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INVESTIGATION OF CIRCUIT IMPLEMENTATIONS OF C-NEGATRONS ON THE BASIS OF NEGATIVE-RESISTANCE CONVERTERS

The paper considers four basic circuits of C-negatrons on the basis of negative resistance converters built on operational amplifiers (Op-Amp). It is shown that when positive voltage feedback is used active C-negatron is realized and in the case of current positive feedback – a passive C-negatron is implemented. Circuits on the basis of U-IC converters have the highest maximal operating frequencies. An advantage of the C-negatron circuits built on Op-Amp is their simplicity, high accuracy, realization of the negative capacitance value, wide operation frequency range.

***Key words**: C-negatron, operational amplifier, converter, negative resistance.*

Introduction

A perspective way to increase the efficiency of modern electronic devices is application of the new element base, particularly, of C-negatrons – electronic devices that have negative differential capacitance value in a definite operation mode [1, 2].

Circuit implementations of C-negatrons are based on the impedance converters (IC) providing the required voltage-current shift and conversion of the load positive capacitance (inductance) into the negative input capacitance. Negative impedance converters are built on the active device – an amplifier covered by a positive feedback. Various active devices could be used as an amplifier in IC, however, operational amplifiers (Op-Amp) are universal and convenient devices that make it possible to build IC with parameters that do not depend on the transfer characteristic of active devices and are determined by the parameters of the feedback loop elements providing simplicity of circuit realization, wide operation frequency range from 0 to hundreds of MHz as the frequency of unity gain of modern high-speed Op-Amps reaches 1.5 GHz [3].

Fundamentals of building impedance converter based on Op-Amp are laid in the monographs of F. Bening [4], J. Marsha [5], I.M. Filanovskiy and others [6], where their own developments as well as those of other scholars are summarized and systemized. It should be noted that IC circuits based on Op-Amp make it possible to realize negative active resistance as well as negative capacitance and negative inductance, which will be determined only by the load impedance type. However, mathematical models of the realized negatrons will be different.

The goal of the research

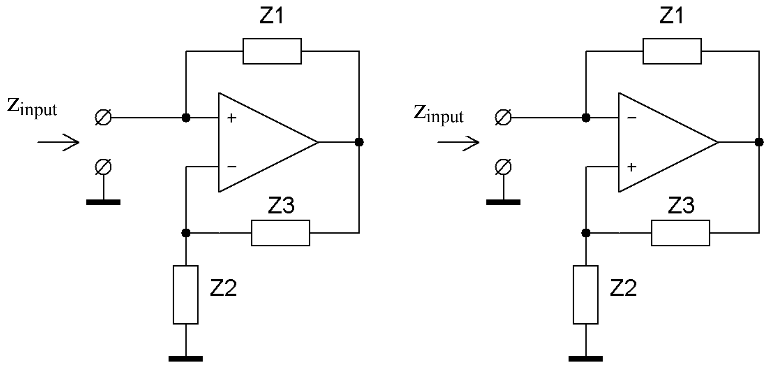
The goal of the research is elaboration of mathematical models and finding basic parameters of the circuit-engineering negatrons built on Op-Amps.

Theoretical substantiation of building C-negatrons on the basis of Op-Amp

Negative impedance converters are built on the active device – the amplifier covered by a negative feedback. In this case, if positive voltage feedback or parallel current feedback is used, negative resistance converters are realized for which negative input impedance Z_{input} is proportional to the load impedance Z_l If positive parallel voltage feedback or serial current feedback is used, inverters (gyrators) have negative resistance for which negative input impedance Z_{input} is inversely proportional to the load impedance Z_l [4].

Negative impedance converters are divided into the impedance converters that change the current direction (I-III) and the impedance converters that change the voltage sign (U-IC).

IC on the basis of Op-Amp are related to the bridge IC [4]. The circuits of IC on the basis of Op-Amp can be represented in the following form (fig. 1). Fig. 1a presents the circuit the input of which is a non-inverting input of Op-Amp and fig. 1b – the circuit the input of which is the inverting input of Op-Amp.



a) b)

Fig. 1. IC circuits on the basis of Op-Amp: a) the input is the non-inverting Op-Amp input; b) the input is the inverting Op-Amp input

For the circuits of fig. 1 the input impedance is determined by the expression [7]

$$Z_{input} = Z2 \cdot Z1 / Z3.$$

From this expression it is clear that substituting positive capacitance as a load instead of *Z1* or *Z2*, we obtain a negative capacitance at the input. The circuit will operate as a negative resistance converter. For impedance *Z3* the circuits operate as negative resistance inverters and, therefore, substituting the inductance instead of *Z3*, we obtain a negative capacitance at the input. Hence, the total number of possible C-negatron circuits on the basis of a negative resistance converter built on Op-Amp is 4. It should be noted that these circuits make it also possible to realize R-negatron and L-negatron, which will be determined only by the load impedance type.

Investigation of C-negatron on the basis of a negative resistance converter built on Op-Amp

Generalized C-negatron circuits on the basis of a negative resistance converter are presented in fig. 2 [5, 7]. In the circuit of fig. 2a resistors $R1$, $R2$ form a negative feedback loop that determines a gain factor $K_g = \frac{R1 + R2}{R2}$. Impedance conversion ratio is described by the expression $K_c = \frac{1}{1 - K_g} = -\frac{R2}{R1}$. Provided $K_g > 1$, i. e. $R1 > 0$, conversion ratio is negative $K_c < 0$. Capacitance C_l is the convertor load that forms a positive voltage feedback loop. Input impedance of the circuit $Z_{input} = K_c Z_l = \left(-\frac{R2}{R1}\right)\frac{1}{j\omega C_l}$. Capacitance at the converter input is described by the expression $C_{input} = \frac{1}{K_c} C_l$. If $R1 = R2$, gain factor $K_g = 2$, conversion ratio $K_c = -1$, input capacity $C_{input} = -C_l$. Circuit of fig. 2 operates as U-IC.

In the literature this circuit is also referred to as negative resistance converter with ungrounded load [5] and as a circuit engineering realization of the negative capacitance based on the Miller effect [8, 9].

Miller effect consists in that input capacitance of the inverting voltage amplifier $C_{input} = C(1 + K)$, where K is a gain factor, C – the cross capacitance. Using a non-inverting amplifier with gain factor $K > 1$ we obtain negative capacitance $C_{input} = -C(K - 1)$.

In the circuit under consideration capacitance C_l is a cross capacitance of the non-inverting amplifier. If $K = 2$, then $C_{input} = -C_l$.

Fig. 2b presents a C-negatron circuit on the basis of I-IC [5, 7]. The impedance conversion ratio is described by the expression $K_c = -\frac{R1}{R2}$. Input capacitance $C_{input} = \frac{1}{K_c} C_l = -\frac{R2}{R1} C_l$. If $R1 = R2$, conversion ratio $K_c = -1$, input capacitance $C_{input} = -C_l$. In the circuit a positive current feedback is used.

Both of the above converter circuits on the basis of Op-Amp make it possible to realize a negative capacitance but, however, they are not interchangeable because the equivalent circuits of the realized C-negatrons will be different, which is determined by the type of positive feedback being used. When positive voltage feedback is utilized, C-negatron of N-type (an active device) is realized [10, 11], and its equivalent circuit consists from the negative capacitance $C^{(-)}$ and negative active resistance $R^{(-)}$ connected in series. When positive current feedback is used, C-negatron of S-type (a passive device) is realized and its equivalent circuit consists from the negative resistance $C^{(-)}$ and positive active resistance R connected in series. For different types of C-negatrons different stability conditions are valid.

To verify the adequacy of the obtained theoretical statements let us perform computer simulation of the given circuits. Fig. 3 shows the circuit for simulating C-negatron on the basis of a negative-resistance converter built on Op-Amp with a positive voltage feedback.

Fig. 4 shows frequency dependence curves of the active and reactive components of the input resistance and the circuit capacitance values.

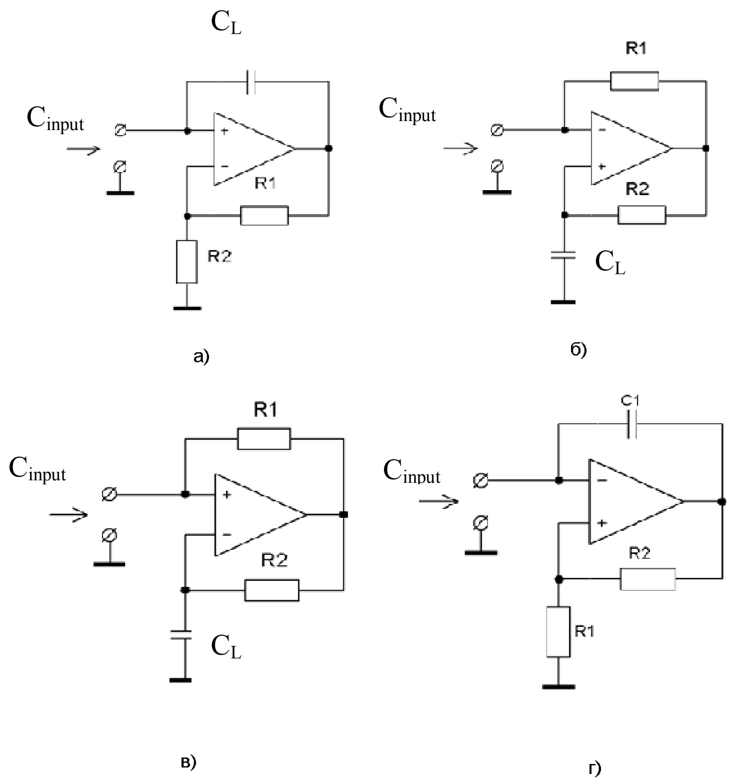


Fig. 2. Circuit engineering C-negatrons on the basis of negative resistance converter built on Op-Amp: a)with a positive voltage feedback; b) with a positive current feedback; c) with a positive voltage feedback; d) with a positive current feedback on the basis of U-IC

From the curves it is evident that the capacitance is negative with the value of – 100 nF at low frequencies. The maximal frequency of the negative capacitance realization is 564 KHz. In this case the maximal realization frequency is understood as the frequency at which the capacitance passes to the positive value. Active resistance is negative and at low frequencies it is 0.318 Ohm. The maximal frequency at which active resistance is negative equals 5 KHz.

It should be noted that this value of the negative active resistance emerges as a result of frequency dependence of the gain factor and does not take into account active resistance of the condenser terminals and connections that will also be converted into a negative value. Provided they will be taken into account, the value of negative active resistance will be respectively higher. E. g, if during simulation resistance of the terminals is taken into account, for instance, 1 Ohm, then the value of the negative active resistance will be – 1.318 Ohm.

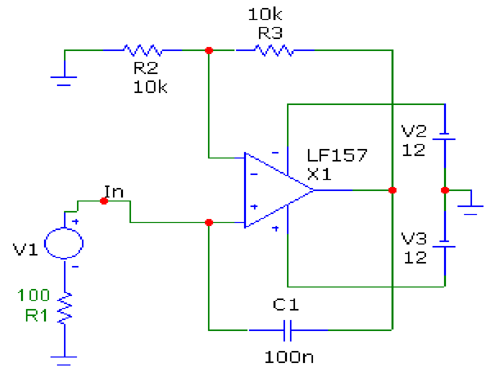


Fig. 3. Electric circuit of the C-negatron based on Op-Amp for simulation in MicroCap 8.0

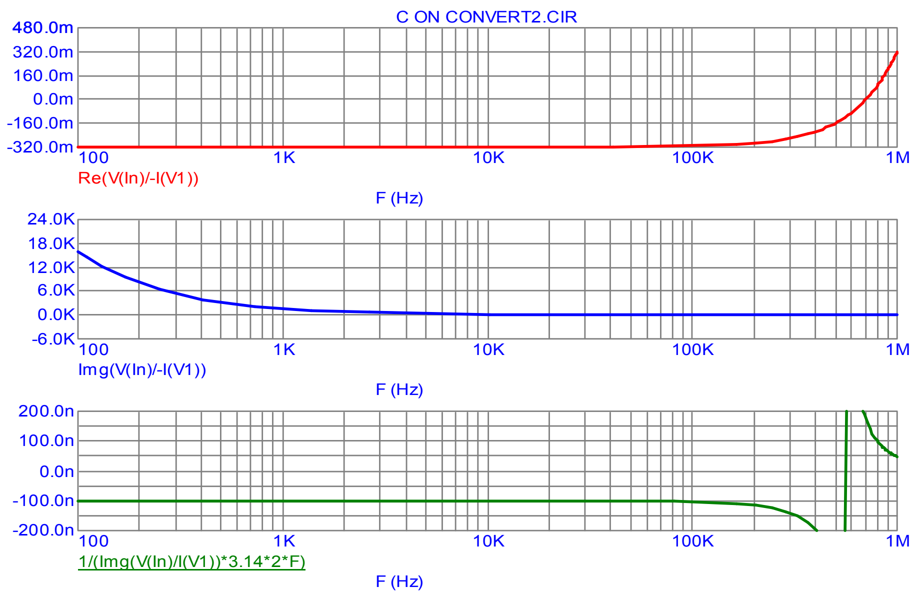


Fig. 4. Frequency dependencies of the active and reactive components of the input resistance and capacitance values of C-negatron presented in fig. 3

For theoretical calculation of the negative resistance value and for the description of the negative capacitance frequency dependence we use a single-pole approximation of the gain factor frequency dependence [13]:

$$K_g = \frac{K_0}{1 + j\dfrac{\omega}{\omega_1}K_0},$$

where K_0 – gain factor of the circuit at low frequencies, ω_1 – angular frequency of the unity gain.

Input impedance of the circuit is defined by the expression:

$$Z_{input} = \frac{1}{1-K_g} Z_l = \frac{Z_l}{1 - \dfrac{K_0}{1 + j\dfrac{\omega}{\omega_1} K_0}}.$$

Hence, active component of the input impedance

$$\mathrm{Re}(Z_{input}) = -\frac{K_0{}^2 \omega_1}{C\left(K_0{}^2\omega^2 + K_0{}^2\omega_1{}^2 - 2K_0{}^2\omega_1{}^2 + \omega_1{}^2\right)},$$

reactive component of the input impedance

$$\mathrm{Im}(Z_{input}) = -\frac{K_0{}^2\omega^2 - K_0{}^2\omega_1{}^2 + \omega_1{}^2}{\omega\, C\left(K_0{}^2\omega^2 + K_0{}^2\omega_1{}^2 - 2K_0{}^2\omega_1{}^2 + \omega_1{}^2\right)}.$$

At low frequencies these expressions could be simplified and represented as:

$$\mathrm{Re}(Z_{input}) = -\frac{K_0{}^2}{\omega_1 C(K_0 - 1)^2},$$

$$\mathrm{Im}(Z_{input}) = \frac{1}{\omega\, C(K_0 - 1)}.$$

For the operational amplifier LF157, that is used for simulation, $f_1 = \frac{\omega_1}{2\pi} = 20$ MHz. Using the obtained expression, the value of C-negatron negative active resistance is calculated (fig. 3) that at low frequencies is – 318.3 mOhm, which agrees with the simulation results.

From the expressions obtained for the frequency dependence of the input impedance it is evident that with growing frequency the values of active negative resistance and capacitance will decrease with the module. However, a single-pole approximation of the gain factor does not make it possible to determine maximal frequencies for active negative resistance and negative capacitance (approximations of higher orders must be used). From the obtained expressions it follows that maximal frequency depends not only on f_1, but also on K_0 and the load capacitance value, which is confirmed by the simulation results.

If with the help of resistors *R2, R3* in the circuit presented in fig. 3 the gain factor coefficient of 100 will be provided, i.e. 50 times greater, than that according to the simulation results, the value of the realized negative capacitance will increase to –9.9 mkF and maximal frequency will drop to 80 kHz, which is approximately $\sqrt{50}$ times lower than the previous value. The value of the negative active resistance will decrease to –81 mOhm, and maximal frequency – to 639 KHz. Thus, increase of the gain factor leads to the increase of the realized capacity value and to the maximal frequency reduction.

If for the circuit of fig. 3 load capacity will be decreased to C1=1 nF, the value of the realized negative capacitance will be -1 F and the maximal frequency will increase to 4.95 MHz. The negative active resistance value decreases to 31.8 mOhm and the maximal frequency increases to 6.86 MHz. This means that the load capacity reduction by 100 times leads to the tenfold increase of the maximal frequency.

The simulation results have shown that f_1 increase by k times leads to the increase of maximal frequency by approximately $\sqrt{k}$ times. Thus, if f_1 of Op-Amp increases by 5 times to the value of 100 MHz, for the circuit of fig. 3 we obtain the maximal frequency of negative capacitance 1.263 MHz, which is 2.24 times higher than the previous value.

The conducted analysis of the circuit operation makes it possible to determine basic parameters of the realized C-negatron and its operation frequency range, using the empiric expression

$f_{\max} \approx 1{,}77\sqrt{\frac{f_1}{20}\Big/\frac{C_l}{10}\frac{K_0}{2}}$ [MHz], where f_1 – a unity-gain frequency of Op-Amp in MHz, C_l – load capacitance in nF, K_0 – gain factor of the circuit at low frequencies. For example, if you realize negative capacitance – 100 pF, using Op-Amp, f_1 = 1000 MHz, K_0 = 2, C_l = 100 pF, then maximal frequency of the realized negative capacitance $f_{\max} \approx 125$ MHz.

Circuit for simulating C-negatron on the basis of a negative-resistance converter built on Op-Amp with a positive current feedback is shown in fig. 5.

Fig. 6 presents the frequency dependence curves for the active and reactive components of the resistance and capacitance values of this circuit. From the plots it is evident that the capacity is negative, which is in agreement with the above theoretical statements. Maximal frequency of the negative capacitance realization is 52 KHz. At high frequencies the reactance begins to grow and take on the character of inductance. The active resistance is positive and has the value of 324 Ohm at the frequency of 10 KHz. The simulation results confirm the above theoretical statements.

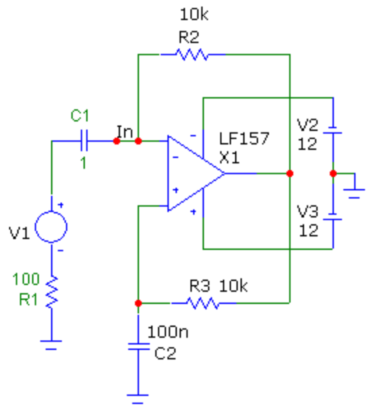


Fig. 5. The circuit of C-negatron based on Op-Amp with a positive current feedback for simulation in MicroCap 8.0

Thus, the circuit under consideration realizes a passive C-negatron. The maximal frequency for C-negatron of the given circuit is considerably less than that for the circuit of fig. 3. Resistance values in the feedback loops influence C-negatron maximal frequency in this circuit. When resistances decrease to R2 = R3 = 100 the circuit realizes the same negative capacitance – 100 nF, but the maximal frequency grows to 425 KHz.

Fig. 2c shows C-negatron circuit on the basis of a negative-resistance converter with a positive voltage feedback based on I-IC [7]. Input resistance of the circuit $Z_{input} = K_c Z_l = -\frac{R2}{R1}\frac{1}{j\omega C_l}$, where $C_l = C_1$. The input capacitance $C_{input} = \frac{C_l}{K_c} = -\frac{R1}{R2}C_l$. If $R1 = R2$, the conversion ratio $K_c = -1$, the input capacitance $C_{input} = -C_l$. The circuit uses a positive voltage feedback.

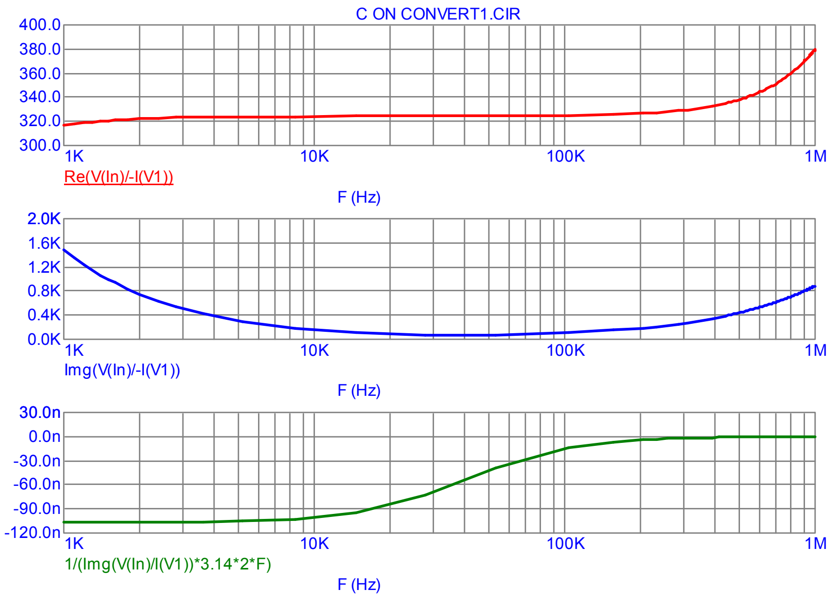


Fig. 6. Frequency dependencies of the active and reactive components of the resistance and capacitance values of C-negatron presented in fig. 5

For simulation the circuit shown in fig. 7 is used.

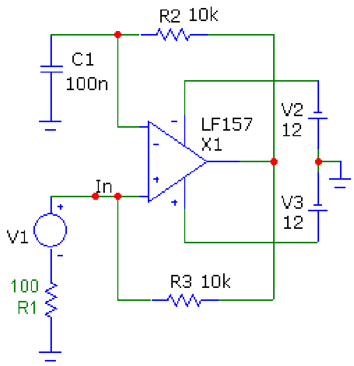


Fig. 7. Electric circuit of C-negatron on the basis of I-IC with a positive voltage feedback

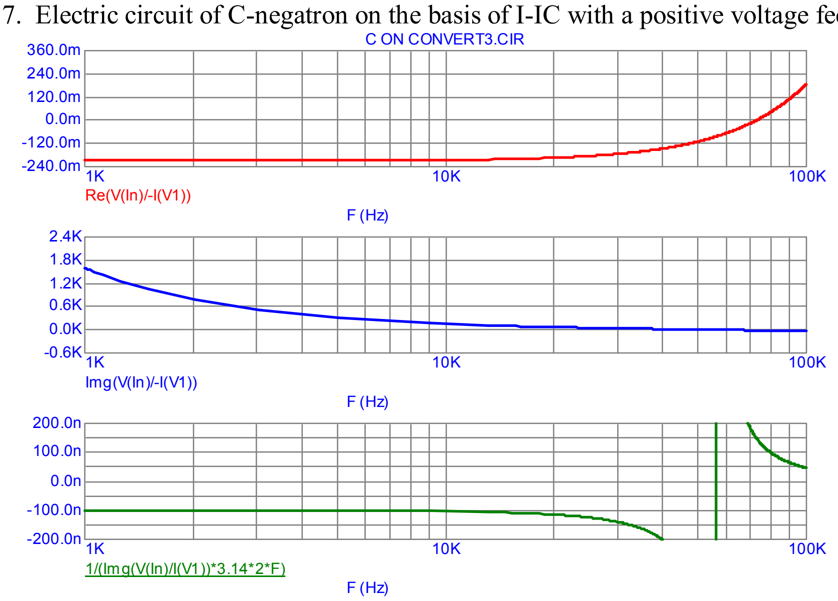


Рис. 8. Frequency dependencies of the active and reactive components of the input resistance and capacitance values of C-negatron presented in fig. 7

From the plots (fig. 8) it follows that the circuit realizes active C-negatron. The value of negative active resistance is –209 mOhm, the value of negative capacitance is –100 nF, the maximal frequency of negative capacitance is 56 KHz. As in the previous case, frequency characteristics of the circuit depend on the values of resistors in the feedback loops. For example, for R2 = R3 = 100 the circuit realizes negative capacitance –100 nF, the maximal frequency is 399 kHz. Frequency properties of the circuit, as of the previous one, are considerably worse than those of the circuit in fig. 3.

Fig. 2d shows a C-negatron circuit on the basis of the negative-resistance converter [7] with a positive current feedback at U-IC. Impedance conversion ratio of the circuit $K_c = -\frac{R1}{R2}$. The input capacitance $C_{input} = \frac{C_l}{K_c} = -\frac{R2}{R1} C_l$. If $R1 = R2$, conversion ratio $K_c = -1$, the input capacitance $C_{input} = -C_l$. Fig. 9 shows the circuit used for simulation.

The results of simulation of the circuit in fig. 9 are shown in Fig. 10. It can be seen from them that the circuit realizes a passive C-negatron. The negative capacitance value is –100 nF, the active resistance value – 318 mOhm, maximal frequency of the negative capacitance – 574 KHz. At high frequencies the reactance begins to grow and takes on the character of positive inductance. Frequency properties of the circuit are analogous to the C-negatron circuit that is also realized on the basis of U-IC (fig. 3) but with a voltage feedback.

The analysis of the operation of the four C-negatron circuits has shown that for the active C-negatron realization the circuit of fig. 2a is the best one according to its frequency properties and for passive C-negatron – the circuit of fig. 2a. The circuits of fig. 2b and 2c also realize passive and active C-negatrons respectively but they have lower operating frequencies.

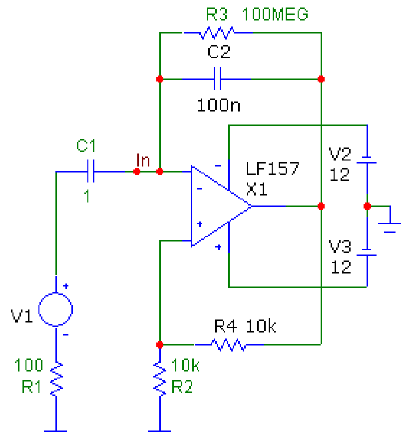


Fig. 9. The circuit of C-negatron based on Op-Amp for simulation in MicroCap

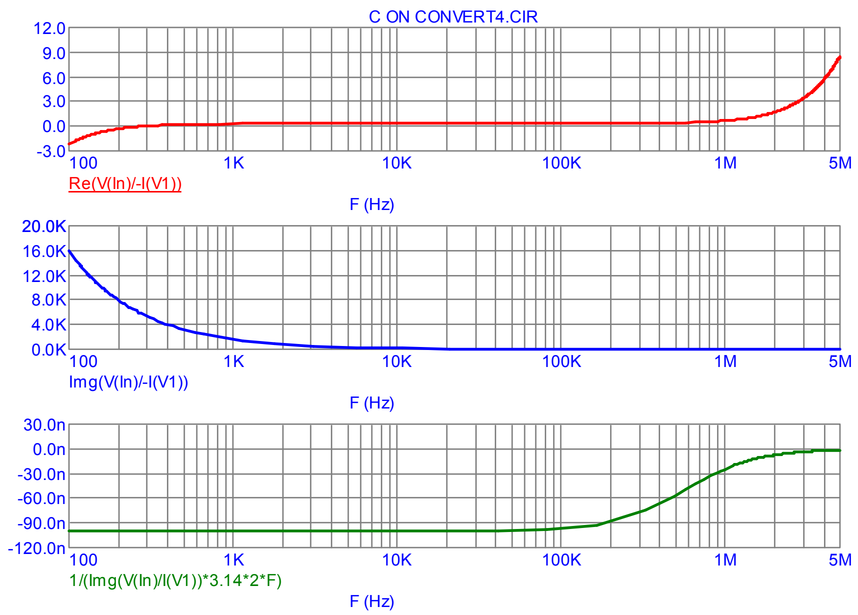


Fig. 10. Frequency dependencies of the active and reactive components of the active resistance and capacitance values of C-negatron in fig. 9.

Conclusions

1. C-negatrons circuits built on Op-Amp are based on impedance converters of the bridge type. There are four main circuits on the basis of negative resistance converters for realization of C-negatrons built on Op-Amp.

2. The considered C-negatron circuits built on Op-Amp operate in the frequency range of 0.01 Hz ... 100 MHz and make it possible to realize negative capacitance in the value range of –0.1 pF ... –1 F. Maximal operating frequencies of C-negatrons depend on the circuit parameters and equal approximately 0.1 f_1, where f_1 is the unity gain frequency of the Op-Amp.

3. The type of positive feedback used in IC circuit determines the C-negatron type. The circuits, where positive voltage feedback is used, realize active C-negatron (or C-negatron of the N-type) the equivalent circuit of which consists of the negative capacitance and negative active resistance connected in series. The circuits where a positive current feedback is used realize a passive C-negatron (or C-negatron of the S-type) the equivalent circuit of which consists of a series-connected negative capacitance and positive active resistance. The obtained results are in agreement with the previous theoretical conclusions given in [10, 11].

4. As to the frequency characteristics, the circuit in fig. 2a on the basis of U-IC with a positive voltage feedback is the best for active C-negatron realization and the circuit of fig. 2d on the basis of U-IC with a positive current feedback – for a passive C-negatron realization.

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