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Article

New and perspective directions for the development of active RC- and RLC- filter architectures of the Sallen-Key family

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Abstract: An extended classification of active RC- and RLC- filters with Sallen-Key architectures, including those created in the last three years, is proposed. This makes it possible to formulate new design directions for an extended family of active RC- and RLC- Sallen-Key filters (PF, LPF, HPF, RF) for the tasks of high-speed and ultra-fast analog-to-digital signal conversion.

Keywords: SALLEN-KEY, active RC- filter, active RLC- filter, low pass filter, high pass filter, bandpass filter, rejection filter

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1. Introduction

Modern circuitry of active RC filters (ARC) for tasks of limiting the spectrum of signals to their analog-to-digital conversion (ADC) is expanding into the field of radio frequencies and work with ultrafast ADCs. One of the widely used for these tasks and well-known structures of active filters are the three basic Sallen-Key schemes [1], first published by American scientists R. P. Sallen and E. L. Key in 1955. In the scientific field of circuit engineering related to the ideology of Sallen-Key, more than 500 articles have been published over the past 5 years, each of which contributes to the study of the functionality of the Sallen-Key structure, reducing errors, reducing energy consumption, etc. However, no new architectures have been created in this class of ARCF in recent years.

An important direction of improvement of Sallen-Key circuit solutions is primarily related to the search for new ARCF architectures and the practical use (about 200 modifications) of existing and annually created new active elements, including on wide-band semiconductors that ensure the operation of ARCF in a wide temperature range and exposure to radiation.

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2. Classification of ARCF Sallen-Key

Based on the analysis of the well-known literature [2-8], it is possible to propose an extended classification of schemes implemented on the basis of three basic Sallen-Key structures:

1. By type of amplitude-frequency response:
   - low-pass filter (LPF);
   - high-pass filter (HPF);
   - bandpass filter (PF);
   - rejection filter (RF).
2. By the implemented filter order:
   - 2-nd order;
   - 3-nd order;
   - 4-nd order and etc.
3. By the active element used:
   - with differential operational amplifier;
   - with a full differential operational amplifier having paraphase outputs;
   - on current conveyors;
   - based on current feedback amplifiers;
   - with multidifferential operational amplifiers;
   - based on non-inverting buffer amplifiers and voltage repeaters;
   - with active elements operating under severe operating conditions (radiation, cryogenic temperatures), etc.
4. By the type of passive frequency-setting elements used:
   - RC- filters;
   - RLC- filters;
   - schemes on memristors.
5. By the number of inputs and outputs:
   - RC- and RLC- filters with non-differential input and differential output;
   - RC- and RLC- filters with differential input and differential output;
   - multidifferential RC- and RLC- filters.
6. RC- and RLC- filters with independent adjustment of the main parameters (pole attenuation, scale factor of transmission, pole frequency).
7. ARC- filters with a reduced effect of the output resistance of active elements on the amplitude-frequency characteristics.
8. By frequency range:
   - low-frequency filters;

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- high-frequency filters;
- Microwave filters.

The considered classification makes it possible to formulate design directions for an extended family of active Sallen-Key RC filters (PF, LPF, HPF, RF) for the tasks of high-speed and ultra-fast analog-to-digital signal conversion.

3. A circuit-engineering method for reducing the influence of the output resistance of a buffer amplifier on the characteristics of the low-frequency ARC filters Sallen-Key

In modern automation, robotics and communications, ARCF are used based on voltage repeaters, which are often implemented on the basis of operational amplifiers with 100% negative feedback. The basis of the LPF and LHF of this class is based on the well-known Sallen-Key circuit on the Op-Amp, which is characterized by a number of disadvantages and limitations, such as sensitivity to the variation of the parameters of the elements, the inability to independently adjust the main parameters, such as the frequency of the pole, the quality factor of the pole and the scale coefficient of transmission.

Circuits of active RC filters on the simplest transistor voltage repeaters made without feedback can have (other things being equal) an extended frequency range, up to ultrahigh frequencies, since they do not use correction circuits to ensure stability. However, in the ARCF of this class, it is necessary to take into account the influence of the output resistance on the amplitude-frequency response (AFR).

Indeed, the dependence of the gain of the operational amplifier (Op-Amp) in the voltage repeater circuit (Fig. 1) on the frequency μ (p), the input and output resistances of the Op-Amp lead to a change in the shape of the frequency response of ARC filters in the passband and a change in the asymptotic attenuation in the delay band. The output impedance of the R_{out} and the frequency of the single gain of the op-amp limit the attenuation of the frequency response in the high frequency region [9].

In this section, using the example of commonly used 2nd order ARC filter circuits (Sallen-Key [1] – Fig. 1), the effect of the output resistance of an operational amplifier in the voltage repeater mode on the frequency response of filters is considered and ways to reduce this effect are proposed.

The transfer function of the active RC filter of the 2nd order [9], [10] is described by the following expression

$$F\,(p) \;=\frac{U_{out.}\,(p)}{U_{in.}\,(p)}=M\,\frac{p^2+pd_0\omega_0+\omega_0^2}{p^2+pd_0\omega_0+\omega_0^2}\;. \qquad (1)$$

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Where ω_0, ω_p is the frequency of zero and the poles of the transfer function, d_0, d_p is the attenuation of zero and the poles of the transfer function, M is the scale factor of the filter transmission.

The classical scheme of active 2nd order Sallen-Key RC- filters [11], [1], (Fig. 1), whose equation corresponds to formula (1), contains an operational amplifier (Op-Amp) in repeater mode, two resistors and two capacitors.

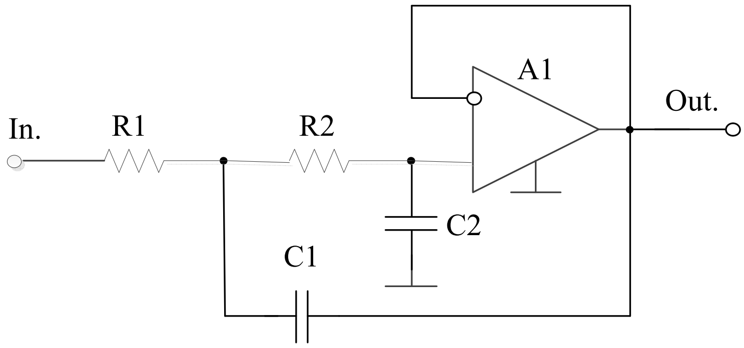
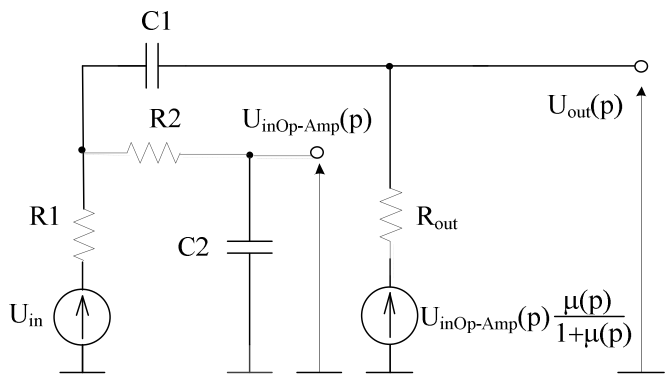
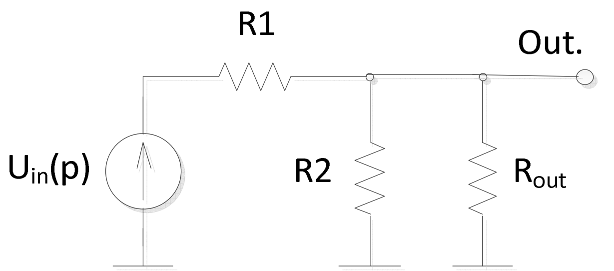


Fig.1 The scheme LHF of the Sallen-Key

To analyze the effect of the output resistance of the Op-Amp on the frequency response of the LPF on Fig. 2a shows an equivalent circuit of the Sallen-Key link, and Fig. 2b shows the same circuit in the high frequency range (at $p \to \infty$).



(a)



(b)

Fig. 2 Equivalent schemes of the Sallen-Key: in the low frequency range (a) and the high frequency range (b)

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As follows from Fig. 2a, one of the features of the Sallen-Key LPF circuit is that in the case of using an ideal Op-Amp, the voltage at the output A1 and the voltage at the capacitor C_2 will be equal. Therefore, the output of the link can serve not only the output of the Op-Amp, but also the junction of the capacitor C_2 and the resistor R_2 (Fig. 2a). Considering that the equivalent resistance of the capacitor C_2 tends to zero with increasing frequency, it can be expected that the asymptotic «tail» in the frequency response, due to the finite value of R_{out}, will be absent.

Fig. 3 shows a diagram of the Sallen-Key link with this ideology. Here an additional Op-Amp is introduced - A2, the output of which is the junction node R_2 and C_2. Fig. 4 shows the frequency response of the LPF circuit on Fig. 3, obtained in a MicroCap environment. From the analysis of the last graph, it follows that the change in the output node in the filter circuit allowed not only to eliminate the influence of the R_{out}, but also the boundary frequency of the Op-Amp gain, which was expressed (in traditional circuits) in the ups and downs of the frequency response in the delay band.

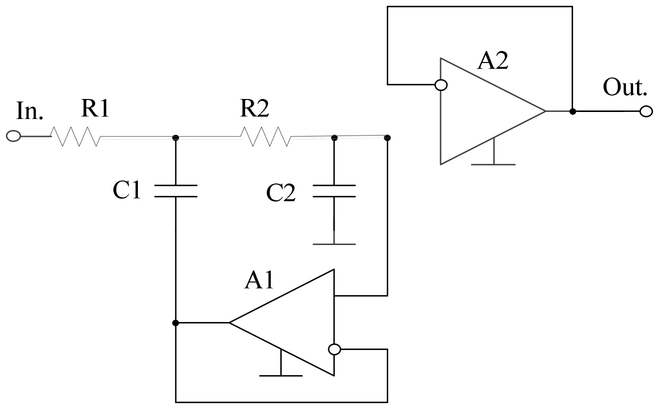

Fig. 3 Diagram of the Sallen-Key link with an additional Op-Amp

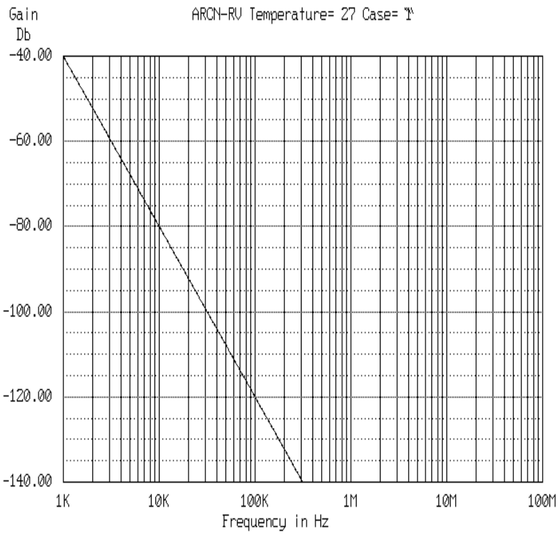

Fig. 4. The ARCF frequency response on Fig. 3 with a reduced effect of the output resistance

It can be assumed that other Sallen-Key schemes (including well-known ones) may have a similar property. Moreover, a necessary condition for reducing the influence of R_{out} is the absence of a direct path of a high–frequency signal from the input of the circuit to its output, and sufficient is the presence in the direct path of at least one RC circuit with a grounded capacitor.

4. ARC rejection filter Sallen-Key on voltage repeaters

Fig. 5 shows the scheme of the proposed rejection ARC- filter of the Sallen-Key family [2-6], which is implemented only on non-inverting voltage repeaters

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(for example, on HF or microwave SiGe emitter or source repeaters). An essential feature of the RF on Fig. 5 is that it provides for independent adjustment of the pole frequency and pole quality factor by different resistors.

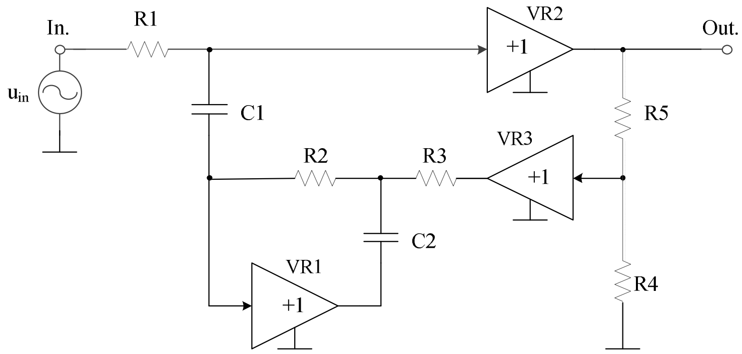

Fig. 5 Diagram of the proposed cutting ARC- filter

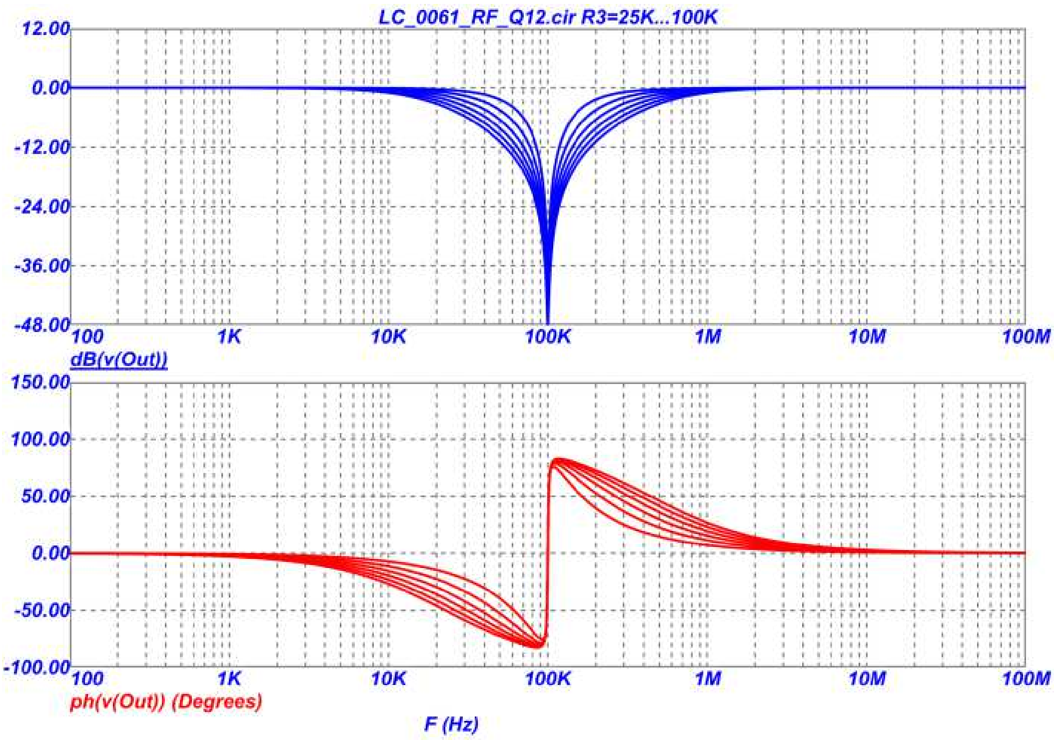

Fig. 6 Amplitude-frequency and phase-frequency characteristics of the RF on Fig. 5 when changing R3

Fig. 7 shows a modification of the RF circuit on Fig. 5 with a minimum number of active and passive elements.

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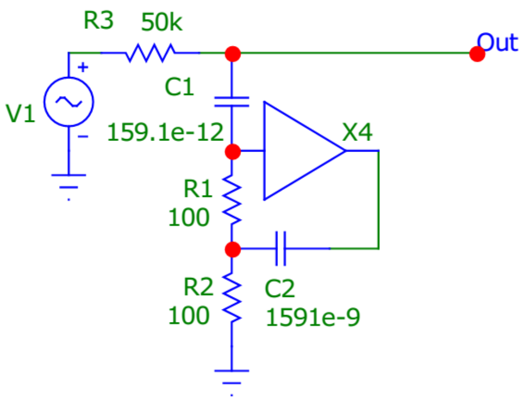

Fig.7 Modification of the scheme on Fig. 5 with a reduced number of elements

Fig. 8 shows the graphs of the frequency response and frequency response when the resistance of the resistor R3 changes on the diagram Fig.7.

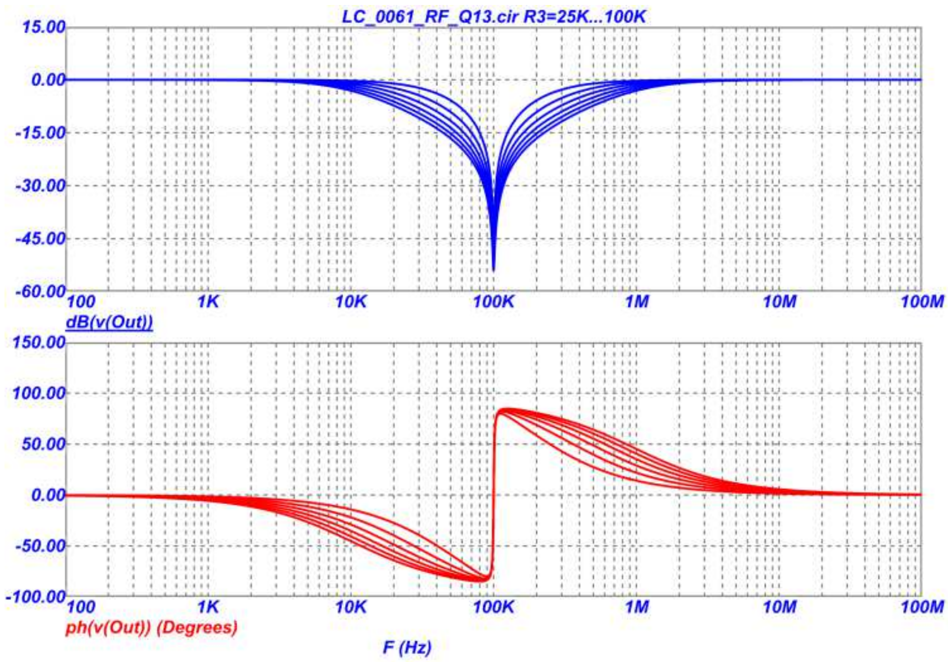

Fig. 8 Amplitude-frequency and phase-frequency characteristics of the RF on Fig. 7 when changing R3

5. Rejection ARLC filter Sallen-Key

Fig. 9 shows the scheme of the proposed notch filter in the MicroCap simulation environment for the special case of choosing numerical values of inductance L1 and capacitor C1, providing a suppression frequency of 1 GHz.

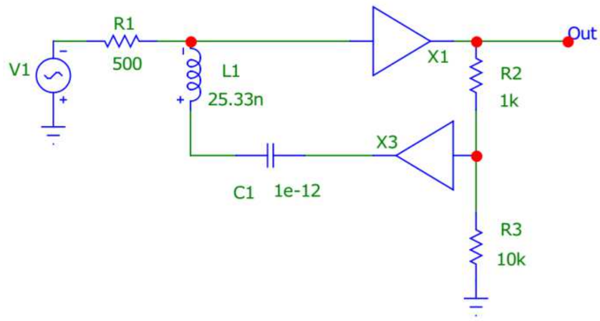

Fig. 9 Diagram of the proposed notch filter in the MicroCap modeling environment

Fig. 10 shows the amplitude-frequency and phase-frequency characteristics of the notch filter on Fig.9.

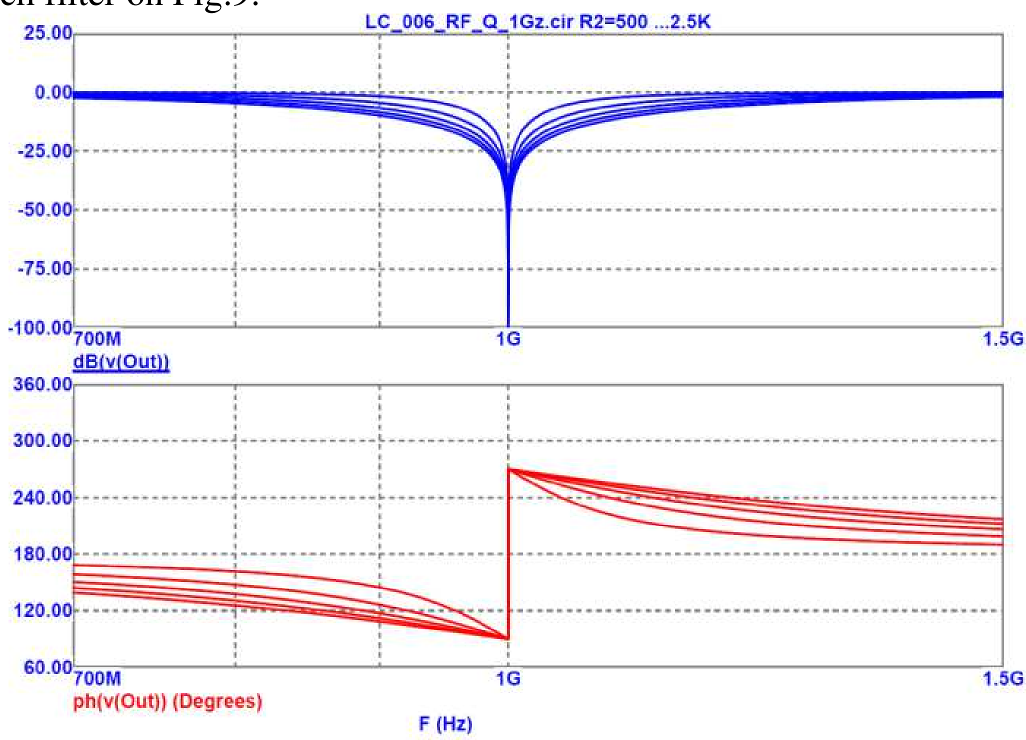

Fig. 10 Amplitude-frequency and phase-frequency characteristics of the proposed notch filter in Fig. 9

Conclusion

The extended classification of active filters of the Sallen-Key family allows us to formulate new directions for their circuit design. As an example, the article presents new RC- and RLC- filters with the Sallen-Key topology, which can be recommended for mobile communication and telecommunications devices.

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References

1. Sallen, R., и E. Key. «A practical method of designing RC active filters». IRE Transactions on Circuit Theory, Semantic Scholar, 1955. doi:10.1109/TCT.1955.6500159.
2. Pactitis, S. A. Active Filters: Theory and Design. CRC Press, 2018, p.274. doi:10.1201/b15881.
3. Self, Douglas. The Design of Active Crossovers. 2-nd edit., Routledge, 2018, p.672. doi:10.4324/9781315187891.
4. Texas Instruments. "Analysis of the Sallen-Key Architecture (Rev. B)". September 2002. [Online]. Available: https://goo.su/EDeCrl4
5. Stornelli Vincenzo, Leonardo Pantoli. Filter Design Solutions for RF systems. Multidisciplinary Digital Publishing Institute, 2020. P.188.
6. Centurelli F. and etc. 10-GHz Fully Differential Sallen–Key Lowpass Biquad Filters in 55nm SiGe BiCMOS Technology. Semantic Scholar, 2020. p.563. doi:10.3390/electronics9040563.
7. X.U. Hang, X.U. Lixiong, W.U. Haixiang. Experimental teaching research on amplitude and frequency characteristics of dual Sallen-Key series wideband pass filter circuit. Experimental science and technology, 2020. pp.86-90.
8. Hercules G. Dimopoulos. Analog Electronic Filters: Theory, Design and Synthesis. Springer Science and Business Media New York, 2015. pp.577.
9. A.A. Demin, V.V. Markin, V.V. Maslennikov, A.P. Sirotkin. Active selective devices of radio equipment. Radio and Communications, 1987. p.216 (in Russian).
10. Kerwin W.J., Huelsman L.P., Newcomb R.W. State variable synthesis for insensitive integrated circuit transfer functions. IEEE J., 1967, v. SC-2(3), p.87-92.
11. Krutchinsky S.G. Structural synthesis of analog electronic circuits. Monograph: Rostov on Don: Publishing house of the North Caucasus Scientific Center of Higher School, 2001. p.180. (in Russian)