Non-linear circuits with CCII+/- current conveyors

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Abstract. In the area of analog techniques and primary processing of analog signals in the last decade, some authors have focused on circuits with current or voltage conveyors. Most of them have concentrated on filters with current conveyors, their design and properties, different connections, sensitivity analysis, etc. The present paper is devoted to the basic theoretical description of non-linear circuits with CCII+/- current conveyors in non-filter applications. The basic connections of circuits with current conveyors are chosen, in which a non-linear three-pole is considered, and the functional relations of these connections are established. The applications of non-linear circuits given in the paper are half-wave and full-wave precise rectifiers, which are an analogy to precise measuring rectifiers with operational amplifiers. Rectifiers with current conveyors operating in the current mode can exhibit some positive properties. Only the basic connections are given and the basic functional computer simulations are made here. The active element chosen for the practical rectifier realization was an appropriately connected OTA amplifier. In conclusion, some measurement results are given.

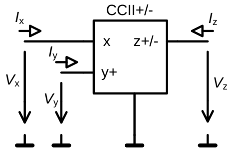
Keywords: current conveyor, non-linear circuits, rectifiers.

1 Introduction

CCII+/- conveyors are active elements that form a numerous group of functional blocks, which realize unit transfers of current and voltage (with either positive or negative polarity) between individual gates. The description of these elements is sufficiently known and can be found in many publications, for example in [1], [2]. Current conveyors enable the design of circuits operating in the voltage, current or hybrid mode. Fig. 1 gives a schematic symbol that describes the conveyor relations and its ideal model with controlled sources of a second-generation current conveyor (CCCS – Current-Controlled Current Source, VCVS – Voltage-Controlled Voltage Source).

The practical availability of these elements is currently poor; and in experimental work elements are utilized which include in their internal structure the CCII element in some form. These are, for example, the AD844 and OPA660 amplifiers. The following amplifiers can also be used: the MAX435 and MAX436 OTA and BOTA (Balanced Operational Transconductance Amplifier) amplifiers by Maxim [3], and the LM13600 amplifiers by National Semiconductor [4].

In the following, only the CCII+ element will be considered, for which the respective relations will be derived. For the other elements, the relations are similar. In the basic connections with CCII+ the relations between input and output signals are linear. Fig. 2 gives the basic connections that represent the non-inverting voltage amplifier, inverting voltage amplifier and inverting current amplifier. For simplification, we will consider the above amplifications to be ideal. In these basic connections the relations between input and output signals are linear.



$$V_{\mathrm{x}} = V_{\mathrm{y}}\,,\; I_{\mathrm{y}} = 0\;,\; I_{\mathrm{z}} = +/- I_{\mathrm{x}}$$

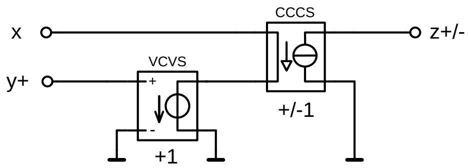
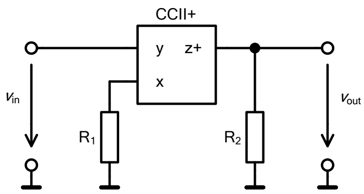
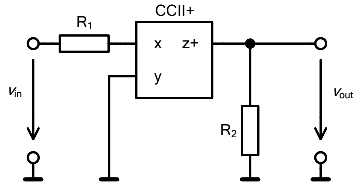


Fig. 1. Definition of CCII+/– current conveyor



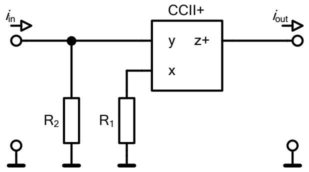
$$A_{\mathrm{V}} = \frac{R_2}{R_1}$$

a)



$$A_{\mathrm{V}} = -\frac{R_2}{R_1}$$

b)



$$A_{\mathrm{I}} = -\frac{R_2}{R_1}$$

c)

Fig. 2. Basic connections of amplifiers with current conveyors: a) non-inverting voltage amplifier, b) inverting voltage amplifier, c) inverting current amplifier

2 Non-linear amplifiers with CCII+ current conveyor

If instead of linear elements we use non-linear elements, the circuit amplification will be non-linear, and the dependence relation between the input and the output signal will be also non-linear.

In technical practice there are a number of non-linear elements controlled by an electric quantity, namely a voltage or a current. These elements thus have three or more poles by which they are connected into a circuit. When analyzing circuits with CCII+ we are interested not only in the output circuit of these elements but also in the input circuit where the control signal is acting, since the control signal source and the non-linear controlled element influence each other. From the basic connections with current conveyors given in Fig. 2 it follows almost immediately that the controlled non-linear element is a non-linear three-pole resistance.

Let us define a non-linear resistance three-pole by currents and voltages as given in Fig. 3. Between the currents i_A, i_B, and i_C flowing into the non-linear three-pole (NTP) and the voltages on three-pole terminals v_A, v_B, and v_C with respect to the common potential the following functional relations hold.

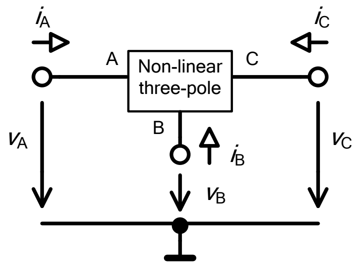


Fig. 3. Non-linear three-pole, designation and definition

$$i_A = r_A(v_A, v_B, v_C) \quad , \tag{2.1}$$

$$i_B = r_B(v_A, v_B, v_C) \quad , \tag{2.2}$$

$$i_C = r_C(v_A, v_B, v_C) \quad . \tag{2.3}$$

Since the three-pole can also be viewed as a node, Kirchhoff's law also holds,

$$i_A + i_B + i_C = 0 \quad . \tag{2.4}$$

The three-pole under consideration can also be described by the characteristics

$$v_A = g_A(i_A, i_B, i_C) \quad , \tag{2.5}$$

$$v_{\mathrm{B}} = g_{\mathrm{B}}(i_{\mathrm{A}}, i_{\mathrm{B}}, i_{\mathrm{C}}) \quad , \tag{2.6}$$

$$v_{\mathrm{C}} = g_{\mathrm{C}}(i_{\mathrm{A}}, i_{\mathrm{B}}, i_{\mathrm{C}}) \quad , \tag{2.7}$$

and the description by hybrid characteristics is also generally known. These characteristics can, for example, be in the form

$$i_{\mathrm{A}} = h_{\mathrm{A}}(v_{\mathrm{A}}, i_{\mathrm{B}}, v_{\mathrm{C}}) \quad , \tag{2.8}$$

$$v_{\mathrm{B}} = h_{\mathrm{B}}(v_{\mathrm{A}}, i_{\mathrm{B}}, v_{\mathrm{C}}) \quad , \tag{2.9}$$

$$i_{\mathrm{C}} = h_{\mathrm{C}}(v_{\mathrm{A}}, i_{\mathrm{B}}, v_{\mathrm{C}}) \quad . \tag{2.10}$$

If the resistance element in the above connections with current conveyors is replaced by a non-linear resistance three-pole from Fig. 3, a number of circuits will be obtained whose transfer characteristic will depend on the properties of this three-pole. When solving these circuits, it is necessary to know the appropriate characteristics describing the non-linear three-pole.

Connecting the non-linear three-pole in place of resistor R_1 in Fig. 2a) will yield the situation given in Fig. 4.

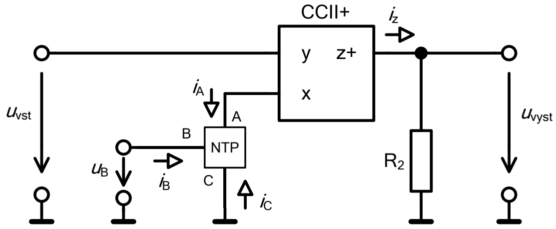


Fig. 4. Non-linear resistance three-pole in the input part of non-inverting amplifier with CCII+

If we consider the relations holding for the CCII+ current conveyor, then $v_{\mathrm{A}} = v_{\mathrm{in}}$, $i_{\mathrm{A}} = i_{\mathrm{x}}$, $i_{\mathrm{z}} = i_{\mathrm{x}}$, and $v_{\mathrm{out}} = v_{\mathrm{in}}R_2/R_1 = i_{\mathrm{A}}R_2 = i_{\mathrm{z}}R_2$; further we consider $v_{\mathrm{C}} = 0$. Then the relations describing the three-pole will be of the form

$$i_{\mathrm{A}} = r_{\mathrm{A}}(v_{\mathrm{A}}, v_{\mathrm{B}}) \quad , \tag{2.11}$$

$$i_{\mathrm{B}} = r_{\mathrm{B}}(v_{\mathrm{A}}, v_{\mathrm{B}}) \quad , \tag{2.12}$$

$$i_{\mathrm{C}} = r_{\mathrm{C}}(v_{\mathrm{A}}, v_{\mathrm{B}}) \quad . \tag{2.13}$$

It can be seen from Fig. 4 that there can be two cases of driving the circuit. The three-pole can be driven either by voltage or by current, and the input terminal “y” can only be driven by voltage since it is the voltage input that is concerned here. For the first case let us consider that ideal voltage sources are connected to the B terminal of the three-pole and the conveyor. In that case it is of advantage to start from the knowledge of the characteristic

$$i_{\mathrm{A}} = r_{\mathrm{A}}(v_{\mathrm{A}}, v_{\mathrm{B}}) \quad . \tag{2.14}$$

Then the amplifier output voltage is determined.

$$v_{\text{out}} = R_2 i_z = R_2 i_A = R_2 r_A(v_A, v_B) \quad . \tag{2.15}$$

Another possible case is that an ideal current source is connected to the B terminal of non-linear three-pole. In this case it is of greater advantage to exploit the hybrid characteristic of non-linear three-pole

$$i_A = h_A(v_A, i_B) \quad , \tag{2.16}$$

and, similarly, the amplifier output voltage will be

$$v_{\text{out}} = R_2 i_z = R_2 i_A = R_2 h_A(v_A, i_B) \quad . \tag{2.17}$$

It can be seen from the relations given above that the output voltage of the circuit under consideration depends directly on the respective characteristic of the non-linear three-pole.

Yet another connection of amplifier with current conveyor is the inverting voltage amplifier given in Fig. 2b). In the input circuit we replace the resistor R_1 as shown in Fig. 5. From the description of current conveyor it is evident that v_C = 0, and the description of NTP is again given by the relations (2.11), (2.12), (2.13) or by their hybrid equivalents.

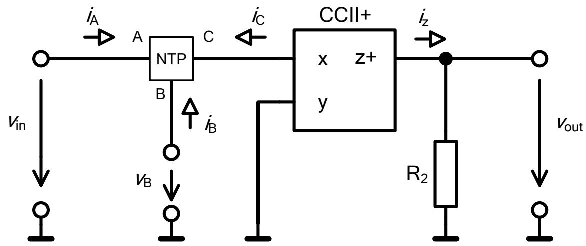


Fig. 5. Non-linear resistance three-pole in the "input circuit" of inverting amplifier

In this case there will be a total of four possible sources being connected to terminals A and B. It is understood that the sources are connected between the respective terminal and the common ground terminal.

A) Ideal voltage sources are connected to the A and B terminals. Then we start from the knowledge of the characteristic

$$i_C = r_C(v_A, v_B) \quad . \tag{2.18}$$

Then the amplifier output voltage is determined.

$$v_{\text{out}} = -R_2 i_z = -R_2 i_C = -R_2 r_C(v_A, v_B) \quad . \tag{2.19}$$

B) If a voltage source is connected to terminal A and a current source to terminal B, the tree-pole will be described using the hybrid characteristic

$$i_C = h_C(v_A, i_B) \quad , \tag{2.20}$$

and then the amplifier output voltage will be determined.

$$v_{out} = -R_2 i_z = -R_2 i_C = -R_2 h_C(v_A, i_B) \quad . \tag{2.21}$$

C) If a current source is connected to terminal A and a voltage source to terminal B, then the hybrid characteristic is

$$i_C = l_C(i_A, v_B) \quad , \tag{2.22}$$

and the amplifier output voltage is

$$v_{out} = -R_2 i_z = -R_2 i_C = -R_2 l_C(i_A, v_B) \quad . \tag{2.23}$$

D) In the case that the two sources are current sources, and if we consider the validity of Kirchhoff's law (2.4), then for the output voltage it holds

$$v_{out} = -R_2 i_z = -R_2 i_C = R_2 (i_A + i_B) \quad . \tag{2.24}$$

It follows from the above relations that in cases A), B), and C) the output voltage of the inverting amplifier under consideration depends directly on the non-linear three-pole characteristic. In case D) the output voltage does not depend on the three-pole properties. The operation described by relation (2.24) can be realized in a simpler way, without using the non-linear three-pole.

In the inverting current amplifier with current amplifier connected as in Fig. 2c) the non-linear three-pole replaces resistor R_2, as indicated in Fig. 6.

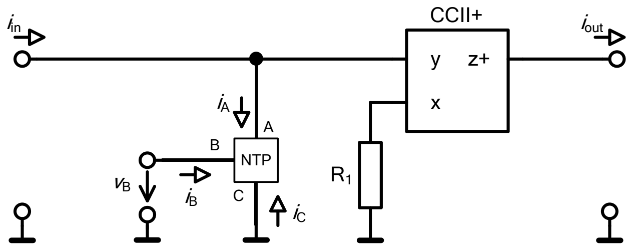


Fig. 6. Non-linear resistance three-pole in inverting current amplifier

Let us consider that an ideal voltage source is connected to the B terminal of the tree-pole and that the current $i_B = 0$. Then the characteristic of non-linear three-pole is

$$v_A = g_A(i_A, i_C) \quad , \tag{2.25}$$

and the output current of current amplifier will be determined as

$$i_{out} = -\frac{v_A}{R_1} = -\frac{g_A(i_A, i_C)}{R_1} \quad . \tag{2.26}$$

There is no use in considering a current source connected to terminal B, the reason being the same as in point D) of the preceding case.

Similar relations can also be found for CCII– current conveyors.

3 Application of circuits with non-linear current-conveyor amplifier

The following section focuses on selected applications of non-linear amplifiers using current conveyors. The processing of the positive and the negative part of the signal being amplified is separate, as made possible by complementary non-linear structures. The latter are the basis for creating rectifier circuits with conversion characteristics approximating ideal characteristics approximated by a broken line. These circuits are known as “operational rectifiers”, “absolute value rectifier”, etc. which have some importance in measuring techniques in particular. Use is made, above all, of high-precision half-wave or full-wave rectifiers, various kinds of clippers or function converters. The subject of the present paper is primarily half-wave and full-wave rectifiers.

3.1 Half-wave rectifier

The connection of fast inverting half-wave rectifier using a CCII- current conveyor is shown in Fig. 7. The output current i_z of the terminal “z” is given by the relation

$$i_Z = -\frac{u_{in}}{R_1} \quad , \tag{3.1}$$

and the rectifier output voltage is then given by the relation

$$v_{out} = i_Z \cdot R_2 = -\frac{R_2}{R_1} \cdot v_{in} \quad . \tag{3.2}$$

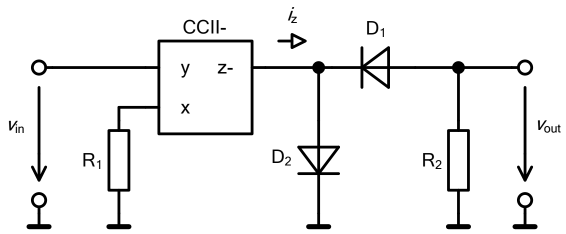


Fig. 7. Inverting half-wave rectifier with CCII–

The operation of half-wave rectifier was simulated by an idealized model of CCII– current conveyor. The voltage applied to the output was of sine waveform, amplitude v_{in} = 10 V, frequency f = 100 kHz, resistance values $R_1 = R_2 = 100\ \Omega$, with models of the Schottky diodes 1PS70SB40 being used. Results of the computer simulation are given in Fig. 8, it can be seen that the circuit implements the function of inverting half-wave rectifier.

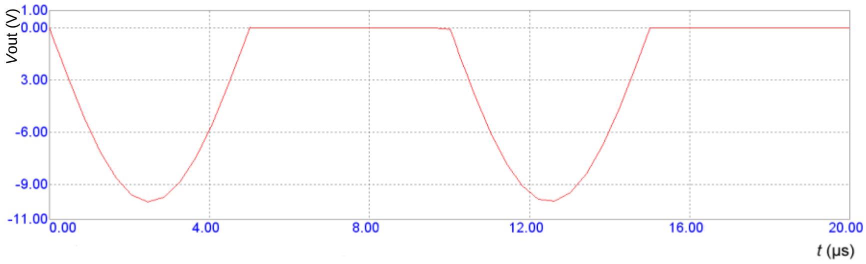


Fig. 8. Inverting half-wave rectifier with CCII–, $f = 100$ kHz

3.2 Full-wave rectifier

A full-wave rectifier with current conveyors is given in Fig 9 [5], [6]. The two CCII+ conveyors form a difference amplifier with current-to-voltage conversion on the output resistor R_2 such that with positive values of input signal the output current values are given by the relation

$$i_z = -\frac{v_{in}}{R_1} \quad . \tag{3.3}$$

The output current i_z flows from the output terminal "z" 1CCII+ through resistor R_2, which has the same value as R_1. Diodes D_4 and D_2 are on, and the voltage on the output is $v_{out} = v_{in}$.

With negative values of input signal, diodes D_3 and D_1 are on. The output current of ^{2}CCII+ conveyor flows again through resistor R_2 and it again holds $v_{out} = v_{in}$. The magnitude of voltage transfer is given by the resistance ratio R_2/R_1.

In the rectifier, the fast Schottky diodes are expected to be used in order to obtain a high operating frequency. Voltage V_x serves to suitably set the operating mode of the diodes.

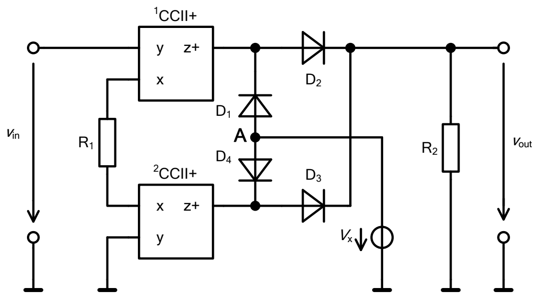
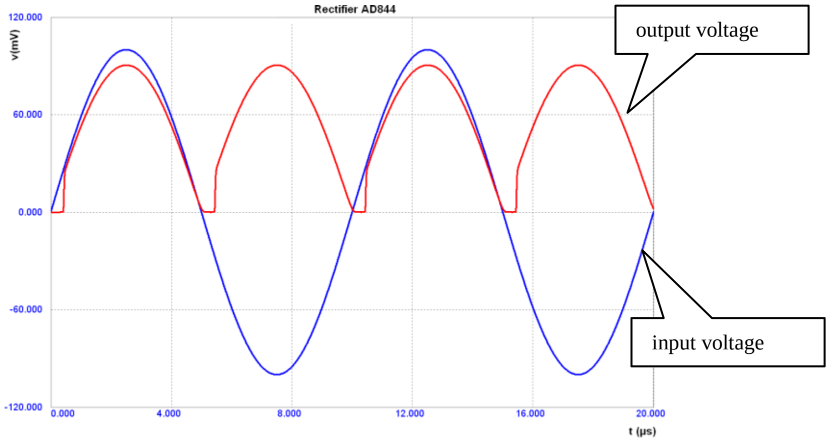
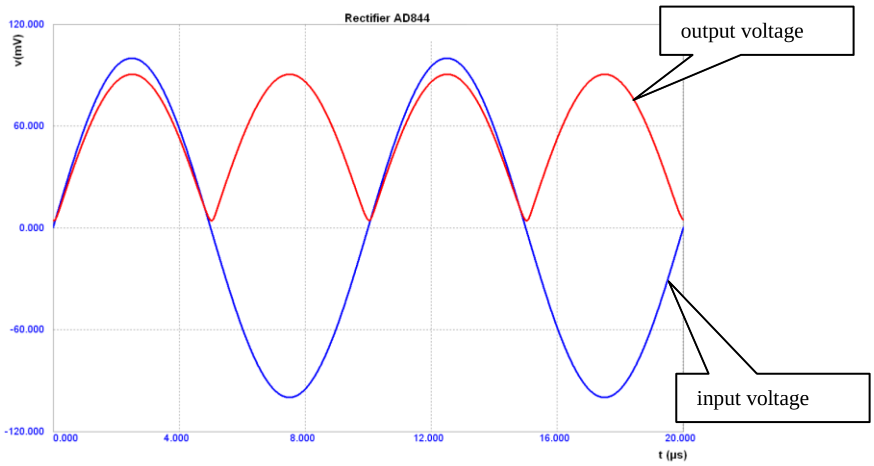


Fig. 9. Full-wave rectifier with CCII+

In the computer simulation of the above connection in the time domain the model of AD844 circuit was used, which is part of the Microcap program library. The diodes used were the Schottky diodes IPS70SB40, $R_1 = R_2 = 100$ kHz. The simulation was conducted for two voltages, $V_x = 0$ V, and $V_x = 1$ V, for the frequency $f = 100$ kHz, and a harmonic input signal amplitude of 100 mV. The simulation results are given in Fig. 10.



a)



b)

Fig. 10. Full-wave rectifier with CCII+, a) $f = 100$ kHz, $V_x = 0$ V, b) $f = 100$ kHz, $V_x = 1$ V

It is obvious from the simulation results that the magnitude of voltage V_x plays a role here. The negative effect of voltage V_x increases at higher frequencies. The voltage on the anodes of diodes D_1 and D_4, that is to say at point A, is influenced by the low impedance (in computer simulation it is zero) of the auxiliary source of voltage V_x while on the diodes there is a small voltage. When these diodes are subsequently connected to the terminal “z”, the output voltage is zero. The magnitude of auxiliary voltage needs to be made balanced depending on the input voltage decrease on the diodes.

4 Practical rectifier realization

The operation of rectifiers was tested experimentally. In the specimen realized, a MAX435 operational transconductance amplifier (OTA) was utilized. With this element, the transfer conductance depends on the control current by means of which the element conductance can be changed. In Fig. 11 the connection of rectifiers with a MAX435 circuit is shown. The setting of the transfer conductance is not critical and therefore it is not given in the schematic.

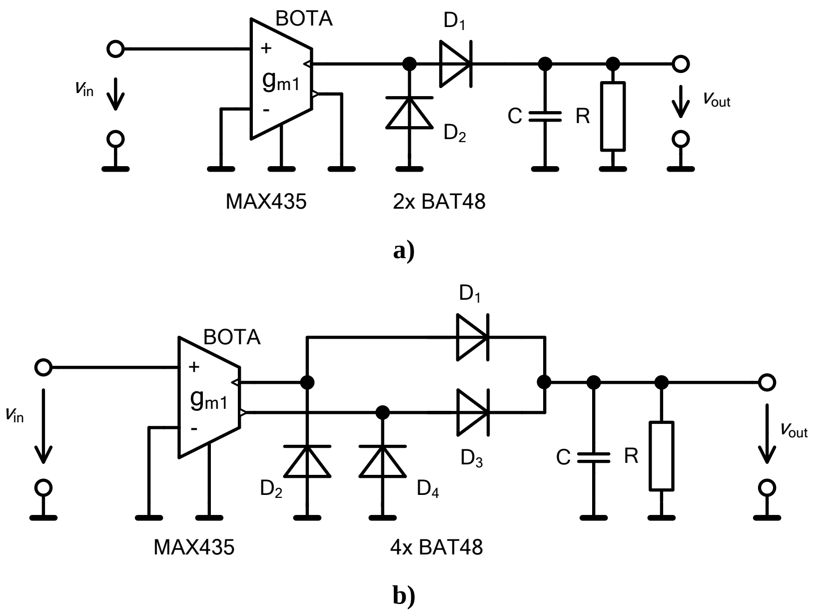


Fig. 11. Ideal connection of rectifiers for experimental verification, a) half-wave rectifier, b) full-wave rectifier

The waveforms measured for the half-wave rectifier are given in Fig. 12. The rectifier was measured at frequency of 5 MHz. The waveforms measured for the full-wave rectifier are similarly given in Fig. 13.

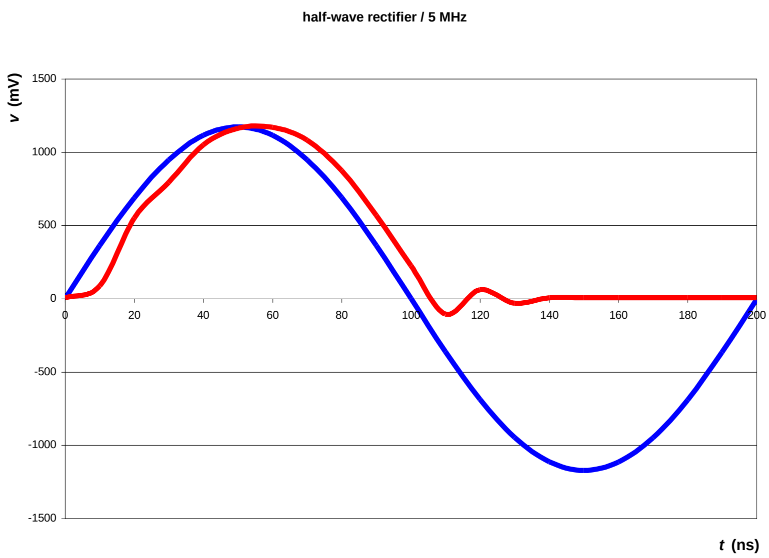


Fig. 12. Time behaviours measured for half-wave rectifier with OTA (MAX435), $f = 5$ MHz

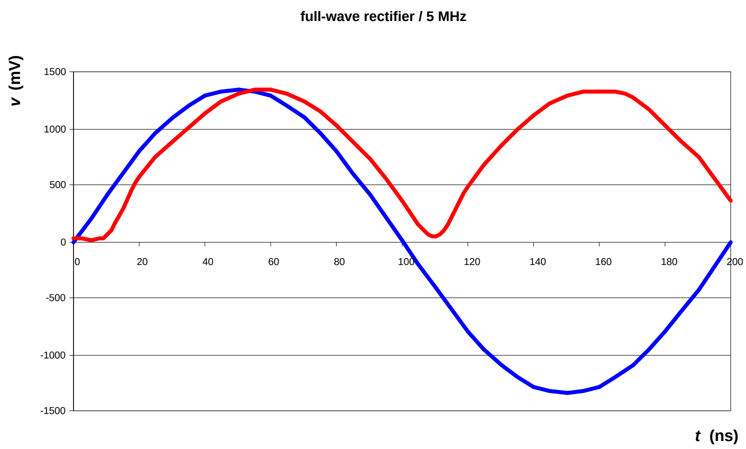


Fig. 13. Time behaviours measured for full-wave rectifier with OTA (MAX435) $f = 5$ MHz

5 Conclusion

The paper is focused on problems of non-linear elements in circuits with current conveyors. A non-linear three-pole is considered and the functional relations of selected basic connections are determined. The application of non-linear elements is verified on the connections of half-wave and full-wave rectifiers. Only the basic connections are given and the basic functional computer simulations are conducted. An experimental verification of the rectifiers was performed using an OTA element. The paper provides a theoretical foundation for the solution of non-linear circuits with current conveyors. The scope of the paper does not allow a more in-depth analysis of the rectifier solution. Practical measurements were only performed to verify the functionality of circuits. It will be necessary to focus on obtainable properties and to analyse also other circuit structures.

References

1. SEDRA, A., and SMITH, K.C. The current conveyor: A new circuit building block. Proc. IEEE, Vol.56, pp. 1368-1369, Aug. 1968.
2. SEDRA, A.S., and SMITH, K.C. A second generation current conveyor and its application. IEEE Trans., 1970, CT-17, pp. 132-134.
3. MAX435/MAX436 - Wideband Transconductance Amplifiers. Datasheet, Maxim, 1993. URL: http://pdfserv.maxim-ic.com/en/ds/MAX435-MAX436.pdf.
4. LM13600 - Dual Operational Transconductance Amplifiers with Linearizing Diodes and Buffers. Datasheet, National Semiconductor, 1998. URL:http://cache.national.com/ds/LM/LM13600.pdf.
5. GRIGORESCU, L. Precision rectifier. The annuals of Dunarea de Jos, 2003. University of Galati, pp. 55-57, URL http://thefibannals.home.ro/anale-fib-2003-16.pdf, ISSN 1224-5615.
6. BIOLEK, D., BIOLKOVÁ, V., KOLKA, Z. AC analysis of operational rectifiers via conventional circuit simulators. Brno, Fakulta elektrotechniky a komunikačních technologií VUT, 2004, URL http://user.unob.cz/biolek/veda/articles/Tenerife04.pdf.