

When developing and determining the principles of construction and algorithms for the operation of electrical impedance tomography devices, it is necessary to verify the adequacy of the adopted circuitry solutions, their technical level and the possibility of practical implementation. To assess the technical capabilities and operating parameters of the device and its components, it is advisable to develop specialized tools for research and adjustment. Considering that the devices for electrical impedance tomography being developed are hardware and software solutions, and their components are complete electronic units that interact with each other, it seems possible to develop an experimental bench.

The development of a virtual automated experimental bench for preliminary tests of the main components of the electrical impedance tomography channel is proposed. On the basis of the operating principles of the hardware bench, the principles of building a virtual bench are formulated. The correspondence of the main elements of hardware and virtual benches in terms of their functional purpose is shown.

For each of the software components of the virtual bench, input actions and output parameters are determined.

A schematic diagram of the analog part of the electrical impedance tomography channel has been developed to test the performance of the virtual bench. Studies have shown that the developed virtual bench is suitable for preliminary testing of all analog components of the channel.

The use of the developed virtual bench will allow optimizing the time and material costs for conducting experimental research in the process of developing hardware for technical means of electrical impedance tomography

Keywords: electrical impedance tomography, test bench, virtual bench, automated tests, experimental research

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1. Introduction

To check the components of the electrical impedance tomography (EIT) channel for compliance with the requirements of regulatory documents, it is necessary to carry out tests that include multiple repeated effects with simultaneous recording of the response [1]. To avoid accidental error during testing, it is also necessary to retest. Thus, due to the large number of repeated measurements, there is an urgent task of automating this process.

Taking into account the set of components included in the electrical impedance tomography device, which include the source of injected current, the switching circuit of the electrode system, and the measuring part, the task is to develop an experimental bench. The bench being developed should provide testing of the operation of the EIT device:

- devices entirely in different climatic conditions;

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DEVELOPMENT AND RESEARCH OF A VIRTUAL TEST BENCH FOR ELECTRIC IMPEDANCE TOMOGRAPHY CHANNEL MAIN COMPONENTS SIMULATION

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- measurement of the strength and frequency of the injected current, its shape;
- measurement of the error of the measuring channel of the device.

To optimize the resource intensity and labor intensity of the design and development of technical means for electrical impedance tomography, it is proposed to build a virtual automated bench for conducting preliminary tests of the EIT channel components.

2. Literature review and problem statement

The work [2] is devoted to the creation of a virtual bench for the study of optoelectronic systems in the conditions of research laboratories and experimental design departments. The actual problem of the absence of computer-oriented technologies for virtual simulation of optoelectronic systems

is noted. The advantages of using a virtual bench in the form of the possibility of demonstrating promising products to potential customers are shown. At the same time, the work does not fully describe the basic principles of creating such a bench. To a lesser extent, attention is paid to the software for virtual testing of electronic circuits, the main emphasis is made on the description of the capabilities of such bench, if created, when designing optical devices.

On the contrary, the work [3] discloses the issues of creating a virtual bench for testing electronic analog components. The paper describes methods for diagnosing faults in analog circuits. The disadvantages of this work include the development of principles for constructing a virtual test bench for work in a highly specialized area (development of a USB oscilloscope that can be used in test benches for gimbal transmissions). Also, the article does not disclose the issues of testing models containing more complex integrated circuits, analog, digital, and mixed.

The work [4] discloses the issues of creating virtual test benches based on various simulators that can be used on a single platform. This article describes the development process for complex systems-on-a-chip, such as trusted personal devices, for which cost and time to market are very important constraints. The development of a virtual test bench for electromagnetic compatibility and power consumption of a Bluetooth transceiver is given as an example. The article is more focused on the description of the development of virtual benches for the design of devices operating in the radio air; not enough attention is paid to the modeling of complex analog circuits.

The work [5] describes the development of the creation of a universal virtual instrumentation in tasks of electrical impedance tomography based on National Instruments LabWindows [5]. It should be noted that the development described in the article is designed to work together with expensive hardware in the form of a data capture card. In addition, the development is aimed at studying various configurations of electrode systems and layouts of the objects under study, but not modeling the EIT technical means.

Work [6] is devoted to the development of a system for carrying out automated research by the EIT method on the models of the investigated objects. The development allows in the automatic mode to carry out experimental studies with a large number of repetitions. At the same time, complex and expensive hardware is used in the form of a data collection system, a model of a biological object, and an industrial robot with six degrees of freedom.

The work [7] describes the creation of a bench for testing various configurations of electrode systems in order to optimize them. At the same time, the issues of testing the electrical circuits of the EIT device did not remain unresolved in the work.

Thus, in [2–4], methods for solving the problems of creating virtual benches for testing electronic circuits within the framework of certain highly specialized tasks are described. These studies could have a certain value for solving the problems of designing technical means of electrical impedance tomography, however, unresolved issues in the form of an insufficient description of the bench development for studying the signal transmission through analog circuits of semiconductor devices, in particular for medical purposes, impede their use. The works [5–7] investigate the issues of creating specialized benches for EIT problems. A common drawback of these works is the widespread use of hardware, which is accompanied by high costs for such studies. In addition, the mentioned works do

not touch upon the issues of testing electrical circuits of EIT technical means.

Thus, some of the analyzed works devoted to the development of test benches describe the solution of highly specialized problems that are not related to the development and design of medical devices. On the contrary, other analyzed works propose solutions to the issues of developing a bench in EIT tasks in the field of researching models of biological objects and electrode systems, which require significant time and money to conduct such experimental studies.

An option for overcoming the corresponding difficulties can be the development of a virtual automated bench for studying the schematic diagrams of the main components of the EIT device. Minimizing the use of hardware at the stage of preliminary tests will reduce the resource intensity of such experimental studies and, thus, increase the relevance and expediency of their implementation.

3. The aim and objectives of research

The aim of research is to develop a virtual automated bench for preliminary tests of the main components of the electrical impedance tomography channel based on schematic diagrams with minimizing the use of hardware. The virtual bench should support testing of as many analog components of the EIT channel as possible. Also, the virtual bench should provide an automated determination of the investigated electrical parameters of electronic components and their display in graphical form.

To achieve the aim, the following objectives are set:

- to develop a structural diagram of a virtual automated bench based on the requirements;
- to develop a structural and schematic diagram of the EIT channel components for conducting experimental research;
- to conduct experimental studies of the developed schematic diagram of the EIT channel on a virtual bench to determine the main parameters of the study.

4. Materials and methods of research of the virtual bench

4.1. Development of a structural diagram of the virtual bench

To develop a virtual bench that matches the functionality of the hardware bench, it is necessary to analyze the requirements for such a bench and the principles of its functioning.

A hardware bench for testing medical devices must meet a number of requirements:

- ability to change the temperature and humidity in a given range;
- ability to supply electrical signals of a given shape, amplitude and frequency;
- ability to process the measuring signal in a wide range of frequencies and amplitudes

Thus, to test the components of the EIT device, the following hardware is required:

- personal computer;
- oscilloscope;
- generator;
- multimeter;
- climate chamber with program control.

Let's consider a block diagram of a hardware bench for testing the components of EIT devices that meets these requirements (Fig. 1).

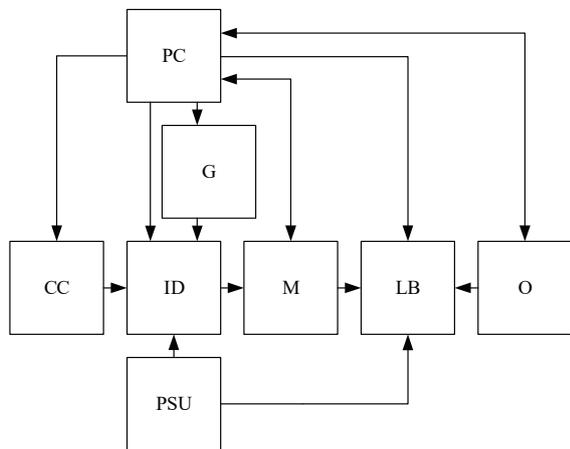


Fig. 1. Block diagram of the bench for testing the EIT module components

The algorithm for the functioning of the hardware bench for EIT tasks is based on the following principles. The bench is controlled using a personal computer PC and software installed on it. The climatic chamber CC provides control of the temperature and relative humidity of the air acting on the investigated part of the device (ID). CC control should be done using a PC. ID power supply is provided by means of an adjustable power supply unit PSU. The influence on the ID is produced by the voltage from the output of the generator G, the shape, frequency and amplitude of which are set using a PC. ID output is loaded onto a different resistive load in the form of a load box LB, which, on command from a PC, switches the loads. The amplitude value of the current at the ID output is measured with a multimeter M, the voltage oscillograms are recorded using an oscilloscope O. Data from M and O are transferred to the PC for further processing. It is possible to control the ID using a PC.

To test the components of an EIT device using a virtual test bench, it is necessary to have software modules with a purpose similar to hardware.

Requirements are put forward for software modules as part of a virtual bench, which are similar to those for hardware bench modules:

- the ability to set the temperature and humidity modes of operation of the investigated device;
- generation of electrical signals of a given shape, amplitude and frequency;
- registration of measuring signals in a wide range of frequencies and amplitudes;

As a package of such software modules, let's consider the Microcap 12 software developed by Spectrum Software [8]. The software in question provides the following functionality:

- analysis of electrical operating modes of analog and digital devices according to the given basic and functional diagrams;

- construction of graphs of amplitude-frequency (AFC) and phase-frequency (PFC) characteristics, as well as graphs of complex dependencies.

- analysis of transient processes, low-signal frequency characteristics of the circuit, transfer characteristics for direct current. In addition, component models in MicroCAP allow for temperature dependences.

Thus, using this software, it is possible to test the components of EIT devices.

The block diagram of the virtual bench for testing the components of EIT devices, developed on the basis of the analysis of the operation principles of the hardware benches, is shown in Fig. 2.

The virtual bench is controlled using the MicroCap software. The climatic chamber was replaced by a software module for setting the temperature (SMT). The influence on the ID is produced by the voltage from the output of the generator program module PM, which allows to set the shape, frequency and amplitude of the signal. The amplitude values of the ID output parameters and frequency characteristics are recorded using software modules for analyzing transient processes and frequency characteristics (TP and FC, respectively).

Thus, to test the components of the EIT device, it is necessary to match the hardware and virtual test benches in terms of their functional purpose. The correspondence of the blocks of the developed virtual bench to those of the hardware bench is reflected in Table 1.

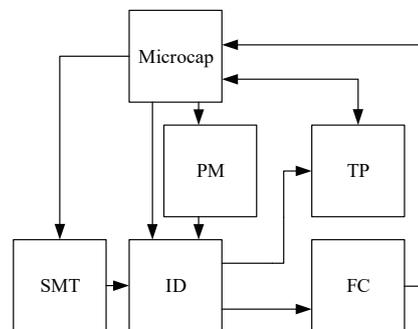


Fig. 2. Block diagram of the virtual bench for testing the EIT module components

Table 1

Correspondence of the main blocks of the hardware and virtual benches

Hardware bench unit	Virtual bench block	Note
Personal computer (PC)	MicroCap medium	In the hardware bench, the PC with the OS installed controls the test process
Climatic chamber (CC)	Temperature setting software module (SMT)	With this program module in the MicroCap software it is possible to set the temperature of the tested blocks. Humidity setting in MicroCap environment is not supported.
Generator (G)	Generator software module (PG)	Like the hardware generator, the PG supports various waveforms, while its basic parameters (frequency, amplitude, phase) can be set in a wider range.
Resistance box (RB)	Not required	With the Microcap software it is possible to set the value of the load resistance in a wide range.
Multimeter (M)	Transient analysis software module (TP)	Using the specified software modules in the MicroCap software, it is possible to measure and record the amplitude values of the voltage, current of the measured signal. Registration, output and storage of amplitude-frequency, phase-frequency characteristics are supported.
Oscilloscope (O)	response analysis software module (FC)	
Power supply unit (PSU)	Not required	When a supported electronic component is added to MicroCap software, the required power supply is automatically added. It is possible to vary the power parameters of each element

As it is possible to see from the Table 1, each for each of the blocks of the hardware bench has a functional analogue in the form of a virtual bench block. In addition, due to the absence of physical limitations, each of the blocks of the virtual bench can operate in a wider range of user-specified parameters. At the same time, as in any other computer simulation, for such a virtual test bench there are simplifications and limitations of use: for example, the direct setting of the ambient air humidity during testing in Microcap software is difficult.

4. 2. Schematic diagram of the study of an electrical impedance tomography device using a virtual bench

The EIT method consists in the following: an electric current of high frequency and low amplitude is supplied to the object under study by means of electrodes located on its surface [9]. The voltages on the surface of the object are recorded, after processing the measurement information, the distribution of the electrical conductivity of the internal structures of the object in tomographic sections is estimated [9].

Thus, to implement the EIT method, it is necessary to use a current source, switching and measurement circuits, control circuits and a computing device.

The block diagram of the EIT device is shown in Fig. 3.

The EIT device includes the following modules [9]:

- microprocessor;
- source of injected current;
- amplifier of the measuring signal;
- analog-to-digital converter;
- switching unit;
- power supply unit;
- electrode system.

Taking into account the need to measure the parameters of the injected current and the measuring channel of the device, it is possible to distinguish two components of the EIT device,

the study of which is necessary and possible with the help of a virtual bench:

- part 1 includes the source of injected current and multiplexers of the injection channel of the switching unit;
- part 2 includes the amplifier of the measuring signal and the multiplexers of the measuring channel of the switching unit.

Fig. 4 shows a schematic diagram created in Microcap software for further research. The diagram shows that the source of injected current (IC), built according to the Howland scheme on operational amplifiers X6 and X7 [10], is connected to one of the multiplexers of the injection channel X1. The multiplexer X2, in turn, is connected to the midpoint. The source of the control voltage for the IC is the PM v19. As an object connected to the multiplexers of the injection channel X1 and X2, as well as the multiplexers of the measuring channel X3 and X4, the equivalent circuit of the biological object [7] on the elements R1 and C1 was chosen.

The X3 and X4 multiplexers are connected to the inputs of the X8 programmable gain operational amplifier [11]. The load for X8 is RA, which simulates the input resistance of the analog-to-digital converter (ADC).

Thus, with the help of the virtual bench, all analog components of the EIT device can be tested.

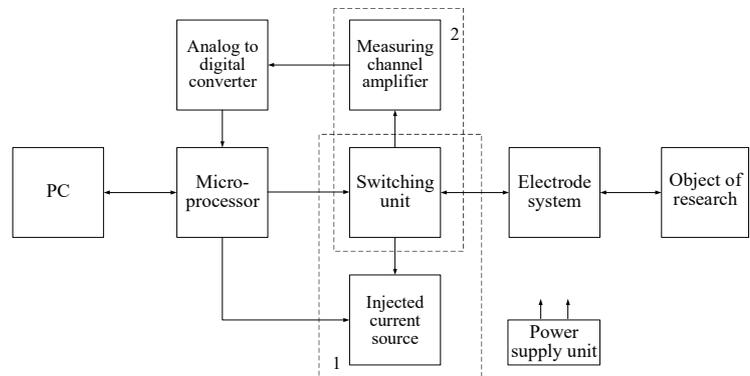


Fig. 3. Block diagram of the EIT device

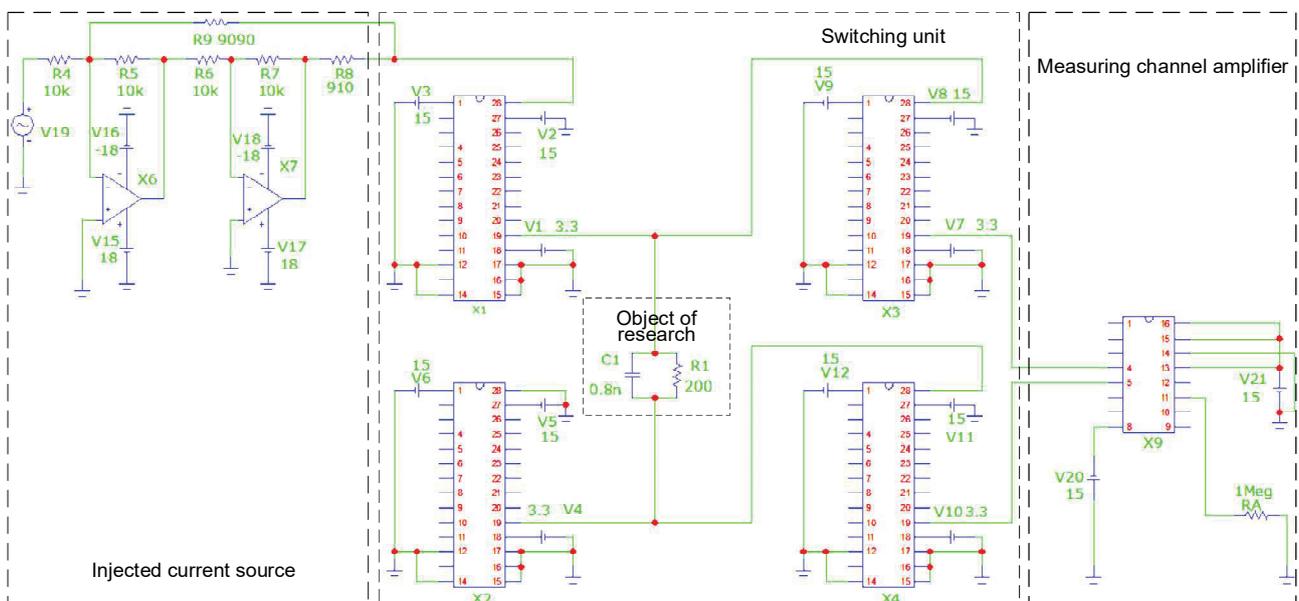


Fig. 4. Schematic diagram of the main components of the EIT device when tested on a virtual bench

5. Experimental studies of the EIT channel components on a virtual bench

5.1. Injection current source tests

The injection channel of the EIT device includes IC and multiplexers X1 and X2. The IC input is connected to the PM output, the IC is controlled by an alternating voltage U_{PM} of high frequency and various waveforms (sinusoidal, rectangular, triangular).

As mentioned, the IC is a source of current with a grounded load, built according to the Howland scheme. The amplitude of the output current I is set by the relation $I = \frac{U_{PM}}{R_s}$ [10] For example, at $U_{PM} = 4.55$ V and $R_s = 910$ Ohm, $I = 5$ mA. The frequency of the injected current is $F = 100$ kHz. The following temperature mode of operation of the circuit is set: from 10°C to 30°C in steps of 2°C

Fig. 5 shows U_{PM} (red graph) and I (blue graph) for sinusoidal (a), rectangular (b), and triangular waveforms (c).

The “Transient” module of Microcap software allows to record the amplitude and period of the signal, its dependence on temperature.

Fig. 6 shows the frequency response (AFC) for a current source for a sinusoidal signal.

Let’s calculate the error of the values of the amplitude of the measured current amplitude I at a frequency of 400 kHz, which is estimated by the formula:

$$\delta = \frac{|I(400) - I|}{I}$$

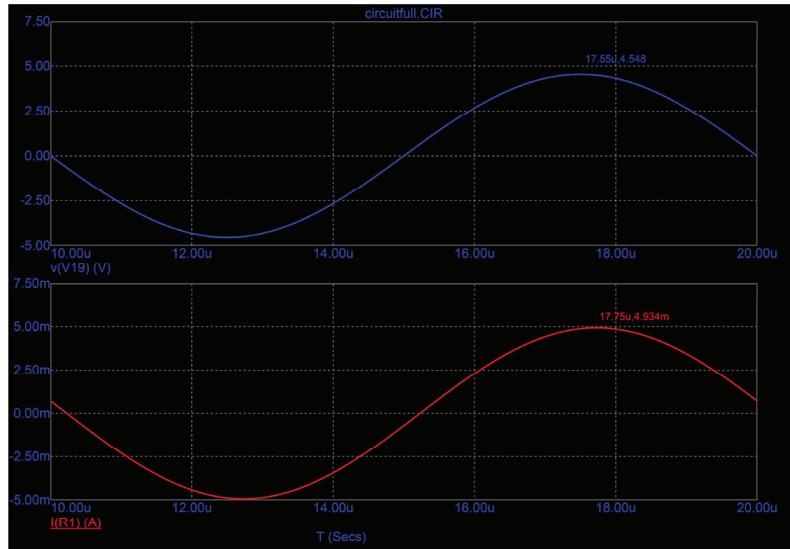
The error δI is

$$\delta = \frac{|4.92 - 5|}{5} = 1.6\%$$

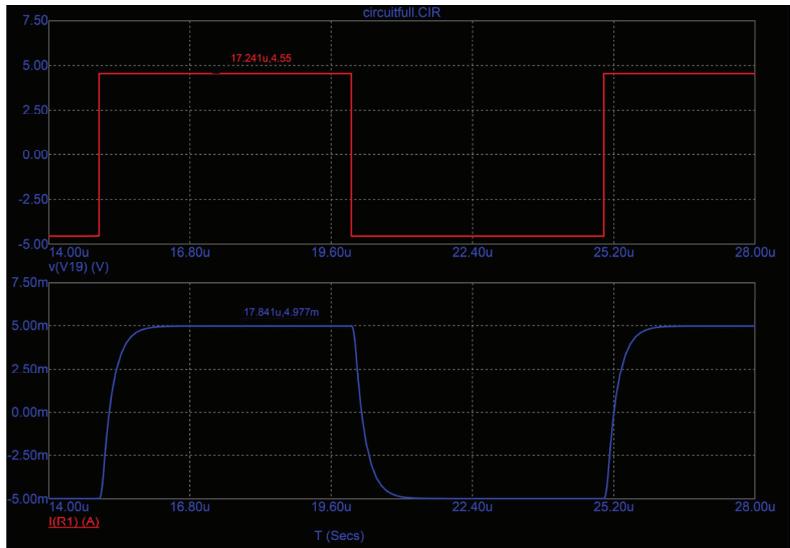
One of the most important parameters of the current source, which determines its main characteristics, is its output resistance R_{out} [9]. As it is known, an ideal current source has an infinitely large output resistance R_{out} . A real current source has a finite resistance R_{out} connected in parallel with the load resistance R_l . (Fig. 7).

As a result of the fact that R_{out} is finite, current I_{in} will flow through it. Thus, the final current I_n through the load R_n will be less than the output current I of the current source by the amount of current I_{in} . It’s obvious that:

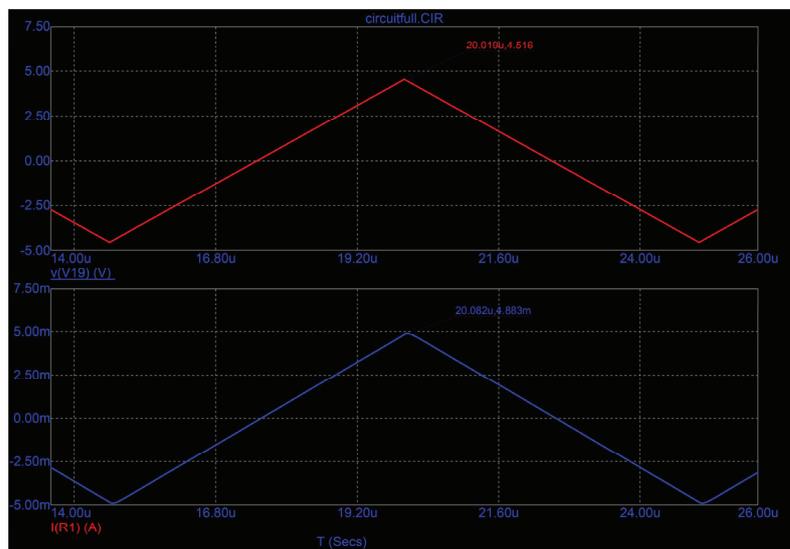
$$\frac{I_{in}}{I_n} = \frac{R_n}{R_{out}}$$



a



b



c

Fig. 5. Graphs U_{PM} and I : a – for sinusoidal; b – rectangular; c – triangular waveform

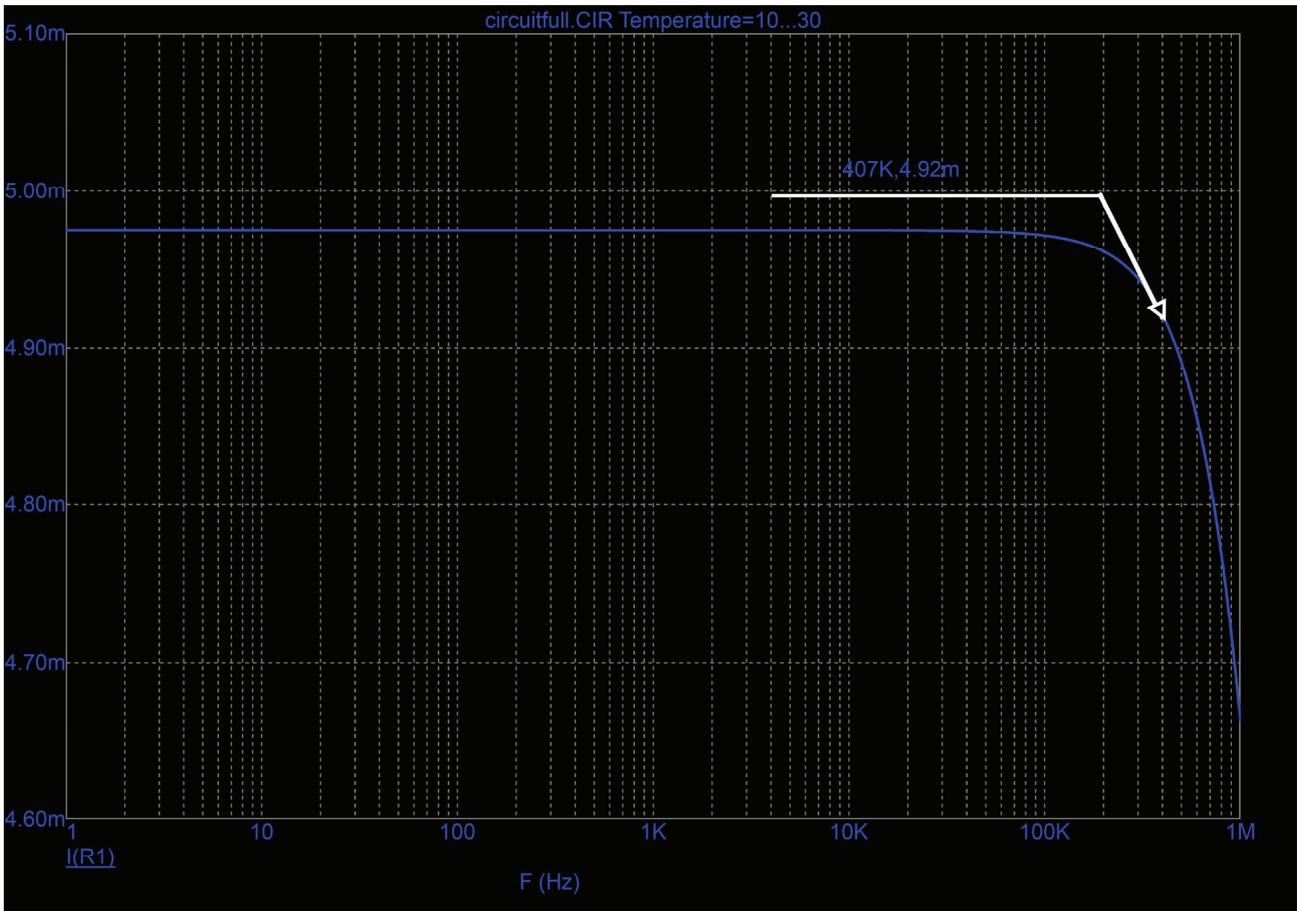


Fig. 6. Amplitude-frequency characteristic (AFC) for the current source

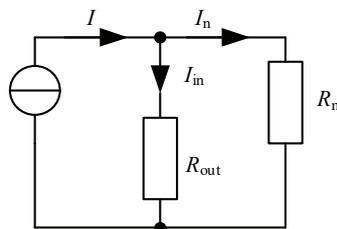


Fig. 7. Electric circuit equivalent current source

Thus, in order for the influence of the output resistance R_{out} on the current I_n through the load R_n to not exceed 1 %, the value R_{out} must satisfy the condition $R_{out} \geq 100 R_{nmax}$. It is impossible to measure the output resistance R_{out} in a direct way. But there are indirect ways of measuring R_{out} . Knowing the set current level I , as well as the value of the current I_n through the load resistance R_n for the maximum and minimum values of the load resistance R_n , it is possible to calculate the value of the output resistance of IC R_{out} by the formula [13]:

$$R_{out} = \frac{I_{n2} \cdot R_{n2} - I_{n1} \cdot R_{n1}}{I_{n2} - I_{n1}},$$

where I_{n1} – the amplitude of the current through R_n at $R_n = R_{n1}$; I_{n2} – amplitude of current through R_n at $R_n = R_{n2}$.

Thus, when conducting experimental studies on a hardware test bench, direct measurement of the output resistance of the current source is impossible. In this case,

the measurement of the amplitude I error is carried out with the simultaneous switching of the load resistors and the recording of intermediate results for the subsequent calculation of R_{out} . This method of determining R_{out} is more complicated in automation and can become a source of additional errors.

On the contrary, in Microcap software, using the built-in frequency response analysis element, it is possible to measure the dependence of R_{out} on frequency and resistance value R_n , as shown in Fig. 8.

As seen from Fig. 8, the output impedance of the current source depends on the load impedance and, to a lesser extent, on the AC frequency.

The test parameters of the components of the injected current source are given in Table 2.

Thus, the use of a virtual bench will allow testing various circuits of current sources with the determination of the amplitude and frequency characteristics of the output signal.

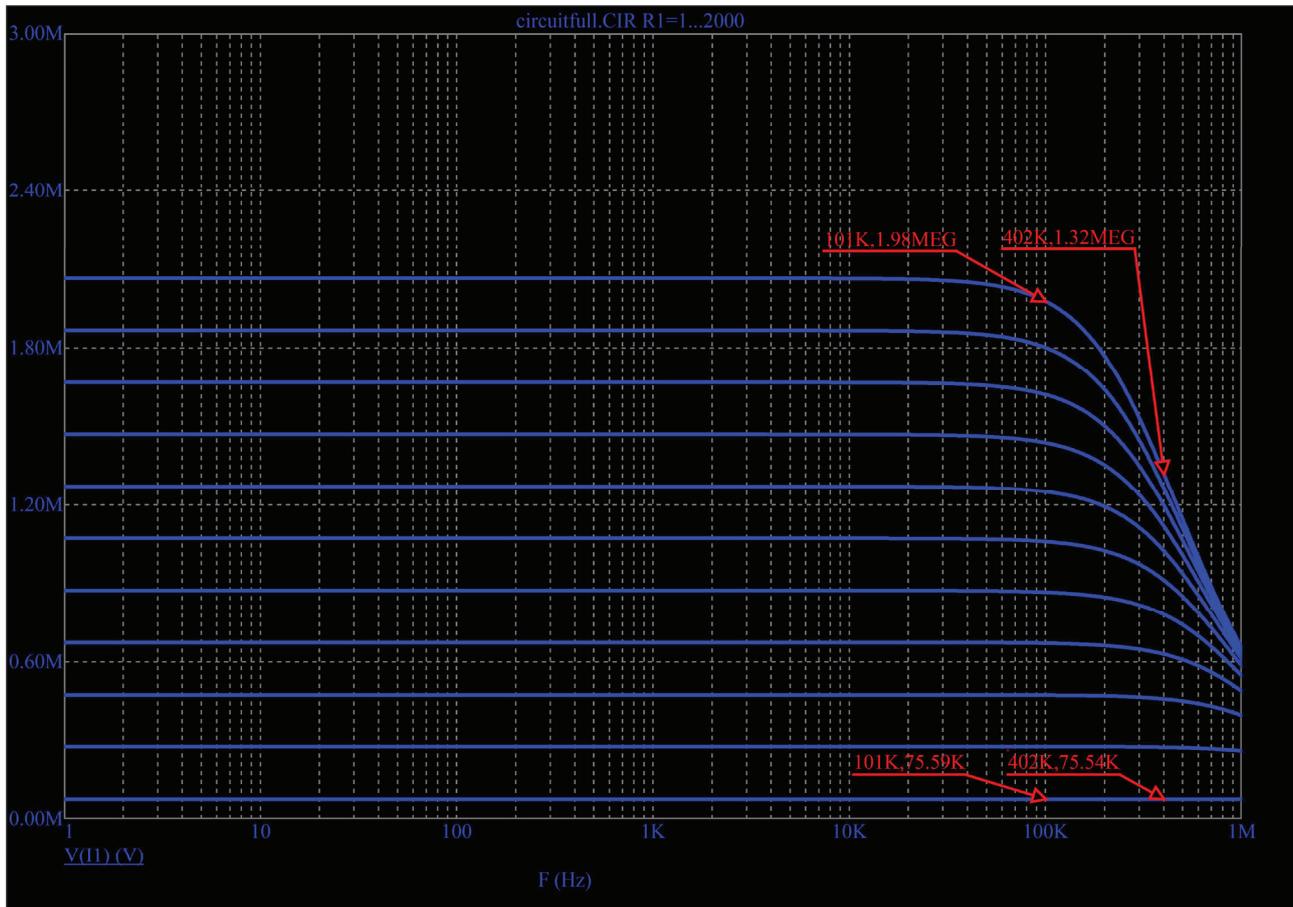


Fig. 8. Dependence of the output impedance IC on frequency

Table 2
Parameters of the study of the components of the injected current source

Component Impact type	Injected current source
Input actions	Control signal $U_{PM}((F, \text{ waveform}))$
	Load impedance R_n
	Temperature T
Output actions	I
Estimated parameter	I
	AFC $(I(F))$
	$R_{out}(F)$

5. 2. Signal amplifier test

An amplifier with a programmable gain k_U (in this case, 1, 10, 100, 1000) was selected as the amplifier of the

measuring channel. The amplifier is connected to the object of study through multiplexers X3 and X4. Resistor R_A simulates the high input impedance of an A/D converter. With the help of the software module for the analysis of frequency characteristics (FC), for each given value k_U , its measured value is determined in a given frequency range.

The amplitude-frequency characteristics of the amplifier of the measuring channel for the supported k_U are shown in Fig. 9.

As can be seen from the graph shown in Fig. 9, for each of the values k_U , it is possible to determine the frequency at which the error level k_U will satisfy the predetermined values.

The test parameters of the amplifier components of the measuring channel are given in Table 3.

Thus, using the virtual bench, the frequency range of operation of the amplifier circuits of the measuring channel can be determined for user-selected values k_U .

Table 3

Study parameters of the amplifier components of the measuring channel

Component Impact type	Amplifier
Input actions	Control signal U
	Specified amplification factor k_U
	Temperature T
Output actions	$U \cdot k_U$
Estimated parameter	AFC $(U(F))$

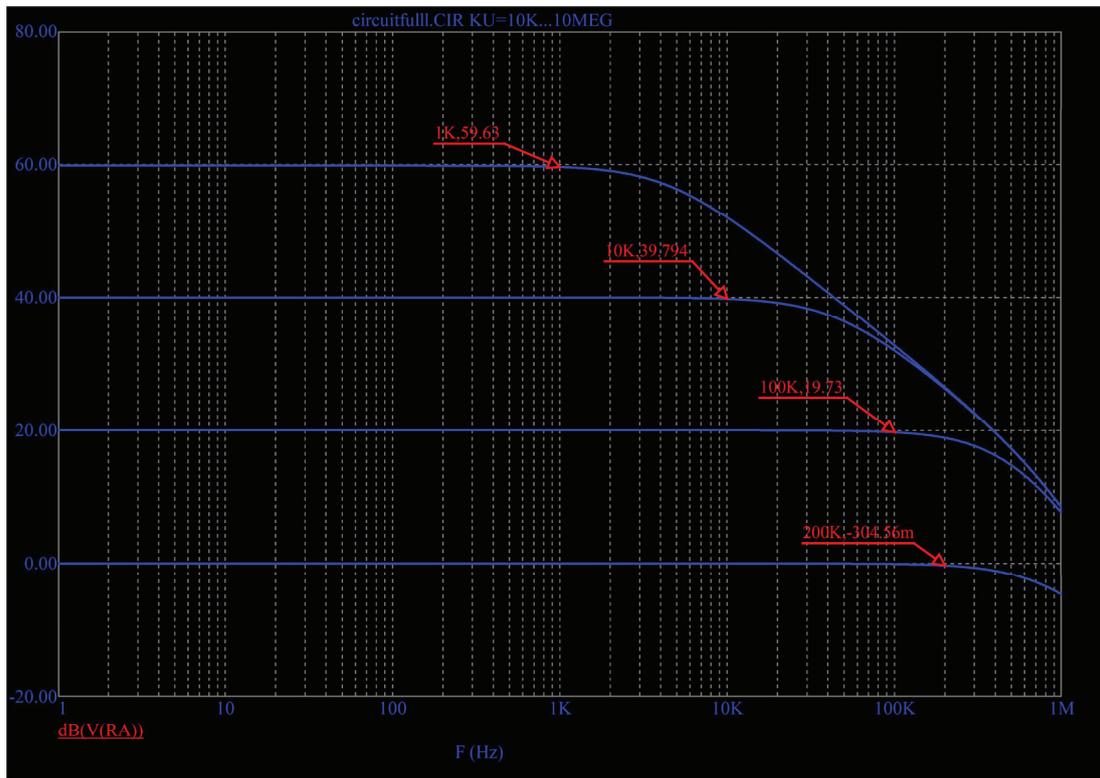


Fig. 9. AFC of the amplifier of the measuring channel for: A – $k_U=1$; B – $k_U=10$; C – $k_U=100$; D – $k_U=1000$ (D)

5.3. Switching unit tests

The main parameter of the multiplexer as an element of the switching unit is the resistance of the open channel R_{Dson} . When testing the switching unit on a hardware bench to calculate this parameter, it is necessary to measure the amplitude value of the voltage drop between the

input and the active output of the multiplexer, as well as the amplitude value I [14]. A similar operation must be carried out when testing the switching unit on a virtual bench.

The results of the measurements performed by R_{Dson} are shown in Fig. 10.

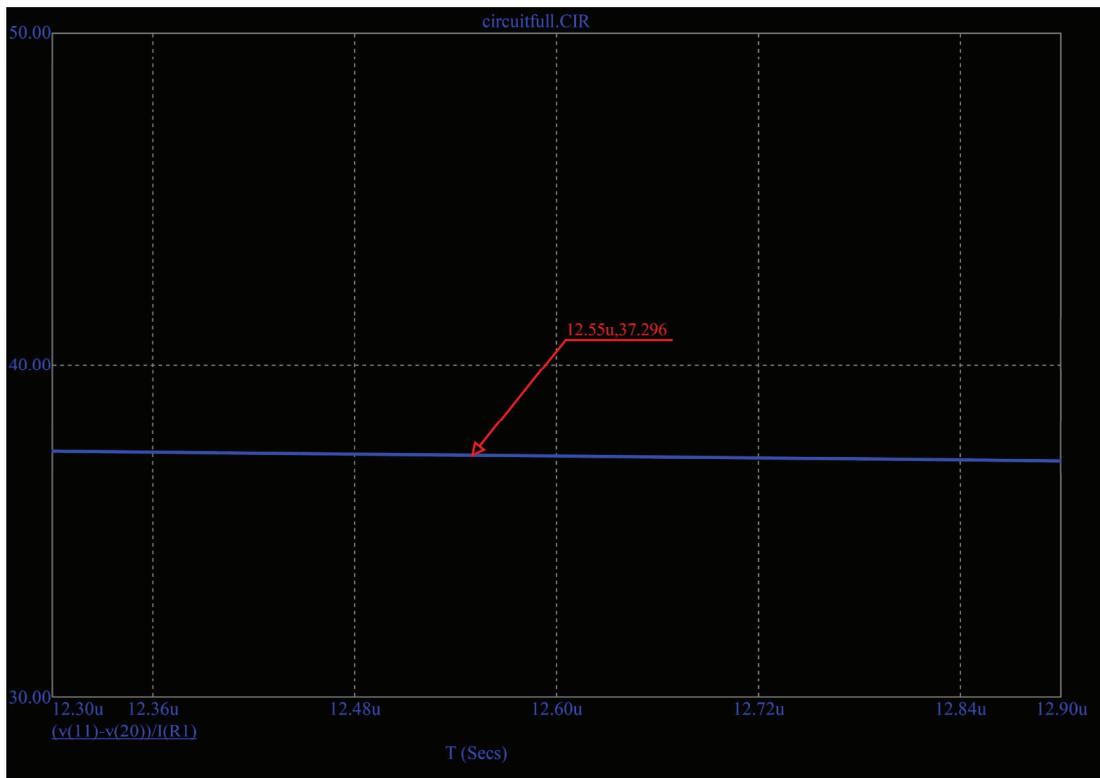


Fig. 10. Graph R_{Dson} multiplexer switching unit

The test parameters for the components of the switching unit are shown in Table 4.

Table 4

Switching unit research parameters

Component Impact type	Injection channel multiplexer	Measuring channel multiplexer
Input actions	Current source signal I	Measuring signal U
	Supply voltage U_{sup}	Supply voltage U_{sup}
	T	T
Output actions	I	U
Estimated parameter	$R_{DSon}(U_{sup}, T)$	$R_{DSon}(U_{sup}, T)$

The measurements made allow the exact R_{DSon} value to be determined for the supply voltage setpoint, temperature, and user-defined signal parameters.

6. Research results of the developed virtual bench

6.1. Results of the development of the virtual bench scheme

At the initial stage of the development of a virtual bench, which corresponds to the functionality of the hardware bench, the requirements for such a bench and the principles of its functioning were analyzed. A block diagram of a virtual bench for testing the components of EIT devices has been built. Correspondence was established for the functional purpose of the software modules of the virtual bench to the blocks of the hardware bench. At the same time, restrictions on the use of such a virtual bench have been established in the form of the impossibility of setting preset air humidity values.

6.2. The results of the development of structural and schematic diagrams of the EIT device

The block diagram of the EIT device, consisting of digital and analog components, is developed. It is shown that the analog components of the developed block diagram can be investigated using a virtual bench.

A schematic diagram of the analog components of the EIT device is built: the source of injected current, the switching unit and the amplifier of the measuring channel. The use of the selected equivalent circuit of the object under study in the developed virtual bench is substantiated.

6.3. Research results of the components of the EIT channel on the virtual bench

Experimental studies of the developed virtual bench have been carried out in terms of determining the possibility of testing the finished schematic diagrams of the EIT channel.

For testing, a schematic diagram of the EIT channel is developed, which includes:

- current source;
- switching unit;
- amplifier of the measuring channel.

For the current source connected to the PM, SMT, TP and FC of the virtual bench, parameters such as I, AFC (I(F)), and R_{out} (F) are determined.

For the amplifier of the measuring channel, parameters such as AFC ((F)) are determined for the given k_U values.

For the multiplexers of the injection and measuring channels of the switching unit, the dependence $R_{DSon}(U_{sup}, T)$ is determined.

7. Discussion of the research results of the main parts of the EIT channel on a virtual bench

As a result of the research carried out on the schematic diagram of the EIT channel (Fig. 4), the capabilities of the developed virtual bench for working with a current source, an amplifier of a measuring channel, and a switching unit were clearly shown. A feature of the proposed bench is the ability to study complete schematic diagrams of electrical impedance tomography devices. With the help of the developed bench it is possible to obtain such parameters as amplitude characteristics (Fig. 5), output resistance of the current source (graphs of dependences are shown in Fig. 8), frequency response (graphs are shown in Fig. 6, 9). Obtaining the described set of measured parameters of the investigated circuit is explained by the possibility of installing an unlimited number of virtual devices with the possibility of automatic recording of these parameters, which is difficult when using a hardware bench.

Among the advantages of the developed virtual bench, it is worth noting a high degree of automation of the process of experimental research of circuit diagrams of EIT devices with a large number of repetitions, and, accordingly, measurement data. This advantage allows to significantly increase the speed of obtaining research results and their analysis. In addition, the use of such a bench can significantly reduce the cost of testing without the use of expensive hardware solutions that require the involvement of a large number of qualified specialists, as required by the research described in [5, 6].

At the same time, it is worth noting the limitations of using the development. So, if it is possible to set the temperature modes of operation of the studied circuits, there is no possibility of setting the humidity of the ambient air. In addition, with the help of the developed bench, it is impossible to create complex models of biological objects with a field of distribution of electrical conductivity of their internal structures; it is assumed that simplified equivalent circuits will be used (Fig. 7).

To eliminate these limitations, it is planned to integrate software products into the virtual bench that implement numerical methods for solving the problem of electrical impedance tomography.

8. Conclusions

1. The basic principles of functioning of the hardware automated bench for the tasks of EIT are analyzed. On the basis of the analysis of the operation principles of the hardware bench, requirements are formed and the principles of functioning of the virtual bench are developed. On the basis of the requirements put forward and the developed principles of operation, a structural diagram of the bench is developed. The correspondence of the main software modules of the virtual bench to the corresponding functional units of the hardware bench is indicated (for example, the hardware generator functionally corresponds to the software module of the generator, the hardware climatic chamber corresponds to the software module for setting temperature operating modes, the oscil-

oscope corresponds to the modules for analyzing transient processes and frequency characteristics of the circuit).

2. A structural and schematic diagram of the components of the EIT channel for experimental research is developed. The EIT channel under study includes the following parts:

- source of injected current;
- switching unit;
- amplifier of the measuring channel.

3. On the basis of the virtual bench, experimental studies of the developed schematic diagram of the EIT channel are carried out.

As a research result, it is found that the developed bench has the following functionality:

- automated determination of electrical parameters of the investigated components (output amplitude and frequency characteristics, output resistances, resistances of an open junction), their presentation in graphical form;
- ability to set the temperature regimes of the investigated circuits;
- generator program module as part of the bench provides the ability to supply electrical signals of sinusoidal, triangular and rectangular shapes of a given amplitude and frequency;

– software modules for analysis of transient processes and frequency characteristics allow processing and registration of the measuring signal in a given range of amplitudes and characteristics. Thus, the amplitude characteristics of the output parameters of the investigated current source, its frequency response and output resistance are obtained. For multiplexers, the values of such an important parameter as the resistance of the open channel are obtained. For the measuring amplifier, the frequency response is also obtained at different temperature operating conditions.

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