Article

Voltage followers for the design of Sallen-Key Active RC-Filters

Chumakov V.E.¹, Pakhomov I. V.¹. Titov A. E.², Butyrlagin N. V.¹, Prokopenko N. N.¹

¹ Don State Technical University, Rostov-on-Don, Russia

² Southern Federal University, Rostov-on-Don, Russia

*E-mail: butyrlagin@gmail.com, ORCID: 0000-0002-6363-5113.

Abstract: In this paper consider the circuitry of voltage followers (VF) with unitygain, intended for practical use in active Sallen-Key RC-filters (LPF, HPF, BPF, RF). The results of research and computer modeling of radiation-resistant and lowtemperature VF in the LTSpice environment on models of CJFET transistors operating under the influence of neutron flux up to 10e14 n/cm2 and cryogenic temperatures up to -197°C are presented.

Keywords: Sallen-Key filters, LPF, HPF, BPF, NF, voltage followers, buffer amplifiers, CJFET, neutron flux, cryogenic temperatures.

1. Introduction

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The active RC-filters (ARCF) of Sallen-Key family are among the most popular devices in frequency selection for radio engineering, automation and telecommunications [1]. As amplifying elements in ARCF of this class used operational amplifiers with 100% negative feedback [2] or buffer amplifiers (BA), which implemented on one or several transistors (BJT, CMOS, SOI, etc.). In recent years this area of practical application of the Sallen-Key ARCF family has emerged as an independent subclass of frequency selection devices [3-4] including for work in severe operating conditions.

Practical realization of Sallen-Key filters family on voltage followers (VF) has, in contrast to ARCF Sallen-Key on operational amplifiers (OPA), an important advantage - VF circuits can be performed in the form of the simplest emitter or source followers [5-10]. As a result, such ARCF active elements are distinguished by a wider operating frequency range and low power consumption in comparison with OPA.

The purpose and novelty of this article is to consider the circuitry of voltage followers and their practical use for Sallen-Key ARCF family, including those operating at low temperatures and a neutron flux.

2. Typical Architectures Sallen-Key ARCF on base voltage followers

Currently, a four basic Sallen-Key filter circuits are known, which implemented on the basis of voltage followers (Figure 1) [11].



(d)

Figure 1. Circuits of filters Sallen-Key family of a low-pass filter [12] (a), a high-pass filter in the structure [13] (IC5, IC6) (b), a band-pass filter (c), a notch filter [14] (d).

Below are the basic equations of Sallen-Key ARCF that allow you to choose their settings [11]. So, for the low-pass filter circuit (Figure 1 (a)) the transfer function is determined by the expression

$$W(p) = \frac{R_1 R_2}{(R_1 C_1 + R_2 C_2) + R_2 C_2 - R_1 C_2},$$
(1)

then pole frequency $\omega_p = \frac{1}{\sqrt{R_1 C_1 R_2 C_2}}$.

The transfer function of the high-pass filter (Figure 1 (b)) is

$$W(p) = \frac{p^2}{p^2 + p\left(\frac{1}{C_1 R_2} + \frac{1}{C_2 R_2} - \frac{1}{C_1 R_1}\right) + \frac{1}{C_1 R_1 C_2 R_2}},$$
(2)

and pole frequency $\omega_{\rm p} = \frac{1}{\sqrt{R_1 C_1 R_2 C_2}}$.

and

In the band-pass filter circuit (Figure 1 (c)), the transfer function is determined

$$W(p) = \frac{\frac{1}{C_{1}R_{1}}p}{p^{2} + p\left(\frac{1}{C_{1}R_{1}} + \frac{1}{C_{1}R_{3}} + \frac{1}{C_{2}R_{3}} - \frac{1}{C_{1}R_{2}}\right) + \frac{R_{1} + R_{2}}{R_{1}R_{2}R_{3}C_{1}C_{2}},$$
(3)
at that pole attenuation $d_{p} = \frac{\frac{1}{C_{1}R_{1}} + \frac{1}{C_{1}R_{3}} + \frac{1}{C_{2}R_{3}}}{\sqrt{\frac{R_{1} + R_{2}}{R_{1}R_{2}R_{3}C_{1}C_{2}}}},$
and pole frequency $\omega_{p} = \sqrt{\frac{R_{1} + R_{2}}{R_{1}R_{2}R_{3}C_{1}C_{2}}}.$

Figure 2 shows examples of the inclusion of a VF [16] in the structures of a 3rd order Chebyshev low-pass filter (LPF) (Figure 2 (a)), in a 4th order Butteworth LPF (Figure 2 (b)), in a 5th order Bessel LPF (Figure 2 (c)). In a particular case, as buffer amplifiers BA1 and BA2 in the circuit on Figure 2 (c) may be using on op amps with 100% negative feedback can be used.









Figure 2. Examples of the inclusion of VF in the structures of a 3rd order Chebyshev low-pass filter (LPF) (a), of a 4th order Butteworth low-pass filter (b), of a 5th order Bessel low-pass filter (c).

3. The Voltage Follower Circuits for Sallen-Key Active RC-Filters

The analysis of the VF circuitry, which are used in Sallen-Key ARCF family [1-4], shows that for these tasks the circuits are used, shown on Figure 3. The voltage followers on Figure 3 (a) and Figure 3 (b) are among the most widespread. Their properties are studied in detail in monographs on analog circuitry [16-17]. The flaw of these circuit solutions is a rather large systematic component of the zero bias voltage (V_{off}), which is determined by the emitter-base (gate-source) voltage of the used transistors.



Figure 3. Voltage followers on bipolar transistors (a, b) and CMOS transistors with an induced channel (c, d).

In VF based on composite transistors (Figure 4 (a), (b), (c)), the difference between the input and output static voltages can be quite small. This is provided by the circuitry of the voltage followers, the topology of the transistors and the applied technological processes.



Figure 4. Voltage followers on composite bipolar transistors (a), CMOS transistors with induced channel (b), CMOS transistors with integrated channel (c).

Construction of VF for the Sallen-Key ARCF family is possible on the basis of the circuitry on simplest OPA with 100% negative feedback (Figure 5), which allows us to reduce V_{off} . However, the frequency characteristics of such voltage followers will be somewhat worse than in control units without feedback. On Figure 5 presented CM1 is a current mirror.



Figure 5. The voltage follower with low voltage offset zero.

To obtain the limiting parameters of the Sallen-Key ARCF family in the frequency range, special VF are designed, including those operating in severe operating conditions [11].

4. Low-temperature and radiation-resistant voltage follower on complementary field-effect transistors with a control p-n junction

In Figure 6 and Figure 7 shows two proposed [18-19] circuit modifications of the VF with small V_{off} , which made on complementary field-effect transistors with a control pn-junction and provide a low noise level, including when operating in the low temperature range.



Figure 6. The first modifications of the JFET VF [19].



Figure 7. The second modification of the radiation-resistant and low-temperature VF on complementary field-effect transistors [18].

Consider the work of the VF (Figure 7) taking into account the results of modeling its characteristics shown in Figure 8 - Figure 12. In static mode, with a large load resistance R_{load} , the source currents of the output and input field-effect transistors J3, J2, as well as the input and output field-effect transistors J1, J4 are determined by the formulas

$$I_{d.4} = \frac{V_{GS.4}}{R_1} = I_{d.1},$$
(4)

$$I_{d.3} = \frac{V_{GS.3}}{R_2} = I_{d.2} .$$
 (5)

where R_1 , R_2 are the resistances of the corresponding current-stabilizing resistors R1, R2;

 $V_{GS.i}$ is the gate-source voltage of the i-th field-effect transistor at a given source current.

From formulas (4) and (5) it follows that the static modes of the input fieldeffect transistors J1, J2 can be set independently of each other by currentstabilizing resistors R1, R2. In this case, the static voltage at the output of the VF (with identical drain-gate characteristics of transistors with p- and n-channels) is close to zero:

$$V_{\text{load}} \approx V_{\text{GS.1}} - V_{\text{GS.4}} = V_{\text{GS.3}} - V_{\text{GS.2}} \approx 0.$$
 (6)

In practical VF circuits, due to the difference in threshold voltages of transistors with p- and n-channels in the circuit in Figure 7, the output voltage (the so-called zero bias voltage VF V_{off}) lies in the ranges of units to tens of millivolts.

In this case, the numerical values of V_{off} can be set, depending on the range of external influences, due to the rational choice of resistances R_1 and R_2 .

If the input voltage in the circuit (Figure 7) receives a positive increment, then the current in the load R_{load} also receives a positive increment due to an increase in the source current of the output field-effect transistor J3.

At negative input voltages, the increase in current in the load is provided by increasing the source current of the output field-effect transistor J4.

In Figure 8 shows the static mode of the VF (Figure 7) in LTSpice CAD at $t=27^{\circ}C$ (Figure 8 (a)) and at $t=-197^{\circ}C$ (Figure 8 (b)). In this case, the computer models of JFET transistors presented in [19] were used.



(b)

Figure 8. Static mode of VF (Figure 7) at $t=27^{\circ}C$ (a) and $t=-197^{\circ}C$ (b).

In Figure 9 shows the dependence of the output voltage (V_{out}) on the input voltage (V_{In}) VF (Figure 8 (a)) at t=27°C and different load resistances (R_{load} =5kOhm/10kOhm/20kOhm/50kOhm/500kOhm/∞).



Figure 9. Dependence of the output voltage (V_{out}) on the input voltage (V_{In}) VF at t=27°C.

In Figure 10 shows the dependence of the output voltage (V_{out}) on the input voltage (V_{In}) VF on (Figure 8 (b)) at t=-197°C and different load resistances (R_{load} =5kOhm/10kOhm/20kOhm/50kOhm/500kOhm/∞).



Figure 10. Dependence of the output voltage (V_{out}) on the input voltage (V_{In}) VF at t=-197°C.

As follows from the graphs on Figure 9 and Figure 10, the proposed voltage follower provides (at large load resistances R_{load}) maximum output voltages close to the voltages on the positive and negative power supply rails, incl. in the cryogenic temperature range (Figure 11).

In Figure 11 shows the dependence of the output voltage of the VF (Figure 8) on temperature in the range of -197°C \div + 27°C at zero input voltage (V_{in} = 0V) and load resistance R_{load}= ∞ .



Figure 11. Dependence of the output voltage of the VF on temperature.

In Figure 12 shows the dependence of the output voltage of the VF (Figure 8) from the neutron flux in the range Fn=1e13÷1e15 n/cm2 at zero input voltage (V_{In}=0V) and load resistance $R_{load}=\infty$. From the graphs in Figure 11 it follows that the proposed VF circuit is efficient in a wide range of changes in the neutron flux.



Figure 12. Dependence of the output voltage of the VF on temperature $t=27^{\circ}C$.

5. Conclusion

The main circuits of voltage follower for Sallen-Key active RC-filters family are considered. Computer simulation shows that the proposed versions of the CJFET VF construction can find application in low-temperature and radiationresistant analog devices [20]. At the same time, due to the appropriate choice of frequency-setting resistors and capacitors in the above-mentioned ARCF circuits, various amplitude-frequency characteristics are realized (Chebyshev, Butterworth and Bessel filters).

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