} = \frac{s^\alpha C_\alpha R - 1}{s^\alpha C_\alpha R + 1}. \tag{9}$$

As it is seen from these equations, both inverting (8) and non-inverting (9) types of CM FOAPF can be realized with the same circuit topology. The magnitude characteristic of both type CM FOAPFs can be expressed after replacing the s^α by $\omega^\alpha [\cos\left(\frac{\alpha\pi}{2}\right) + j \sin\left(\frac{\alpha\pi}{2}\right)]$ as:

$$|T_1(j\omega)| = |T_2(j\omega)| =$$
$$= \sqrt{\frac{\omega^{2\alpha} C_\alpha{}^2 R^2 - 2C_\alpha R\omega^\alpha \cos\left(\frac{\alpha\pi}{2}\right) + 1}{\omega^{2\alpha} C_\alpha{}^2 R^2 + 2C_\alpha R\omega^\alpha \cos\left(\frac{\alpha\pi}{2}\right) + 1}}, \tag{10}$$

while the phase responses of the filter are given as:

$$\angle T_1(j\omega) =$$
$$= \angle \frac{\left[1 - C_\alpha R\omega^\alpha \cos\left(\frac{\alpha\pi}{2}\right)\right] + jC_\alpha R\omega^\alpha \sin\left(\frac{\alpha\pi}{2}\right)}{\left[1 + C_\alpha R\omega^\alpha \cos\left(\frac{\alpha\pi}{2}\right)\right] + jC_\alpha R\omega^\alpha \sin\left(\frac{\alpha\pi}{2}\right)}, \tag{11}$$
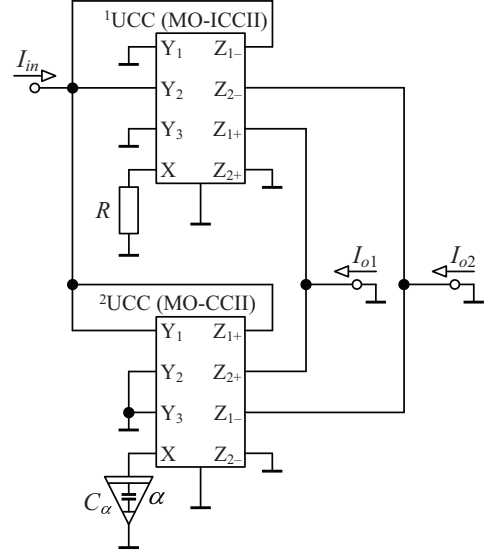

Fig. 4. Proposed inverting and non-inverting current-mode APF using UCCs: variant #7

$$\angle T_2(j\omega) =$$
$$= \angle \frac{\left[C_\alpha R\omega^\alpha \cos\left(\frac{\alpha\pi}{2}\right) - 1\right] + jC_\alpha R\omega^\alpha \sin\left(\frac{\alpha\pi}{2}\right)}{\left[C_\alpha R\omega^\alpha \cos\left(\frac{\alpha\pi}{2}\right) + 1\right] + jC_\alpha R\omega^\alpha \sin\left(\frac{\alpha\pi}{2}\right)}. \tag{12}$$

Hence, the phase (11) and (12) of current TFs alter from $0°$ to $-180°$ and $180°$ to $0°$, respectively, while ω changes from $0 \rightarrow \infty$. Finally, the resulting pole ($\omega_{p,\alpha}$) and zero ($\omega_{z,\alpha}$) frequencies are evaluated. The resulted expressions are:

$$\omega_{p,\alpha} = \left\{ \frac{\left[-\cos\left(\frac{\alpha\pi}{2}\right) - \sqrt{\cos\left(\frac{\alpha\pi}{2}\right)^2 - 1}\right]}{C_\alpha R} \right\}^{\alpha^{-1}}, \tag{13}$$

$$\omega_{z,\alpha} = \left\{ \frac{\left[\cos\left(\frac{\alpha\pi}{2}\right) - \sqrt{\cos\left(\frac{\alpha\pi}{2}\right)^2 - 1}\right]}{C_\alpha R} \right\}^{\alpha^{-1}}. \tag{14}$$

To verify the theoretical study, the proposed all-pass filter has been numerically validated. From above analysis it is evident that first-order APF exists only at $\alpha = 1$. However, both magnitude and phase responses are dependent on value of α. MAPLE plot given in Fig. 5(a) shows the effect of FoC order in range $\alpha = \{0 \text{ to } 1\}$ on magnitude responses of the filter. Subsequently, the effect of $\alpha = \{0.25, 0.5, 0.75\}$ of FoC (that having the same impedance @$f_{p,z} = 1$ MHz and $\mp 90°$ phase shifts) on phase responses vs. first-order responses are depicted in Fig. 5(b). Here, resistor and capacitor values used are as follows $R = 10$ kΩ, $C_{0.25} = 2$ μF $\cdot$ sec$^{-0.75}$, $C_{0.5} = 39.9$ nF $\cdot$ sec$^{-0.5}$, $C_{0.75} = 796.1$ pF $\cdot$ sec$^{-0.25}$, and $C_1 = 15.9$ pF, respectively.
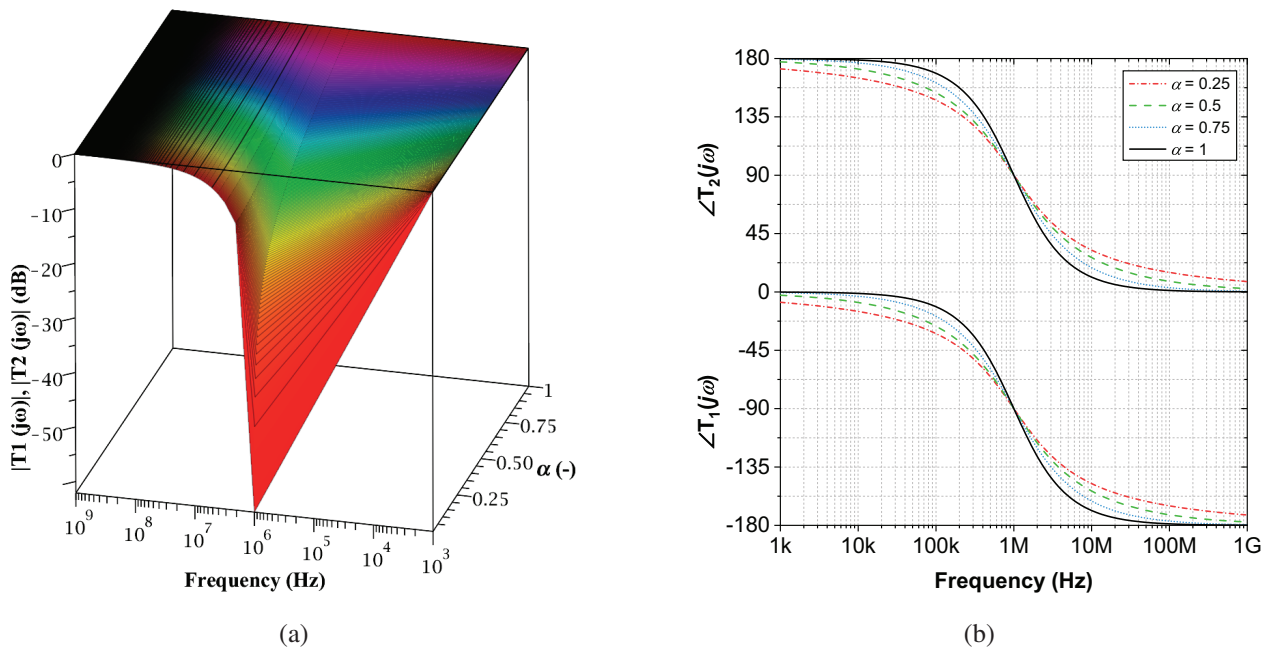
(a)

(b)

Fig. 5. FOAPF (a) magnitude and (b) phase responses for different α.

V. CONCLUSION

The paper presents a general design of CM FOAPFs using GCC5s. The circuit topology is versatile and a total of eight variants have been derived from the general topology; all of which are capable of simultaneously realizing both inverting and non-inverting all-pass filtering functions. The variant #1 is same as that in [4]. Considering only ICCII-based topologies (variants #6 and #8) our literature survey has showed that no such CM APF exists in the open literature. A theoretical study of the selected variant #7 created using universal current conveyors has been included to verify its concept. It is expected that the used general design methodology is of wider use to the circuit designers and researchers in the field and such a technique is further used for designs of biquad filters and sinusoidal oscillators. Future works will be focused on following this direction.

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