

Direct Interconnection of Ports in Modern Functional Blocks Based on Current Conveyor and CCTA for Circuit Design

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Abstract—The paper deals with modern functional blocks based on current conveyors and their utilization in analogue signal processing. Multi-port elements with directly interconnected ports (terminals) are the main topic of our discussion. Interconnections of ports in frame of complicated active element or functional block allow functional transformation to simpler block than primary selected one where additional useful transfer or port features are available. Known circuits can be modified to obtain interesting features or it is possible to create completely new circuits by using of standards synthesis. New functional blocks suitable for circuit synthesis are obtained in this way, namely k-class conveyors, frequency dependent current amplifiers and grounded impedance converters and inverters. The main focus is on a novel current conveyor transconductance amplifier (CCTA) and its possibilities to construct the functional blocks and applications discussed. No special view on circuit principles concerning mainly CCTA with interconnected ports was explained in the past, although more complicated applications of CCTA have been developed by using different and not very designer-friendly principles. Applications of these blocks in filters and oscillators are also given. An analysis of selected oscillator was supported by simulations.

Index Terms—Analogue signal processing, current conveyor transconductance amplifier, electronic control, impedance converter and inverter.

I. INTRODUCTION

The main purpose of this article is to show the variety of meaningful opportunities to interconnect directly the terminals of modern multi-port functional blocks (FBs), based on classical current conveyors (CCs), and thus obtain another FB, suitable for the synthesis of a given circuit.

Recall that the first such interconnection is well known as the operational amplifier (OA), where by connecting the output to the inverting input the voltage follower is obtained. Far more of these options are given by the multi-port FBs especially by the CCs.

Continuous-time analogue circuits based on these FBs attract considerable attention today. Many convenient applications in signal processing have been given especially in filters and oscillators, as one can see in [1], [2] and others. This comes from inherent advantages of the CC, namely simple circuitry, operating in the current mode (CM) [1] and with a higher frequency range than classical OA [3].

Since the introduction of the standard 3-port CC by Smith and Sedra [4] (titled CCII) a lot of multi-port CCs have appeared (briefly mentioned as: CCII+/-, DVCC, DDCC, FDCC, UCC etc. [2], [5], [6]). Furthermore, the classical CCs have been ingeniously supplemented with other sub-blocks such as voltage follower (VF), current follower and/or transconductor (OTA) to obtain new FBs [5]–[13]. A combination of the CC and the VF is known as the current feedback OA (CFOA) [3], [5]. Very attractive is the novel current conveyor transconductance amplifier (CCTA) [8]–[13], which is given due attention.

All FBs given above allow a certain interconnection of some ports (often e.g. Y-Z) to obtain a new FB. This will be discussed in this paper in detail. Recently a number of new applications using this principle have appeared [10]–[13], although the authors do not even know about it (from the practical point of view). Therefore we give our attention to the study of its utilization and explanation of blocks which are established by interconnecting available ports.

Direct interconnection of ports leads to a synthesis of impedance converters in most cases. Approaches to the design of negative impedance converters were investigated in the past. For example, Toumazou et al. [14] introduced a generalized impedance converter (GIC), which was also suitable for floating applications. However, GIC was based on OA and the solution was quite complicated and without any possibilities of electronic control. A negative impedance converter (NIC) is frequently required for the application of active elements. The idea of utilizing NIC with OA in

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applications was widely investigated by Martin and Sedra [15], for example. Nevertheless, NICs utilized many passive elements and non-adjustable active elements in the past. Soliman et al. proposed NIC structures [16] and L-C converters (mutators) [17], [18] employing also CCs. His work is focused directly on the design of NIC blocks with basic CCs (CCII+/-) using nodal admittance matrix methods. However, many presented solutions require at least two active and at least 2-3 passive elements (also floating) [19], similarly in [20]. A more comfortable solution with two intentionally grounded impedances and two CCs was introduced in [21]. Controllable versions of NIC were presented in [22], for example. However, their complexity (number of active and passive elements) is high.

Modifications of CCs are frequently used also in other interesting applications (not only NIC). We can mention, for example, Godara et al. [23], where a similar conception of CC was used to develop a wideband matching block and similar applications resulting from recently reported works. Multi-terminal feedback can be used in synthesis of special current conveyor based current-mode filters as also shown Lakys et al. [24], but this synthesis is not directly based on circuit implementation of current conveyor as NIC.

The main benefits of the approaches discussed are:

- 1) Understandable design of applications with prepared FBs. The most frequently used classical approaches enter into the synthesis procedure with active and passive elements only (state variable methods, autonomous circuit with general admittances, for example), not very often with FBs.;
- 2) CCTA allows the construction of more advanced feedbacks (interconnections) than simple active elements discussed in many old and current papers [14]–[22] and offer interesting constructions of FBs.;
- 3) Low number of passive elements.;
- 4) Passive elements are grounded in most cases.;
- 5) Electronic control of parameters of blocks and their further applications.;
- 6) Very simple usability in existing applications (especially in active filters and oscillators).

Important note: We used a different terminology that should avoid some obfuscation in the notation of the active elements discussed. It was the reason for new the terminology, classification and definition of the CCs that were given in [25]. The number of ports is a basic criterion for CC description. Furthermore, new terms of the CCs were defined in [25], namely the order, kind and class. The classical standard conveyors (briefly labelled by the symbol CC-0C) are first order (one input current port X), zero class (no current is conveyed into voltage ports Y) and of several kinds, which is given by the number of voltage ports Y. Note that in the literature the CC-0C is often titled incorrectly as second-generation CC (briefly CCII). Such a 3-port CC-0C is commercially available as the first part (input sub-block) of the AD844.

II. EXAMPLES OF BLOCKS WITH INTERCONNECTED PORTS EMPLOYING CURRENT CONVEYORS

A. Immittance converters created from the current conveyor with interconnected Y-Z ports

A unique application of the CC-0C can be obtained, if the terminals Y and Z are connected together as shown in Fig. 1. This circuit represents the negative immittance converter (NIC) with unity transfer coefficient (UNIC), where it holds $Z_{inp} = -Z_L$. Like this UNIC, the CC can be ingeniously used as discussed in [2], [26], for example. However, let us look at this Y-Z interconnection from another point of view.

As mentioned above, the classical conveyor is zero-class CC-0C, where all currents $I_Y = 0$. However, a different block is required in some applications, namely k -class CC- k C, where, conversely, $I_Y \neq 0$, i.e. some auxiliary current flows into the voltage port Y. Such a simple FB is given in Fig. 2, namely it is a 3-port 1st-order 1st-class CC. Note that the auxiliary current I_Y (and the class of CC) is denoted by a small triangle on the port Y (with appropriate orientation) similar to the other current outputs (I_X, I_Z). However, this CC-1C can be obtained from the standard 0-class 4-port conveyor (CC-0C), interconnecting ports Y-Z as shown also in Fig. 2. This idea can be generalized to several multi-port CC and the following lemma can be defined.

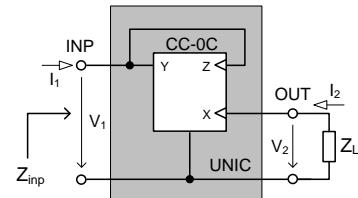


Fig. 1. Negative impedance converter from the standard 3-port 0-class conveyor.

Lemma. The k -class n -port CC can be ingeniously replaced (simulated) by 0-class CC-0C containing $(n+k)$ ports and interconnecting the ports Y with adequate Z.

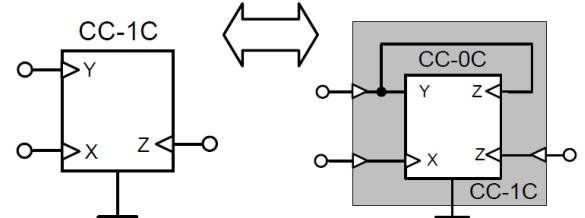


Fig. 2. Three-port 1st-class current conveyor CC-1C based on 4-port 0-class CC-0C.

The interconnection of Y-Z ports is well-known [2]. Some similarity to Fig. 1 exists also in [17] (Fig. 9), where such an interconnection was used but with two CCs and a floating impedance. However, the following principles are not so evident and are not employed.

The other, a little complicated example, is shown in Fig. 3. The 2nd-class 4-port (2nd-kind, 1st-order) CC-2C in Fig. 3 is simulated by 6-port CC-0C, with directly interconnected corresponding ports Y-Z. By the way, the above discussed types of the k -class n -port conveyors can be also obtained.

B. Applications of the approaches discussed

1) Notch filter based on a single negative converter

High-order Cauer filters can be realized by a cascade of notch biquads with transmission zeros at real frequency. This building block realizes the second-order transfer

function with two poles located at frequency f_p with quality factor Q_p and two zeros located at f_N , with Q_N . Usually the zeros are on the imaginary axis $j\omega$ with the $Q_N \rightarrow \infty$.

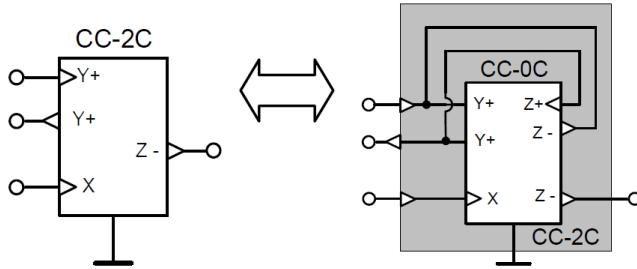


Fig. 3. Simulation of the 4-port 2nd-class current conveyor CC-2C by the 6-port 0-class conveyor CC-0C.

This notch biquad can be realized by a single UNIC implemented with the classical CC-0C as shown in Fig. 4. The condition $R_1 = R_2 = R = 1/G$ must be valid for infinite quality Q_N of the zeros.

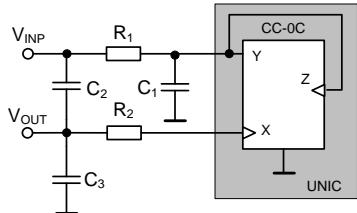


Fig. 4. Second-order notch filter based on the unity negative impedance converter.

The voltage transfer function of the notch biquad (LPN or BR) has the form

$$H_V(s) = \frac{V_{OUT}}{V_{INP}} = \frac{s^2 C_1 C_2 + G^2}{s^2 C_1 (C_2 + C_3) + s C_1 G + G^2}. \quad (1)$$

The frequency of the poles ω_p or the cut-off frequency (2) and the quality factor of the poles Q_p (3) can be derived in the following forms:

$$\omega_p = \frac{1}{R} \sqrt{\frac{1}{C_1(C_2 + C_3)}}, \quad (2)$$

$$Q_p = \sqrt{\frac{C_2 + C_3}{C_1}}. \quad (3)$$

Similarly, the parameters of the zeros are given from the numerator of (1) as:

$$\omega_N = \frac{1}{R} \sqrt{\frac{1}{C_1 C_2}}, \quad (4)$$

$$Q_N \rightarrow \infty. \quad (5)$$

Equations (2)–(5) can be used to design this low-pass notch biquad. The circuit in Fig. 4 represents the band-reject filter in the case of omitted C_3 ($C_3 = 0$), where:

$$f_{BR} = f_N = f_p, \quad (6)$$

$$Q_N \rightarrow \infty \quad (7)$$

and Q_p is proportional to the capacitor spread C_2/C_1 only. But there the quality factor Q_p cannot be adjusted without affecting the frequency f_p .

High-pass second-order notch filter is dual to this circuit (Fig. 4) and can be obtained by interchanging the components $R \leftrightarrow C$. Similar filters based on one and two conveyors are given in [26].

2) Oscillator employing second-class conveyor

An oscillator with 2nd-class 2nd-kind 4-port conveyor (CC-2C) and four grounded passive elements (R, C) has been designed, using the special procedure given in [27]. In this procedure the CC-2C can be ingeniously replaced by 6-port CC-0C (Fig. 3) to obtain the circuit in Fig. 5.

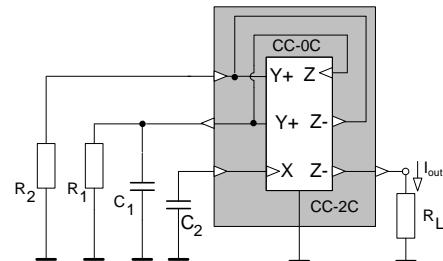


Fig. 5. Oscillator based on the 2nd-class 4-port current conveyor CC-2C and four grounded passive elements.

A straightforward symbolic analysis of this circuit (Fig. 5) provided the characteristic equation in the form

$$C_1 C_2 s^2 + s [C_1 G_2 + C_2 (G_1 - G_2)] + G_1 G_2 = 0. \quad (8)$$

We can determine the design equations, namely the oscillation condition (9) and the formula for the frequency of oscillation (10):

$$G_1 = G_2 \left(1 - \frac{C_1}{C_2}\right), \quad (9)$$

$$\omega_o = \sqrt{\frac{G_1 G_2}{C_1 C_2}}. \quad (10)$$

III. PROPOSED BLOCKS WITH INTERCONNECTED PORTS EMPLOYING CCTA

As it was mentioned above, the CCTA is a very attractive active element. The CCTA [5], [8]–[10] is based on the cascade connection of the standard n -port CC (zero-class, first-order, with one or more different outputs $\pm Z$) and standard OTA (with one or more different outputs $\pm O$). The symbol of CCTA can be seen in Fig. 6–Fig. 10. The ideal CCTA is described by the following set of definition equations:

$$I_Y = 0, \quad (11)$$

$$I_{Z\pm} = \pm B I_X, \quad (12)$$

$$I_{O\pm} = \mp g_m V_Z, \quad (13)$$

$$V_X = V_Y, \quad (14)$$

$$V_Z = -I_Z \cdot Z_Z, \quad (15)$$

where g_m is the transconductance, and B is the current gain,

which in the standard CCTA [5], [8], [9] has the value $B = 1$.

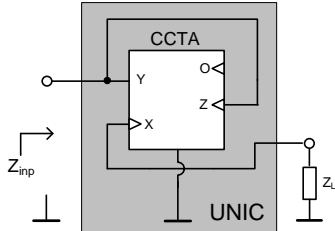


Fig. 6. Unity negative impedance converter from the CCTA.

Furthermore, the practical CCTA has a finite input resistance R_x at the current port X as indicated in Fig. 7, then the voltage

$$V_X = V_Y + I_X \cdot R_X. \quad (16)$$

Several approaches to electronic control of applications with the CCTA have been widely discussed in the literature, e.g. [10], [11]. The modified CCCCTA [10] allows the control of intrinsic resistance R_x by DC bias current. The transconductance g_m is also very favourable for control purposes as was shown in [11]. A modification with the controlled current gain B was given in [12] and labelled CGCCTA.

A. Immittance converters created from the CCTA with interconnected ports

The CCTA seems to be convenient for direct interconnection of the ports Y-Z (Fig. 6) as was discussed in connection with the CC (Fig. 1) to obtain the auxiliary current at the port Y ($I_Y \neq 0$) and the CCTA can implement the UNIC. Nevertheless, other direct interconnections of other ports can be also meaningfully used to obtain another suitable FB (a positive impedance inverter (PII) or a gyrator). The first attractive example is shown in Fig. 7, where the ports Y and O(+) are connected together.

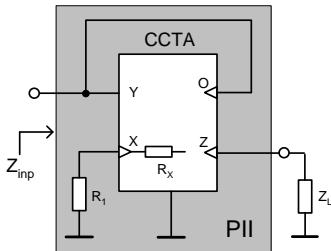


Fig. 7. Positive impedance inverter from the CCTA.

The input impedance of the PII has the form (R_x and g_m of the real CCTA were taken into account)

$$Z_{inp} = \frac{R_1 + R_X}{g_m} \frac{1}{Z_L} = k \frac{1}{Z_L}. \quad (17)$$

The circuit in Fig. 7 can operate even when $R_1 = 0$ (port X is shorted). A loading capacitor with impedance $Z_L = 1/sC$ allows obtaining a grounded synthetic inductor with the inductance

$$L_{eq} = \frac{R_1 + R_X}{g_m} C. \quad (18)$$

The inductance can be electronically adjusted by bias control currents I_{SET} changing R_x or g_m .

B. Frequency dependent current amplifier using CCTA

The other appropriate direct interconnection of the ports of the CCTA, namely the ports X and O(-), is used in the circuit given in Fig. 8 and the following current transfer function is obtained

$$H_I(s) = \frac{I_2}{I_1} = \frac{1}{1 + g_m Z_2 + \frac{R_X}{Z_1}}. \quad (19)$$

The circuit represents a current amplifier with frequency dependent gain or a filter operating in CM. If both of the impedances (Z_1, Z_2) are the capacitors (C_1, C_2), the circuit in Fig. 8 creates a band-pass second-order filter in CM with the transfer function

$$H_I(s) = \frac{I_2}{I_1} = \frac{s C_2}{s^2 + s \frac{1}{C_1 R_X} + \frac{g_m}{C_1 C_2 R_X}}. \quad (20)$$

The pole frequency (21) and the quality factor (22) can be expressed as:

$$\omega_p = \sqrt{\frac{g_m}{C_1 C_2 R_X}}, \quad (21)$$

$$Q = \sqrt{\frac{C_1}{C_2} g_m R_X}. \quad (22)$$

This filter is electronically controllable by I_{SET} , changing R_x and g_m (with their ratio remaining the same).

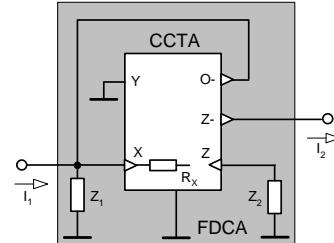


Fig. 8. Frequency dependent current amplifier using CCTA.

The second and simpler frequency dependent current amplifier is shown in Fig. 9. We used a different interconnection of the ports (Z and O(+)), and an analysis yields the following transfer function

$$H_I(s) = \frac{I_2}{I_1} = \frac{g_m}{g_m + Z^{-1}}. \quad (23)$$

The replacement of impedance Z (in Fig. 9) by capacitor C creates a lossy integrator operating in the CM with the current transfer function

$$H_I(s) = \frac{I_2}{I_1} = \frac{1}{1 + s\tau} = \frac{1}{1 + sCg_m^{-1}}. \quad (24)$$

A similar integrator is obtained if the impedance Z

(Fig. 9) is created by a parallel connection of R and C . Then the current transfer function is

$$H_I(s) = \frac{I_2}{I_1} = \frac{g_m}{g_m + sC + R^{-1}}. \quad (25)$$

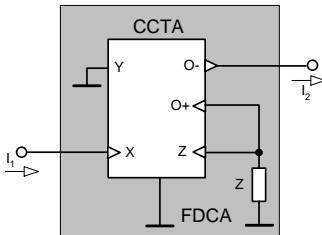


Fig. 9. Second version of simpler frequency dependent current amplifier using CCTA.

C. Application example of proposed approaches - simple quadrature oscillator

General approaches to design of second-order active filters or oscillators suppose general form of characteristic equation [27]. Suitable autonomous circuit structure (general admittances and active element(s)) selection is key action in the first step of the design (the most known example of synthesis [27]). Characteristic equation ($\det\mathbf{Y} = 0$) with appropriate selection of passive elements (instead of general admittances \mathbf{Y}) or their combination and selection of parameters of active element(s) leads to specific circuit features. Linear member of the characteristic equation should be equal to 0 (infinity quality factor) in case of oscillator [27]. Our approach supposes existence of prepared building blocks (NICs, frequency dependent amplifiers and their direct implementation in applications).

An attractive example of the application was given in Fig. 10 and it illustrates the discussed interconnections in Fig. 9. The quadrature oscillator employs a single CCTA and four passive grounded elements (R , C), where two direct interconnections are used, namely of the ports $Y-O_1(-)$ and $Z-O_2(-)$.

This oscillator was proposed as two current transfer blocks connected in a loop. The first part is a lossless integrator, formed by the left part of this circuit (Fig. 10), namely C_1 , R_1 and sub-block Y-X-O₁. The second one is formed by C_2 , R_2 and sub-block X-Z-O₂ (right part). The oscillator utilizes frequency dependent amplifier (Fig. 9) that works as special lossy transfer function (integrator) with adjustable time constant (g_m). However, its input terminal Y is not grounded (as in Fig. 9) because internal part of the CCTA (current conveyor CC-OC) and additional output of the OTA section serves as loss-less integrator together with grounded capacitor C_1 . The relation between input terminals X and Y ($V_X = V_Y$) completes a positive feedback loop of this transfer (from OUT₁ to the Z terminal). The resistor R_1 connected to X terminal transfers voltage given by eq. $V_X = V_Y$ to current (the first part of the CCTA - Y, X serves as loss-less integrator). In fact, core of the oscillator is circuit in Fig. 9 (special lossy section) because partial subsection of the CCTA realizes special transfer (25), in current state (Fig. 10) as

$$H_2(s) = \frac{-g_m R_2}{sR_2C_2 - g_m R_2 + 1}. \quad (26)$$

This type of the transfer function is not easily available without special feedback interconnection (only different polarity of O terminals than in Fig. 9). The feedback loop is completed by lossless integrator with transfers function $H_1(s) = 1/sC_1R_1$. Specific appearance of R_2 gives very valuable feature for the design of the oscillator. If we evaluate closed loop transfer $H_1(s)H_2(s) = 1$, resistor R_2 disappear from term for oscillation frequency in characteristic equation. Therefore, special transfer function established by special CCTA interconnection (Fig. 9) is very suitable for the oscillator synthesis.

The characteristic equation, the oscillation condition and the oscillation frequency are as follows:

$$s^2 + \frac{1-g_m R_2}{R_2 C_2} s + \frac{g_m}{R_1 C_1 C_2} = 0, \quad (27)$$

$$g_m R_2 = 1, \quad (28)$$

$$\omega_0 = \sqrt{\frac{g_m}{R_1 C_1 C_2}}. \quad (29)$$

The sensitivity study indicates that this circuit exhibits a good sensitivity performance, because all sensitivities are low:

$$S_{R_2}^{\omega_0} = 0, \quad (30)$$

$$S_{g_m}^{\omega_0} = -S_{R_1}^{\omega_0} = -S_{C_1}^{\omega_0} - S_{C_2}^{\omega_0} = 0,5. \quad (31)$$

The oscillation frequency can be adjusted by R_1 , and R_2 allows controlling the oscillation condition without disturbing the frequency ω_0 . The oscillation frequency can be electronically adjusted by the bias (I_{SET}) control of R_x . A modification of this circuit (Fig. 10) using CGCCCTA is given in [12], where electronic adjustment is easy to perform by controlling the current gain B .

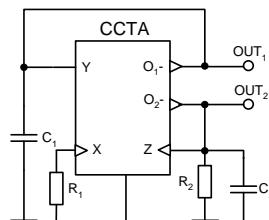


Fig. 10. Oscillator based on CCTA with interconnected ports.

IV. REALIZATION AND SIMULATION

An interesting oscillator given in Fig. 10 was chosen to evaluate the principles discussed above and to document the performance of the proposed circuits. From the experimental purpose point of view, the CCTA was built from commercially available integrated circuits, namely EL2082 [28] as a controllable CC and two OPA860 [29] as a multi-output transconductor. The passive components for our simulation were designed using equations (24), (25) and they

yield the following values: $C_1 = C_2 = 47 \text{ pF}$, $R_1 = 1005 \Omega$, i.e. 910Ω and plus intrinsic $R_x = 95 \Omega$. For good starting of the oscillation the resistance R_2 has a slightly higher value ($R_2 = 1050 \Omega$). The main parameter of the OPA860 is transconductance with the value $g_m = 1 \text{ mS}$. The current gain of the EL2082 must be $B = 1$ (it can be adjusted by an added DC voltage source). This voltage had the value 1 V in our case and the supply voltage was $V_{CC} = \pm 5 \text{ V}$.

The proposed oscillator was simulated using the PSpice program to obtain in steady-state two output voltage waveforms with quadrature form. The ideal theoretical value of the oscillation frequency is $f_{0I} = 3.378 \text{ MHz}$ (resulting from above given $R_1 = 1005 \Omega$, $C_1 = C_2 = 47 \text{ pF}$). Nevertheless, the non-idealities must be taken into account in real circuit, especially the parasitic C_p in high-impedance nodes caused by real active FBs. Then the expected values of the components are as follows: $C'_1 = 47 \text{ pF} + 4 \text{ pF}$ (2 pF at the terminal Y of EL2082 and 2 pF at the terminal C of OPA860) and $C'_2 = 47 \text{ pF} + 9 \text{ pF}$ (5 pF at the terminal Z of EL2082 and 2 pF + 2 pF at both terminals B of OPA860). The exact value of the transconductance is $g_m = 1/(R_{3,4} + R_e) = 1/(1k + 13) = 0.987 \text{ mS}$. Considering

these presumptive parameters the expected value of the oscillation frequency was $f_{0P} = 2.951 \text{ MHz}$. Simulation in PSpice provides (Fig. 11) a comparable exact value $f_{0E} = 2.817 \text{ MHz}$. The suppression of higher harmonic components is more than 45 dBc, which yields a THD value of about 0.7 %.

Independent controll of the oscillation frequency f_0 is documented in Fig. 12 (driving of R_1). A simulated frequency range of 898–3870 kHz was achieved, while the resistance value of the R_1 was changed from 400 Ω to 10 k Ω .

Admittedly, one drawback of the presented solution is the dependence of produced amplitude on the tuning process (driving R_1). For this purpose the following relation between both output amplitudes (outputs OUT₁, OUT₂) was derived

$$V_{OUT1} = -j \sqrt{\frac{g_m R_1 C_2}{C_1}} \cdot V_{OUT2}. \quad (32)$$

The voltage amplitude of V_{OUT2} is constant but V_{OUT1} changes its value while f_0 is being tuned (through R_1). This causes increasing the THD for higher values of R_1 , due to insufficient linear dynamical range of the active FBs.

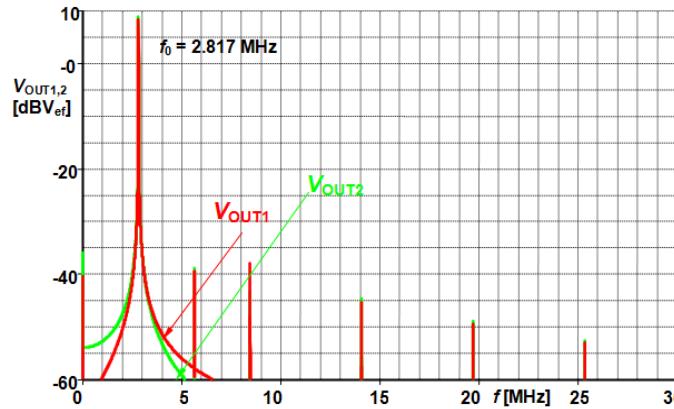


Fig. 11. Output FFT spectrum.

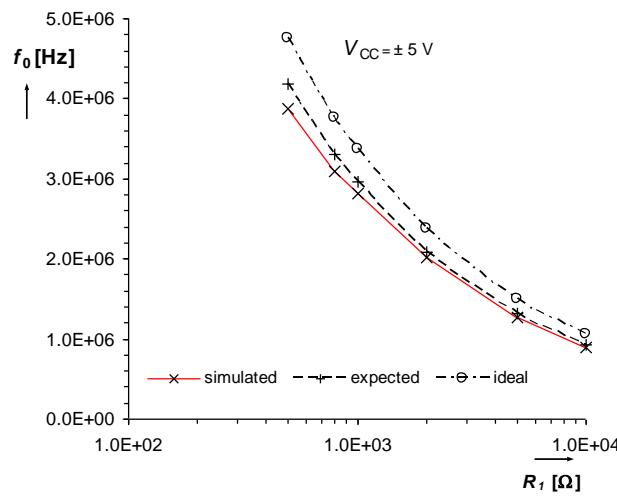


Fig. 12. Dependence of f_0 on R_1 .

V. CONCLUSIONS

When some terminals of modern blocks based on current conveyors (and similar elements like CCTA, CFOA and all types of CCs) are directly interconnected, new FBs

(impedance converters, invertors, etc.) are obtained, which can be ingeniously used in circuit synthesis. Some applications based on this interconnection have been found quite recently (for example [10]–[12]), although the authors do not even know about the principle discussed there. This

idea was also generalized to several multi-port CCs, where more interconnections of these ports Y-Z are possible. The new active element CCTA allows many interesting possibilities. The main novelty and contribution of this work is the proposal and explanation of novel FBs with CCTA based on interconnected ports. The FBs obtained are useful to synthesize some new applications in filters and oscillators especially. Theoretical presumptions were supported by a practical example and computer simulations.

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