Development of the injection current source for the information-measuring system of electrical impedance tomography of biological object

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Abstract. To implement an electrical impedance tomography device, it is necessary to develop one of its most important components - an injected current source, which characteristics affect the metrological characteristics of whole device. In this regard, the task was set to develop such a current source that satisfies a number of requirements regarding the stability of its operation in a given range of frequencies and output current amplitudes, as well as load resistances. As a result of the work performed, a voltage-controlled injected current source for an electrical impedance tomography device was developed, manufactured, and investigated. The error of the amplitude of the output current and the error of the frequency of the output current were studied using a mathematical model and during a full-scale experiment. Active resistance and a biological object were used as a load. As a result of the simulation, it was found that the error in the amplitude of the output current does not exceed 1-5% for a given range of load resistances and frequencies.

1 Introduction

One of the main components of an electrical impedance tomography (EIT) device, the characteristics of which affect the stability and metrological characteristics of the entire device, is the injected current source.

The developed CS injected current source for the EIT device must meet the following requirements:

- control of the shape, frequency f_I and amplitude I_m of the current by control voltage U_{cont} ;
- amplitude I_m output current I through load R_{load}: 1-5 mA [1];
- error δ_I amplitude I_m output current I – no more than 5%;
- maximum frequency f_{Imax} – 100 kHz;
- grounded load with resistance R_{load} 50 Ohm -2 kOhm [1].

These requirements are met by an CS circuit with automatic measurement and regulation of current in the load [2, 3].

2 Materials and methods

The functional diagram of the developed source for the EIT device is presented in Figure (1).

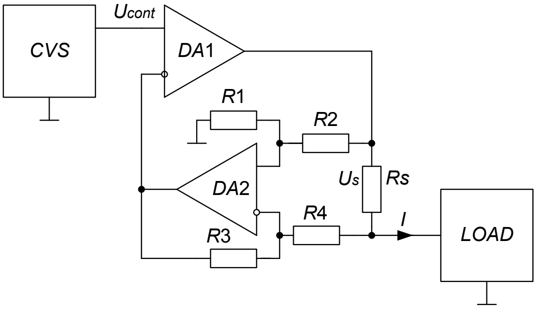


Fig.1. Functional diagram of CS EIT device

The output current *I* is directly proportional to the voltage drop U_s across the resistor R_s and inversely proportional to the resistance of the resistor R_s. To measure the voltage drop U_s, a differential amplifier is used on the operational amplifier *DA*2. If the gain of the differential amplifier [4] on *DA*2 $K_U = 1$ ($K_U = \frac{R_a}{R_b}$, ($R_a = R1 = R3$; $R_b = R2 = R4$)), then the output voltage of the operational amplifier *DA*1 is set such that the voltage drop U_s across the resistor R_s is equal to the input voltage. Increasing the gain K_U allows to proportionally reduce the nominal resistance of the resistor R_s. The maximum value of the load resistance is determined by the ratio of the maximum output voltage of operational amplifiers *DA1, DA2* to the amplitude I_m output current *I* through the load R_{load}.

The circuit diagram of the developed CS injected current source for the EIT device is shown in Figure 2.

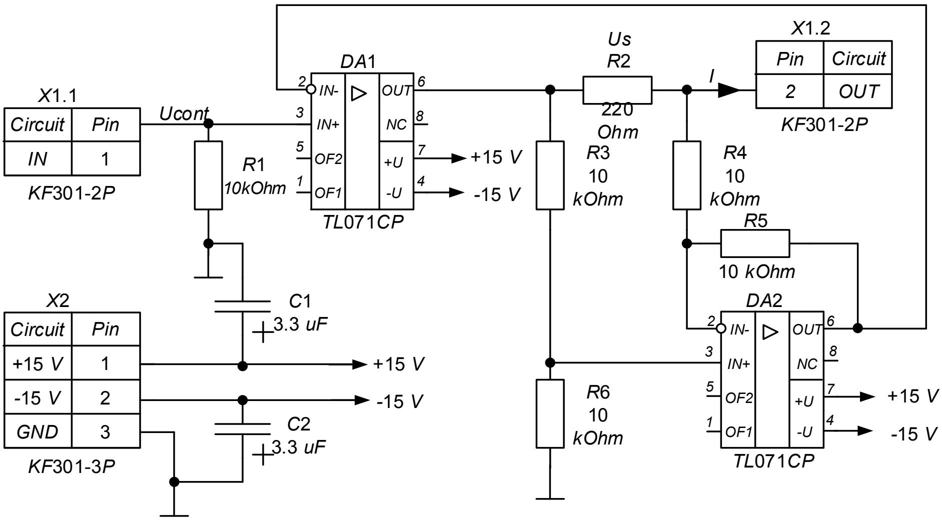


Fig.2. Schematic diagram of CS EIT device

When power is connected, all EIT device units are supplied with supply voltage. The shape and frequency f_I of the current *I* at the *OUT pin* of the current source correspond to the shape and frequency f_{cont} of the control signal U_{cont} at the *IN pin* of the current source. The amplitude I_m of the current *I* at the CS output is proportional to the amplitude U_m control voltage U_{cont} at the *IN* CS pin. The current source starts working immediately after power appears. Current source *IN* pin is connected to the common point through resistor *R*1 to avoid the appearance of current *I* at the *OUT* pin of CS due to the effect of induced voltage on the *IN* pin of CS.

3 Simulation of a current source circuit

Schematic electrical diagram of the developed CS for the EIT device in the *Micro-Cap* 10.0 circuit modeling package [5] is shown in Figure (3). The *GENERIC* model was selected as an op-amp with parameters corresponding to the parameters of the Texas Instruments *TL* 07 *CP* op amp [6].

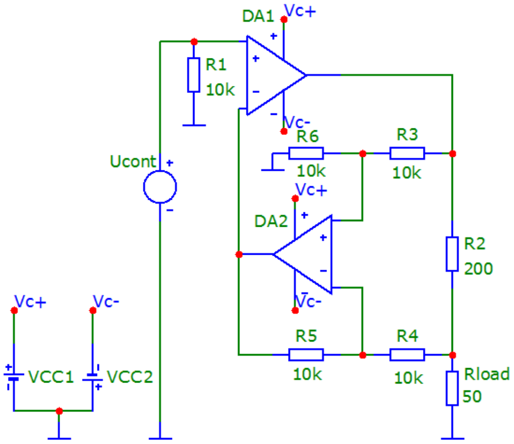


Fig.3. Model of CS EIT device in the *Micro - Cap environment*

Based on the simulation results, an estimate was made of the error δ_I of the amplitude I_m of the current *I* through the load R_{load} under various CS operating modes. The model parameters simulating various CS operating modes are summarized in Table 1.

Table 1. Model parameter values

Parameter	Range of variation
Load resistance R_{load}, Ohm	50;1 00;500;1000;1500;2000
Amplitude U_m control voltage U_{cont}, V	0.22;0.44;0.66;0.88;1.1
Resistance resistor R_s, Ohm	220
Frequency f_{cont} control signal U_{cont}, *kHz*	1;10;20;30;40;50;60;70;80;90;100

I_m of the current *I* through the load R_{load} was calculated. Next, the calculation of the reduced δ_I error in establishing the amplitude I_m of the current *I* was carried out. The calculation is made according to the formula:

$$\delta_I = \frac{|I_{m\_mod} - I_m|}{I_M} \cdot 100\%,$$

where I_{m_mod} is the calculated value δ_I of the amplitude I_m output current *I*; I_m – specified value δ_I of the amplitude I_m output current *I*, I_M – maximum specified value δ_I of amplitude I_m output current *I*.

Estimation of the spread of error values δ_I of amplitude I_m output current *I* depending on the load resistance R_{load} is presented in the form of a Box-Whiskers diagram in Figure (4). The diagram was built using the Statistica package.

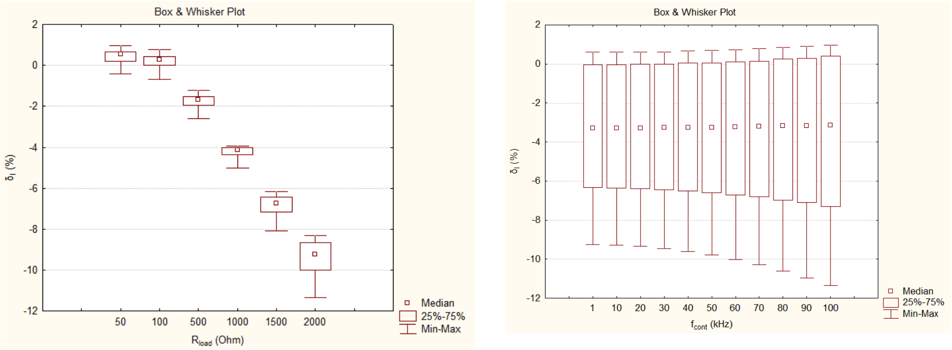


Fig.4. Estimation of error values δ_I for different values of R_{load} and f_{cont}

Estimation of the spread of error values δ_I of amplitude I_m output current I depending on the frequency f_{cont} of the control signal U_{cont} is presented in the form of a Box-Whiskers diagram in Figure (4) too.

As can be seen from Figure 4, as the value of the load resistance R_{load} increases, the error δ_I of the amplitude I_m increases output current I. This is caused by the influence of the load on the current-generating circuit. The minimum error δ_I is observed at $R_{load} \approx R_s$. With increasing frequency f_{cont} of the control signal $U_{cont,}$ the error δ_I of the amplitude I_m output current I also increases, but the influence of frequency f_{cont} is significantly less than the influence of the resistance value R_{load}. The increase in error δ_I with increasing frequency f_{cont} is caused by the imperfection of operational amplifiers. According to the simulation results, the error δ_I of the amplitude I_m output current I does not exceed 1% at resistance values R_{load} = 50.. 100 Ohms and frequency f_{cont} = 1..100 kHz. With load resistance R_{load} = 0.5..1 kOhm and frequency f_{cont} = 1..100 kHz error δ_I amplitude I_m output current I does not exceed 5%.

4 Making a current source

The electrical circuit diagram of the developed CS injected current source for the EIT device is shown in Figure (2).

When power is connected, all EIT device units are supplied with supply voltage. The shape and frequency f_I of the current I at the *OUT* pin of the current source correspond to the shape and frequency f_{cont} of the control signal U_{cont} at the *IN* pin of the current source. The amplitude I_m of the current I at the CS output is proportional to the amplitude U_m control voltage U_{cont} at the *IN CS* pin . The current source starts working immediately after power appears. *IN CS* pin is connected to the common point through resistor $R1$ to avoid the appearance of current I at the *OUT pin* of CS due to the effect of induced voltage on the *IN pin* of CS. For selected operational amplifiers *DA1, DA2,* the maximum output voltage is at least ±10 V

A drawing of a printed circuit board has been developed and an assembly drawing of the CS injected current source for the EIT device is shown in Figure (5). Development carried out in *DipTrace software* [7].

Fig.5. Appearance of assembled CS for EIT device

5 Results and discussion

In experimental studies of CS for EIT device, it is necessary to check the following characteristics:

- error δ_f of output current *I* frequency f_I;
- error δ_I output current *I* amplitude I_m.

To experimentally estimate the error δ_f of the frequency f_I of the output current *I,* we will estimate the frequency f_{load} voltage U_{load} at the reference load R_{load}. Load resistance $R_{load} = 220$ Ohm. To measure frequency, a frequency meter FM-63 is used. The main characteristics of the device are summarized in table (2).

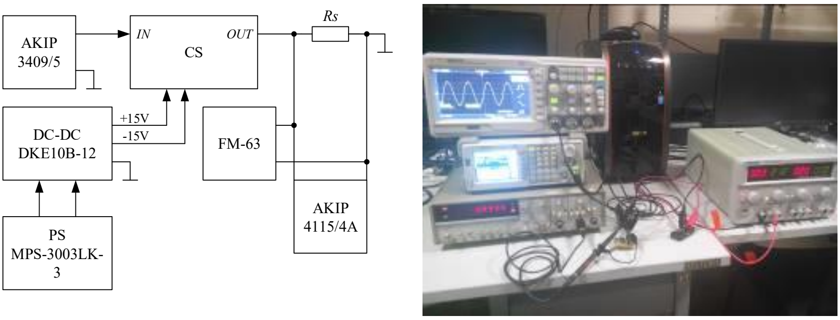
To generate the control signal $U_{cont,}$ a special form signal generator AKIP-3409/5 is used [8]. The main characteristics of the generator are summarized in table (3).

The error δ_f of the frequency f_I of the output current *I* will be calculated using the formula:

$$\delta_f = \frac{|f_{meas} - f_{cont}|}{f_{Mcont}} \cdot 100\%,$$

where f_{meas} is the measured value of the frequency f_I of the output current *I*; f_{cont} – set value of frequency f_I of output current *I*, f_{Mcont} – maximum set value of frequency f_I of output current *I*.

The experiment is carried out for frequencies $f_{cont} = 1;10;20;30;40;50;60;70;80;90;100$ kHz. The number of experimental experiments was 11 repeated experiments. The diagram and appearance of the experimental stand are presented in Figure 6.



a) b)

Fig.6. Scheme (a) and appearance (b) of the experimental setup

The results of assessing the error δ_f of the frequency f_I of the output current I are presented in Figure 7. The figure shows the arithmetic mean value of the error δ_f for each value of the frequency f_I of the output current I indicating the standard deviation.

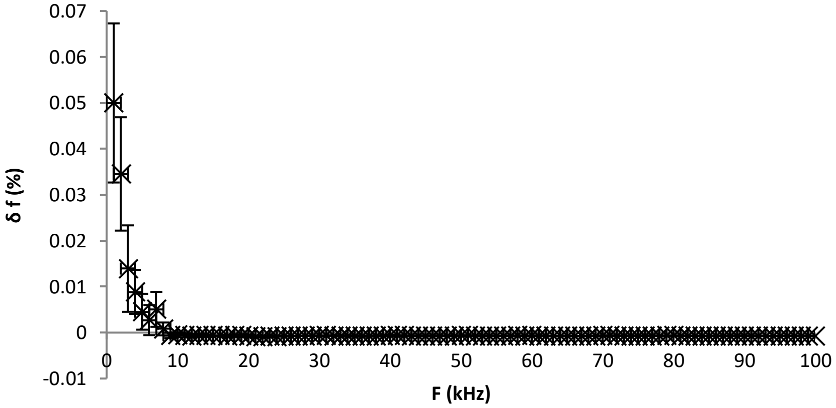


Fig.7. Estimation of error δ_f frequency f_I of output current I

As can be seen from Figure 7, the maximum relative error δ_f of the frequency f_I of the output current I does not exceed 0.07%. Starting from frequency f_I = 8 kHz error δ_f does not exceed 0.001%.

To experimentally estimate the error δ_I of the amplitude I_m output current I we will estimate the amplitude I_m current I through the reference load R_{load}. The resistance store P4831 [9] is used as the load R_{load}. Load resistance R_{load} = 50;100;500;1000;1500;2000 Ohm. The main technical characteristics of the resistance store are presented in table (4).

To measure the amplitude I_m of the current I_{load}, a universal voltmeter AKIP-2101 is used [10]. The main characteristics of current measurement with the AKIP-2101 voltmeter are summarized in table (5).

The AKIP-2101 voltmeter allows you to measure the effective I_{RMS} value [10] of the current, taking into account the signal shape and distortion (*True RMS*). The amplitude I_m value is calculated using the formula:

$$I_m = I_{RMS} \cdot \sqrt{2},$$

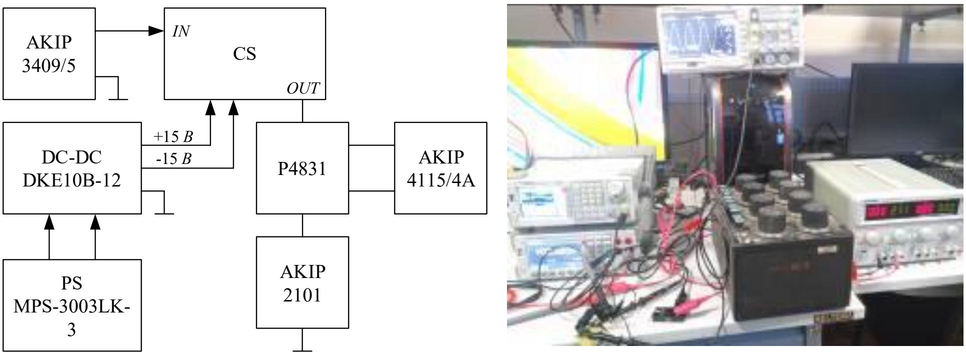
where I_m is the amplitude of alternating current; I_{RMS} – effective value of alternating current.

Calculation of the error δ_I of the amplitude I_m output current I will be produced according to the formula:

$$\delta_I = \frac{|I_{m\_meas} - I_m|}{I_M} \cdot 100\%,$$

where I_{m_meas} is the measured value δ_I of the amplitude I_m output current I; I_m – specified value δ_I of the amplitude I_m output current I, I_M – maximum specified value δ_I of amplitude I_m output current I.

The experiment is carried out for frequencies f_{cont} = 1; 10; 20; 30; 40; 50; 60;70; 80; 90;100 kHz and amplitudes I_m =1; 2; 3; 4; 5 mA. The number of experimental experiments was 11 repeated experiments. The diagram and appearance of the experimental stand are presented in Figure 8.



a) b)

Fig.8. Scheme (a) and appearance (b) of the experimental setup

After calculating the error values δ_I amplitude I_m output current I for each series of repeated experiments, the arithmetic mean value of the error δ_I was calculated and processing was carried out similar to the processing of the simulation results. Estimation of the spread of error values δ_I of amplitude I_m output current I depending on the load resistance R_{load} is presented in the form of a Box-Whiskers diagram in Figure (9). The diagram was built using the Statistica package.

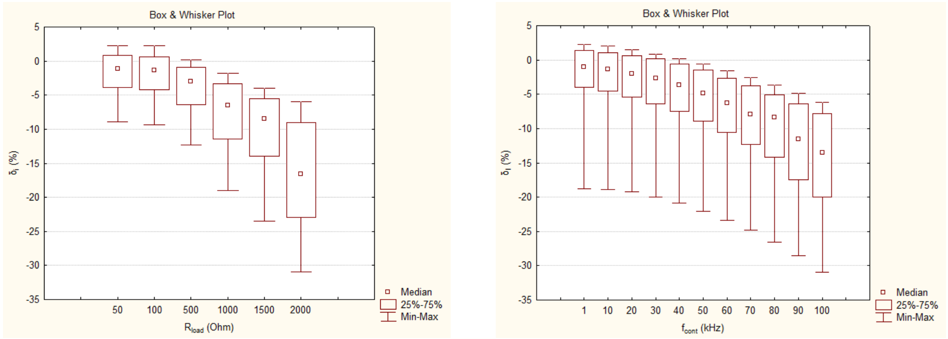


Fig.9. Estimation of error values δ_I for different values of R_{load} and f_{cont}

Estimation of the spread of error values δ_I of amplitude I_m output current I depending on the frequency f_{cont} of the control signal U_{cont} is also presented in the form of a Box-Whiskers diagram.

As can be seen from Figure 9, as the value of the load resistance R_{load} increases, the error δ_I of the amplitude I_m increases output current I. This is caused by the influence of the load on the current-generating circuit. With increasing frequency f_{cont} of the control signal $U_{cont,}$ the error δ_I of the amplitude I_m output current I also increases, but the influence of frequency f_{cont} is significantly less than the influence of the resistance value R_{load}. The influence of frequency in the experiment is more obvious than in the simulation. According to the experimental results, the error δ_I of the amplitude I_m output current I does not exceed 5% at resistance values R_{load} = 50..500 Ohm and frequency f_{cont} = 1..50 kHz. With load resistance R_{load} = 1 kOhm and frequency f_{cont} = 1..30 kHz, amplitude error δ_I of I_m output current I does not exceed 5%. With load resistance R_{load} = 1.5 kOhm and frequency f_{cont} = 1..10 kHz error δ_I amplitude I_m output current I does not exceed 5%.

The human forearm was also used as a load. To do this, using a special medical belt, two rheographic electrodes were attached approximately in the middle of the forearm. The electrodes were located diametrically opposite. The appearance of the CS connection to the

BO is shown in Figure 10. To improve contact between the electrodes and the skin, pieces of fabric moistened with water were placed. The experiment is carried out for frequencies f_{cont} = 1; 10; 20; 30; 40; 50; 60; 70; 80; 90;100 kHz and amplitudes I_m =1; 2; 3; 4; 5 mA.

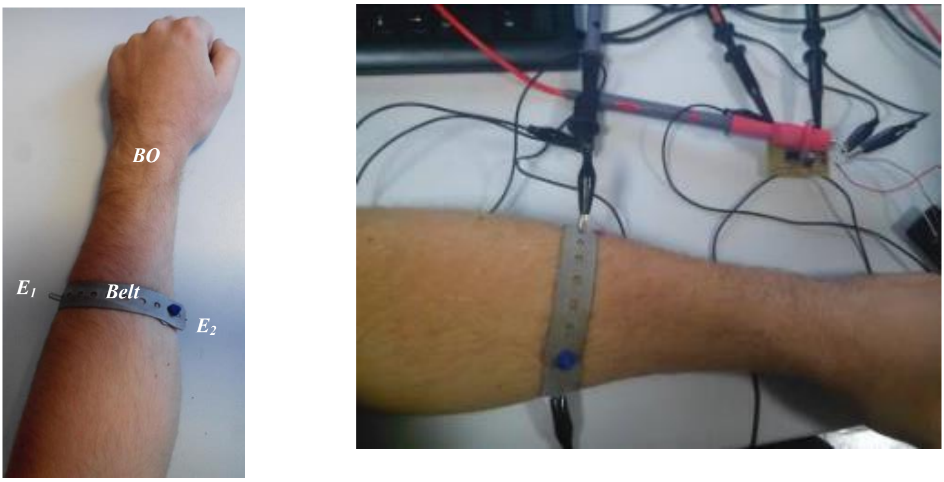


Fig. 10. Appearance of CS connection to BO

Figure (11) shows a graph of the error δ_I versus frequency f_{cont} control signal U_{cont} at different amplitudes I_m of current I when using a biological object as a load.

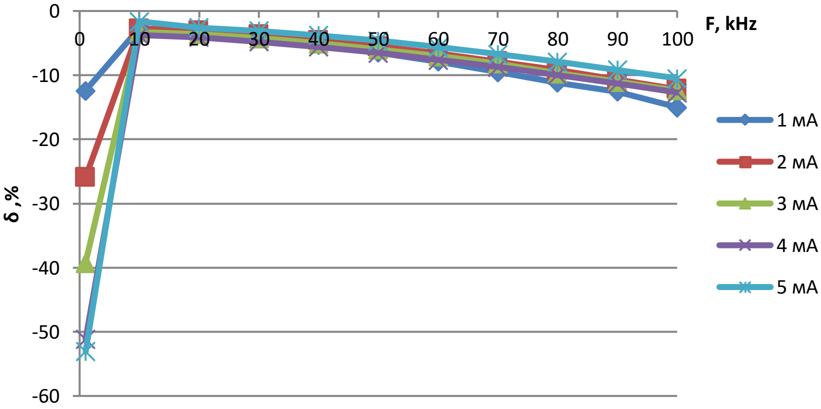


Fig. 11. Results of calculating the error δ_I

As can be seen from Figure (11), at low frequencies the resistance exceeds 2 kOhm, which does not allow the CS to deliver the required current. The highest accuracy was achieved with amplitude I_m = 5mA and frequency 10 kHz. Error δ_I of amplitude I_m output current I does not exceed 5% frequency f_{cont} = 10..30 kHz.

6 Conclusion

As a result of the work, an CS injected current source for the EIT device was developed, assembled and investigated. This current source is controlled by voltage and allows you to pass through a grounded load R_{load} up to 2 kOhm a current with an amplitude I_m of up to 5 mA. Study of the error δ_I of the amplitude I_m output current I and error δ_f frequency f_I output current I was produced on a mathematical model and during a full-scale experiment. Active resistance and a biological object were used as the load R_{load}. As a result of the simulation, it was established that the error δ_I of the amplitude I_m output current I does not exceed 1% at resistance values R_{load} = 50..100 Ohm and frequency f_{cont} = 1..100 kHz. With load resistance R_{load} = 0.5..1 kOhm and frequency f_{cont} = 1..100 kHz error δ_I amplitude I_m output current I does not exceed 5%. As a result of a full-scale experiment, it was established that when using active resistance as a load R_{load}, the error δ_I of the amplitude I_m output current I did not exceed 5% at resistance values R_{load} = 50..500 Ohm and frequency f_{cont} = 1..50 kHz. With load resistance R_{load} = 1 kOhm and frequency f_{cont} = 1..30 kHz error δ_I amplitude I_m output current I does not exceed 5%. With load resistance R_{load} = 1.5 kOhm and frequency f_{cont} = 1..10 kHz error δ_I amplitude I_m output current I does not exceed 5%. However, this error can be compensated by changing the amplitude U_m control voltage U_{cont}. To do this, it is necessary to introduce an exemplary resistance into the load circuit and measure the voltage drop across it. Based on the measured data, it is possible to calculate the amplitude value I_m output current I and compensate for the error δ_I. As a result of a full-scale experiment when using a biological object as a load R_{load}, the amplitude I_m error δ_I of the output current I does not exceed 5% at frequency f_{cont} = 10.. 30 kHz.

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