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Performance analysis of a three-stage quadrature RC generator with operational amplifiers

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ABSTRACT

This paper presents the special features of RC harmonic oscillation generators and their widespread use and in particular the quadrature generators which provide two output signals dephased at 90° or 270°. Quadrature generators can be classified as those with an aperiodic frequency-determining circuit or with a phase inverter group which are used to generate oscillations of one or more fixed frequencies. Studies of a three-stage quadrature RC generator circuit with operational amplifiers have been performed. The results obtained from the simulation and experimental studies performed are presented for the selected circuit. It can be assumed that the experimental and simulation results completely coincide to an accuracy of up to 20% for the amplitude of the generated signals and to the total accuracy for the generated frequency. Quadrature generators are very widely used in communication technology and, most importantly, in the structure of digital frequency, phase and quadrature-amplitude modulators and demodulators, in vector RLC meters and many other electronic circuits and devices in practice.

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1. INTRODUCTION

Generators have an extremely wide and important application in practice. They are used in radio transmitters during the implementation of modulations, in radio receivers during selection of a certain radio station and formation of intermediate frequency signals, in computational equipment for generating clock signals, in measurement equipment during formation of test signals, in automated means of controlling production and others processes and many others. The amplitude and frequency of the generated oscillations are determined by the mode of operation of the active element, the parameters of the selection chain, the feedback and the load.

RC generators are used to generate oscillations with frequencies from several Hz to several MHz. Their selective system is made up of only R and C elements. This determines their main advantages: small overall dimensions, suitable for integrated implementation and incorporation into hybrid ICs, they are not affected by external fields. Because RC selective circuits do not have good selectivity, obtaining oscillations with small nonlinear distortions is related to the introduction of additional nonlinear negative feedback. The negative feedback also stabilizes the amplitude of the oscillations. RC generators are also characterized by relative instability of the generated frequency $\Delta f / f_0$ in the range from 10^{-2} to 10^{-3}.

Very often, in practice, it is necessary for a generator to provide two output signals dephased at a certain angle. The generator is quadrature when the angle is 90° or 270° (-90°). Quadrature generators are widely used in communications technology for the implementation of digital angular modulations [1], and in particular quadrature-amplitude modulation (QAM). Quadrature generators are included in the structure of digital modulators and demodulators as well. In scientific publications of recent years, e.g. [2]–[8], [9]–[15], [16]–[21], no in-depth design, studies, analyses and conclusions of the RC harmonic oscillation generator circuits as well as their selective chains are available.

2. REPRESENTATION

2.1. Quadrature RC generators of harmonic oscillations

RC generators are divided into two main groups according to the nature of the selective circuit [22]: i) with aperiodic frequency-determining circuit or phase-rotating RC generators; and ii) with selective frequency-determining circuit-with maximum or minimum feedback transmission coefficient β for the frequency generated and zero dephasing between output and input signals.

Quadrature generators can be classified as those with a phase group which are used to generate oscillations at one or more fixed frequencies. As one RC unit can dephase at an angle less than 90°, a minimum of three units is required to meet the condition of phase-angle balance. The quadrature generator in Figure 1 is based on the dephasing of the signal in the feedback with the help of three RC units, each of which introduces a phase shift of 90°. This provides sinusoidal and cosinusoidal signals at its outputs, which are quadrature, with a phase difference of 90°. In this case, double sine wave integration is used which results in a 180° phase dephased. The phase of the second integrator is inverted and used for positive feedback. This results in the onset of non-attenuating oscillations.

The transmission coefficient of the feedback chain β is determined by (1).

$$A.\beta = A.\left(\frac{1}{R_1.C_1.s}\right).\left[\frac{R_3.C_3.s+1}{R_3.C_3.s(R_2.C_2.s+1)}\right] \quad (1)$$

When $R_1C_1 = R_2C_2 = R_3C_3$, (1) is simplified to (2).

$$A.\beta = A.\left(\frac{1}{R.C.s}\right)^2 \quad (2)$$

When ω=1/(R.C), (1) is simplified to an angle -180° since generation occurs for frequency ω. *A* is the voltage gain without feedback.

Both outputs are characterized by the presence of nonlinear distortions as the sinusoidal output signal has smaller distortions than the cosinusoidal. Gain control can increase the amplitude of the output signal. The disadvantage of such a generator is the limited frequency range in which it can provide non-attenuating oscillations.

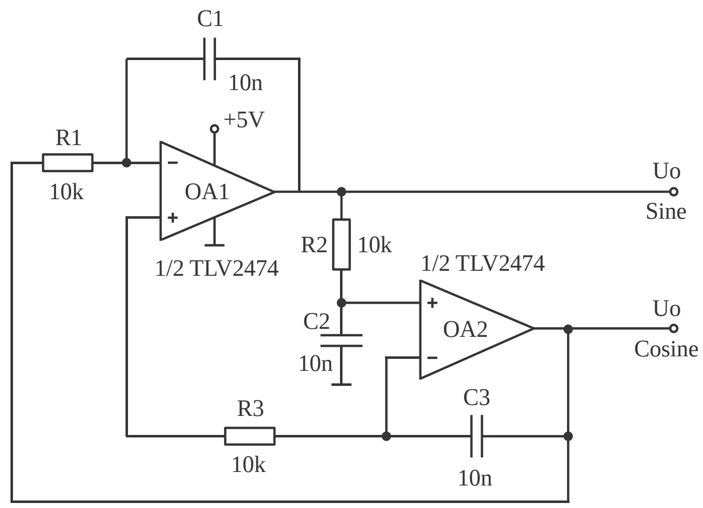

Figure 1. Circuit of a quadrature generator [23], [24]

Another circuit of a quadrature generator is shown in Figure 2. 90° dephasing is achieved by using two integrators and an RC (Rf, Cf) chain used as feedback. OA1 has the function of a non-inverting integrator whose input is connected to the OA2 output via RC feedback. OA2 is an integrator that converts the sinusoidal output of OA1 to its cosinusoidal output.

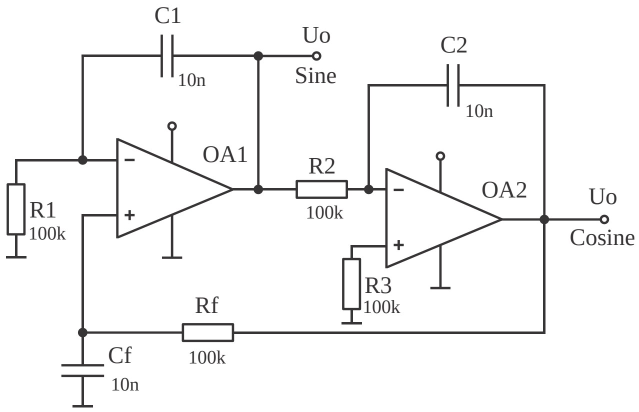

Figure 2. Circuit of a quadrature generator

The integrator output voltage is an integral of the input signal. Their transfer function in real and operator form is, respectively.

$$u_0(t) = -\frac{1}{R.C}\int u_i(t)dt;\ u_0 = -\frac{1}{pR.C}u_i \tag{3}$$

The frequency characteristics of the integrators are determined by the complex transmission coefficient.

$$\dot{A}_F = -\frac{1}{j\omega R.C} \tag{4}$$

from where for the amplitude-frequency response is obtained $A_F(\omega) = \frac{1}{\omega R.C}$. Integrators are mainly used as low-pass filters when operating within a wide frequency range of signals as the voltage transmission coefficient decreases with an increase in frequency (ω is in the denominator).

A variant of the circuit of a quadrature generator is shown in Figure 3 [25]. It consists of an inverting amplifier with operational amplifier (OA3) and connected between its input and output are two or more phase units (all-pass filters) of the first order connected in chain (series). The voltage dephasing from each unit is about 90°, so the total dephasing is $\varphi_{\beta+}\approx\varphi_1+\varphi_2=180°$ ($\varphi_1\approx90°$ and $\varphi_2\approx90°$) for a certain frequency f_0. The inverting amplifier, consisting of OA3 and the resistor divider P-R_N also dephases the amplified voltage to 180°. Then for the frequency f_0 the condition for balance of the phase angles is fulfilled in general for the circuit $\varphi_{Au}+\varphi_{\beta+}=360°$ and in the outputs U_{01} and U_{02} (U_{03}) of the circuit conditions are created for the occurrence of continuous oscillations. The elements of the circuit of Figure 3 in [25] are without values.

For the transmission coefficient of the selector chain of the generator is obtained

$$\dot{\beta}^{+} = \frac{\dot{U}_{03}}{\dot{U}_{01}} = \left(\frac{1-j\omega R_2C}{1+j\omega R_2C}\right)\cdot\left(\frac{1-j\omega R_3C}{1+j\omega R_3C}\right) \tag{5}$$

In case $R_2=R_3=R$ dependence (5) acquires the form

$$\dot{\beta}^{+} = \frac{\dot{U}_{03}}{\dot{U}_{01}} = \frac{(1-j\omega RC)^2}{(1+j\omega RC)^2} \tag{6}$$

Im [$\varphi_{\beta+}$]=0° is required for the fulfillment of the phase condition of self-excitation, where the frequency of the oscillations is determined by dependence (5).

$$f_0 = \frac{1}{2\pi RC} \tag{7}$$

Then at frequency f_0 for the phase-shift between the voltages u_{01}-u_{02} and u_{03}-u_{02} is found

$$\phi_1(f_0) = \phi_2(f_0) = 2arctg(2\pi f_0 RC) = 2arctg(1) = 90^o \tag{8}$$

or

$$\phi_1(f_0) + \phi_2(f_0) = 180^o \tag{9}$$

In Figure 4 are given exemplary time-diagrams of the output voltages of the quadrature generator.

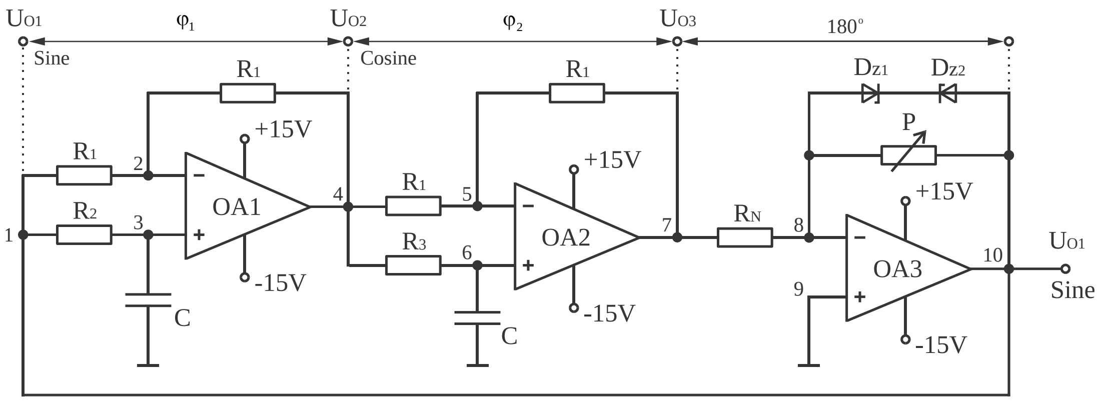

Figure 3. A quadrature three-stage RC generator circuit with operational amplifiers [25]

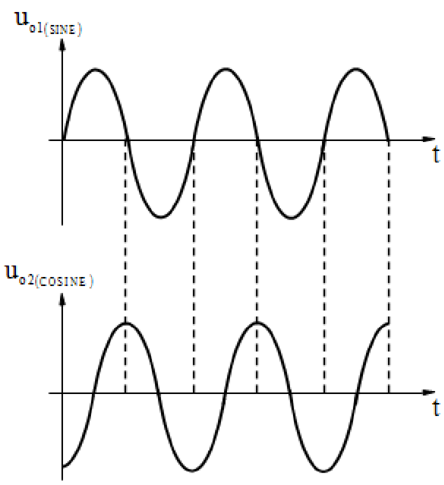

Figure 4. Time-diagrams of the output voltages of a quadrature generator

Since the modulus of the coefficient $\dot{\beta}^+$ for each frequency is equal to 1, for meeting the condition of balance of the amplitudes for self-excitation it is sufficient for the inverting amplifier (OA3) to operate with a small gain, i.e., with deep negative feedback. As a result, the transmission characteristic of the amplifier is almost linear and the process of self-excitation continues until the amplitude of the output voltage U_{01} reaches the maximum output voltage of the OA. Zener diodes D_{Z1} and D_{Z2} are connected in parallel to potentiometer P to limit the output voltage U_{01}. The design of the quadrature generator circuits in Figure 3 (and also in Figure 1) consists of selecting the capacitance value of the compound capacitors, which is the same as $C_1=C_2=C_3=C$ and determining the resistors whose values are also equal-$R_1=R_2=R_3=R$. The value of the resistors R at the selected operating frequency f_0 and the capacitance C of the capacitors is determined by

$$R = \frac{0,125}{C.f_0} \tag{10}$$

The widespread and widely used in practice with universal use and application μA741 can be selected as an operational amplifier (OA) in quadrature generator circuits. It is main qualitative parameters are presented in Table 1.

Table 1. The main qualitative parameters of OA μA741

OA	U_{DD}, V	U_{IO}, μV	BW, MHz	Slew/Rate, V/μs	I_{DD}, μA of OA	Output drive	CMRR, dB
μA741	<±18	1000	1	0.5	1700	±25 mA	90

3. RESULTS AND DISCUSSION

3.1. Simulation studies of the quadrature three-stage RC generator with operational amplifiers

The circuit of the quadrature generator from Figure 3 with values of the constituent elements, which is the subject of research, has been introduced in the working environment of the MultiSIM module of circuit design suite package. The created connection diagram of the experimental setup is shown in Figure 5. The obtained oscillogram from the performed simulation study for the output voltages U_{01} and U_{02} is shown in Figure 6. It is found that for both output signals the frequencies are the same f_0 =1.28 kHz and that there is a difference in their amplitudes-*U*msin=5.022 V and *U*mcos=6.726 V, respectively. The operating frequency of both outputs is also measured with Frequency counter (XFC1 and XFC2) and has the value of 1.28 kHz. The DC components at both outputs are determined by the performed Fourier analysis U_{DCsine}=-0.65 mV and $U_{DCcosine}$≈1.6 mV as well as the difference in the coefficients of total harmonic distortions (THD) THD_{SINE}=7.6 % and THD_{COSINE}=12.3 %. The THD factor for RC generators with operational amplifiers can reach up to 10-15% due to its high output voltages.

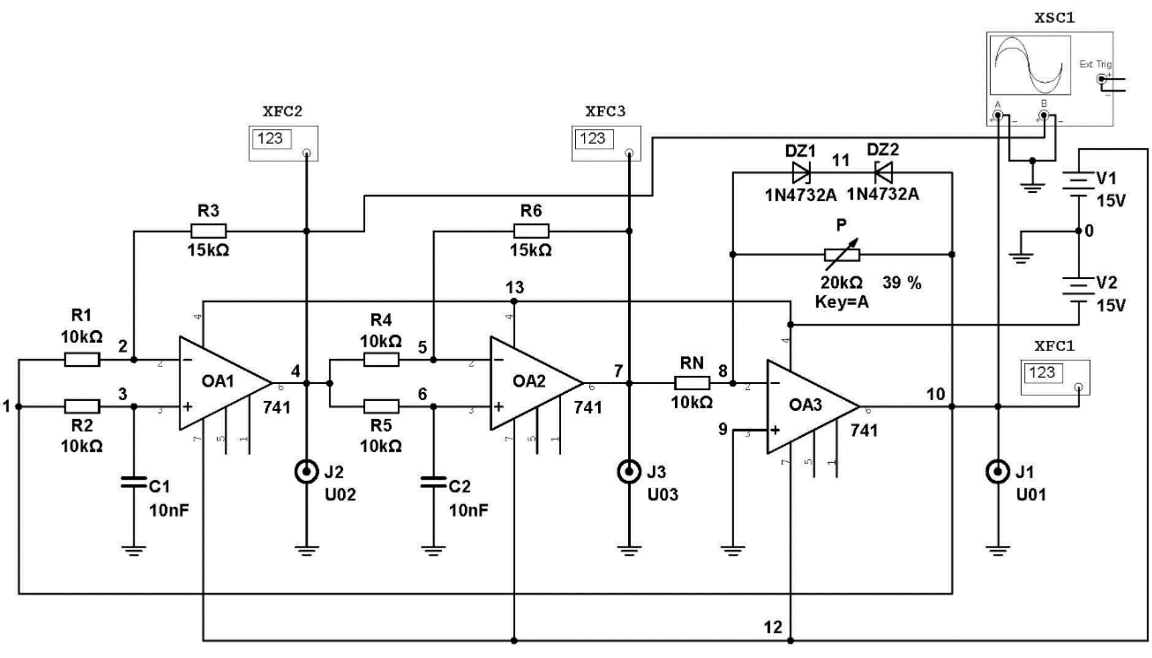

Figure 5. Connection diagram of the experimental setup for simulation study of the quadrature three-stage RC generator

3.2. Experimental study of the implemented quadrature three-stage RC generator with operational amplifiers

The quadrature RC generator of Figure 3 is implemented practically using an experimental set for analog circuits analog experimenter Type 3205. Table 2 presents the measured DC voltages in the specified nodes of the circuit of the implemented quadrature generator. Figures 7-10 show oscillograms of the output signals obtained from the experimental study of an implemented laboratory model of a quadrature RC generator with bipolar power supply ±15 V as shown in Figure 3, respectively for both outputs J1 (Sine) and J2 (Cosine): frequency f_0 =1.28 kHz, phase-shift $\Delta\varphi\approx 90^o$ and output voltages Um_{01}=6.1 V and Um_{02}=4.5 V. It is found that there is always a difference in the amplitudes of the two output signals. The oscillogram of the output signal of the quadrature generator J1 (U_{01}) and the intermediate J3 (U_{03}) is shown in Figure 11. It establishes their exact dephasing of 180º and the operation of OA3 as a voltage inverter.

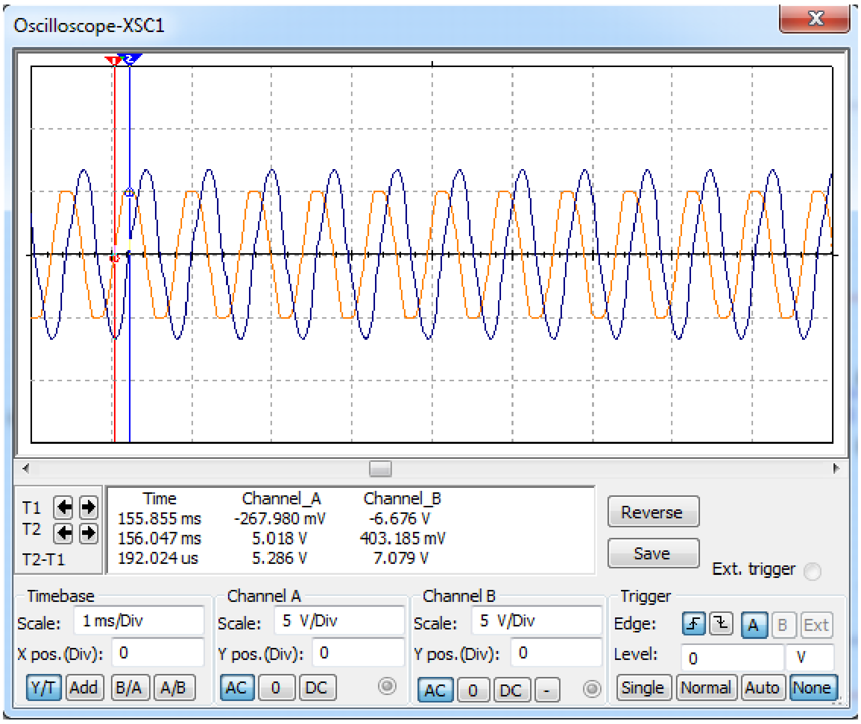

Figure 6. Oscillogram of the output signals of the simulation studied three-stage RC generator circuit with operational amplifiers of Figure 3

Table 2. DC voltages in the specified nodes of the quadrature generator

Node №	1	2	3	4	5	6	7	8	10
U₌, V (exper.)	0	-0.024	0	0.033	0.046	0.021	0.027	0	0

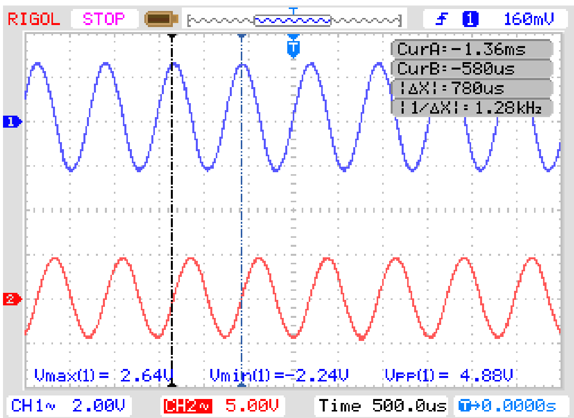

Figure 7. Oscillogram of the output signals of the quadrature generator U_{01} and U_{02}-f_0=1.28 kHz

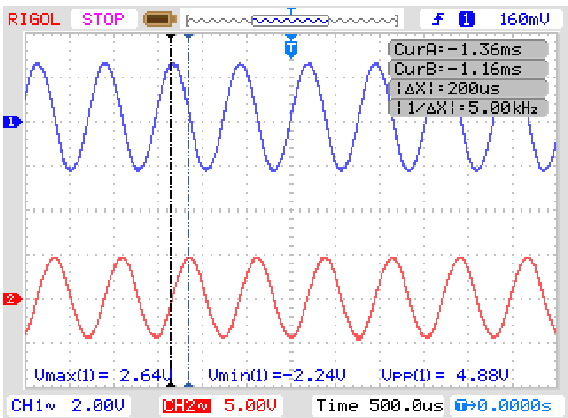

Figure 8. Oscillogram of the dephasing of the output signals U_{01} and U_{02} of the quadrature generator-$\Delta\varphi\approx 90^o$ ($\Delta t\approx$195 µs)

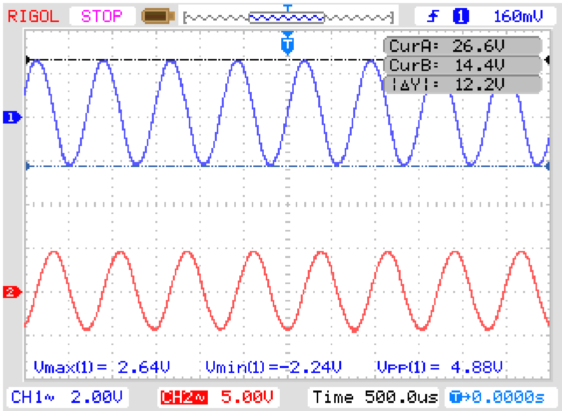

Figure 9. Oscillogram of the output signals of the quadrature generator-amplitude Um_{01}=6.1 V

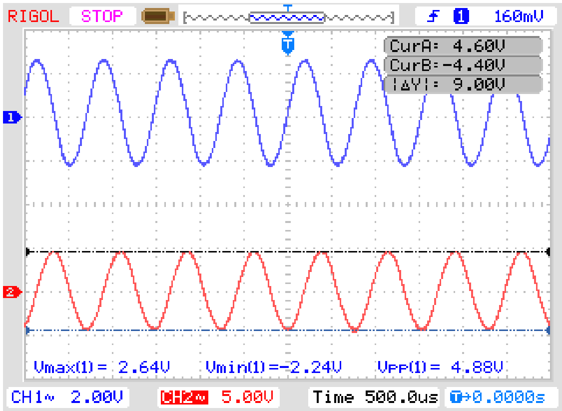

Figure 10. Oscillogram of the output signals of the quadrature generator-amplitude Um_{02}=4.5 V

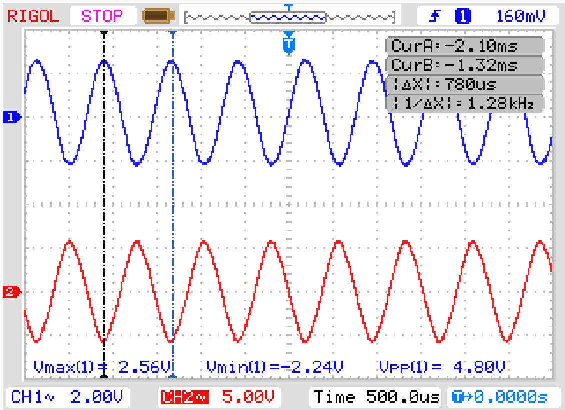

Figure 11. Oscillogram of the dephasing of the output signal of the quadrature generator U_{01} and intermediate U_{03}-$\Delta\varphi$=180°

The experimental studies were carried out with a resistance of the potentiometer P=7.5 kΩ. The amplitude balance condition is not satisfied at lower values of potentiometer resistance and for higher ones the gain is significant and the output signals are accompanied by nonlinear distortions. The minimum voltage transmission coefficient for the three stages with operational amplifiers is 1.68. A comparative assessment of the obtained parameters of the quadrature generator circuit is presented in Table 3. It can be assumed that the experimental and simulation results coincide with an accuracy of up to 20% for the amplitude of the generated signals and with total accuracy for the generated frequency.

Table 3. Comparative assessment of the parameters of the quadrature generator

Parameter	Output J1 (Sine)			Output J2 (Cosine)		
	Simulation results	Experimental results	$\mathcal{E}$, %	Simulation results	Experimental results	$\mathcal{E}$, %
u_{m0}, V	5.027	6.1	“-”17.6	6.726	6.5	3.5
f_0, kHz	1.28	1.20	**0**	1.28	1.28	**0**

4. CONCLUSION

RC generators with operational amplifiers are limited in operating frequency since they do not have the necessary bandwidth to obtain low dephasing at high frequencies. Modern operational amplifiers with current feedback have a significantly wider bandwidth, but they are very sensitive to the capacities in the feedback circuit. Operational amplifiers with voltage-controlled feedback (with frequency correction) have a limited operating range with frequencies of up to about 100 kHz. The frequency bandwidth is further reduced by cascade connection of the operational amplifiers in order to multiply/add dephasing.

The presented circuit of the three-stage quadrature RC generator in Figure 3 has the characteristics of RC generators of harmonic oscillations with a phase-rotation group. From the performed simulation and experimental studies and the obtained results it is established that they coincide with an accuracy of "-" 17.6% to 3.5% for the amplitude of the generated signals and with total accuracy for the generated frequency f_0. The THD factor of the three-stage quadrature RC generator is different for the two output signals and is of order of up to 12-13%. A problem in bringing the implemented quadrature RC generators to operation is determining and setting the necessary gain factor of the operational amplifiers themselves. Quadrature generators are widely used in communication technology and especially in the structure of digital frequency, phase and quadrature-amplitude modulators and demodulators, in vector RLC meters and many other electronic circuits and devices in practice.

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