SPECIALIZED SOFTWARE AND HARDWARE FOR IMPEDANCE SPECTROSCOPY OF THERMOELECTRIC ENERGY CONVERTERS

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Abstract

The technique of characteristics of thermoelectric energy converters based on the study of the frequency dependence of their impedance is presented. Specialized hardware and software for impedance spectroscopy of thermoelectric modules have been developed. For the analysis of the obtained spectra, an electrothermal model was taken as a basis, which describes the experimental results well and allows one to obtain not only electrical but also thermal characteristics of a thermoelectric energy converter.

Keywords

Software, Hardware, Impedance Spectroscopy, Laboratory Research, Thermoelectric Converter

1. Introduction

At present, renewable energy is of considerable scientific attention. A certain branch in alternative energy is occupied by thermoelectric semiconductor energy converters, which permit to recycle of waste thermal energy emitted into the environment. The main problem is their low efficiency. Many groups of scientists are carrying out a lot of research to increase it. In particular, semiconductor nanomaterials are promising for applications, due to the possibility of an independent increase in the Seebeck coefficient (S) and a decrease in thermal conductivity (κ) [1]. Such studies require the measurement of electrical conductivity, Seebeck coefficient, thermal conductivity, which, when using classical methods, is a rather laborious task, since the required samples are of various configurations. One of the newest methods for studying thermoelectric parameters of energy converters is impedance spectrometry, which provides obtaining a complete characterization of the converter without the need to measure thermal characteristics. For the effective realization of this technique, an urgent task is the development of hardware and software for obtaining impedance spectra in a wide frequency range and their subsequent processing to determine the operational characteristics of thermoelectric energy converters.

2. Analysis of Literature Data and Problem Statement

The widespread use of thermoelectric converters, ranging from local cooling to the recycling of waste heat, became possible due to the scientific achievements of recent years in the synthesis of semiconductor materials. This greatly increased their efficiency and expanded the scope of implementation of thermoelectric energy [2,3]. The most commonly used direct methods of thermoelectric measurements demand gradient heater, accurate maintenance, and measurement of a small temperature gradient [4], considering various heat losses. It introduces a significant error in the assessment of the thermoelectric figure of merit. These problems of apparatus design and analyzing experimental data are considered in works [5-6]. The average error in measuring the figure of merit is 20% including an error in measuring individual thermoelectric parameters of about 5%. In [7], based on LabVIEW expansion card and a precision electrometer, a system for direct studies of thermoelectric characteristics by the differential method is presented. The authors of [8] developed a system based on a high-speed digital oscilloscope for measuring the thermoelectric figure of merit by the Harman method with the ability to transfer data to a computer for further processing.

The authors of [8-9] have shown that studies of thermoelectric parameters based on impedance spectroscopy are promising. It permits to obtain all the main characteristics of one sample and do not cause degradation of the material under study. These methods require the development of high-speed research tools and computer processing of the results.

There are various methods for measuring impedance, in particular, the auto-balancing bridge method, the resonant method, the I-V method, and a large number of means for their implementation have been described. In particular, the authors of [11-13] described precision impedance measuring instruments, but most of these instruments are not adapted for scientific research.

Considering the advantages and disadvantages of the methods described above, we have developed software and hardware that provide, in one technological cycle, using non-destructive methods to acquire all the necessary parameters of the studied sample, in particular electrical conductivity, thermal conductivity coefficient, heat capacity, and thermoelectric figure of merit, as well as to carry out express quality control of thermoelectric modules according to the specified parameters.

3. The Aim and Objectives of the Study

The purpose of the work is to develop software and hardware for automated impedance spectroscopy of thermoelectric energy converters and quality control of finished thermoelectric energy conversion modules.
To achieve this goal, the following tasks were solved:
- analysis and selection of optimal research methods;
- development of a structural diagram of a hardware-software complex for impedance spectroscopy of thermoelectric energy converters;
- development of an electrical circuit and selection of the element base of individual blocks;
- development of algorithms and software for evaluation of the obtained spectra and quality control of finished thermoelectric energy conversion modules.

4. Methods of Research of Thermoelectric Parameters

Impedance spectroscopy is a very powerful method and is used to study a wide range of electrical properties of materials and devices, including solar panels, fuel cells, batteries, and supercapacitors. This technique allows you to separate the frequency domains of most processes that affect the efficiency of devices. However, models that adequately describe physical processes are required to interpret an equivalent scheme. For thermoelectric converters, there are physical models capable of partially interpreting the information obtained from the impedance spectra described in [9,10].
An important property of a thermoelectric energy converter is the ability to work as a generator of electrical energy when a temperature gradient is applied and the ability to transfer heat, creating a temperature gradient when an electric current flows. When an alternating current flows, the thermoelement behaves like a capacitor, accumulating part of the energy into heat and vice versa. When decoding impedance spectra, this can be represented by an equivalent electrical circuit (Fig. 1).

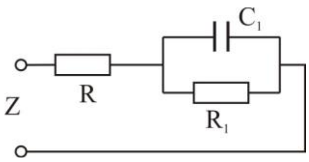


Fig. 1. Equivalent thermoelement circuit.

The total impedance is determined by the equation:

$$Z(s) = \mathrm{Re}[Z] + j\,\mathrm{Im}[Z] = \frac{(R_1C_1)^2 R\omega^2 + R_1 + R}{(R_1C_1)^2\omega^2 + 1} + j\frac{-R_1^2C_1\omega}{(R_1C_1)^2\omega^2 + 1}, \qquad (1)$$

where $\omega = 2\pi f$ $s=j\omega$.
Within the electrothermal model [9], the total impedance of the thermoelement Z consists of the internal electrical resistance R and the impedance $Z_T=S\Delta T/i$ (S is the Seebeck coefficient, ΔT is the temperature difference, i is the current) caused by thermoelectric heat transfer. The impedance Z_T must be equal to the resistance of the voltage source caused by thermoelectric effects and is determined by the heat capacity of C_T and thermal resistance R_T, which are associated with R_1 and C_1 as in [9]:

$$C_T = S^2TC_1, \qquad (2)$$

$$R_T = \frac{R_1}{S^2T}. \qquad (3)$$

Thermoelectric figure of merit can be found without the need of thermal measurements but by analyzing zero $\omega_z=(R_1+R)/(R_1C_1R)$ and poles $\omega_p=1/(R_1C_1)$ of the function Z(s) [9] as $ZT=(\omega_z/\omega_p)-1$.
If the geometric dimensions l, s, the number of elements n in thermoelectric modules are known, it can be determined its thermal conductivity $\kappa=l/(nsR_T)$ and electrical conductivity $\sigma=nl/(sR)$. Therefore, having the dependence of the real and imaginary components of the impedance or phase on the frequency, the basic thermoelectric parameters of the module, that determine its performance, can be estimated.
Now let us estimate the parameters that the measuring system must comply with. Since the means should be universal with the ability to measure both massive samples and commercial modules with an internal resistance of 10 mOhm, as well as a thin-film thermoelectric material with a resistance of up to 100 kOhm, it becomes necessary to use shunts of different ratings and schemes for their automatic switching. In absolute terms, the voltage across the sample substantially depends on the thermopower. material, sample resistance, selected electric current magnitude in the sample. For different materials, shapes, and sample thicknesses, the voltage can vary from 1 mV to 0.5 V. Therefore, to bring the voltage to the operating range of the ADC, an instrumental operational amplifier with a software-controlled gain is required, and the ADC itself must have a capacity of at least 12 bits to ensure sufficient resolution.
The parameter ω_p allows us to assess the minimum frequency sufficient to establish the thermoelectric figure of merit. The minimum frequency for the finished module in the housing of ceramic plates, due to their large heat capacity can be 10 MHz. This situation creates additional technical difficulties and significantly increases the time of measurement.

For thin films, this frequency can be hundreds of kHz. To ensure a wide range of film thicknesses, it is optimal to choose an ADC with a sampling frequency of at least 5-40 million samples per second.
The system must have enough memory to store an array of digitized experimental data. The ADC sampling rate should be chosen according to the scanning frequency so that the data is stored in memory and the number of points is sufficient for further software processing. Other units, in particular, the heating control unit, the interface unit with external devices need no special requirements for performance and can be controlled by the microcontroller in the main cycle.

5. Development of Software and Hardware and Discussion of the Results of the Study of Thermoelectric Parameters

The direct impedance measurement is based on obtaining impedance because of dividing the complex voltage on the measured element by the complex current flowing through it. This requires measuring the amplitudes of the sinusoidal voltage and current of the test sample and simultaneously measuring the phase shift between them, by applying the sinusoidal voltage to the sample in series with the reference resistor.
The choice of hardware and circuitry solutions was carried out based on the set goal, available modern element base. The block diagram of a specialized hardware and software system for studying thermoelectric properties and express diagnostics of thermoelectric power conversion modules is shown in Fig. 2. Fig. 3 is a displayed block diagram of the measurement unit.

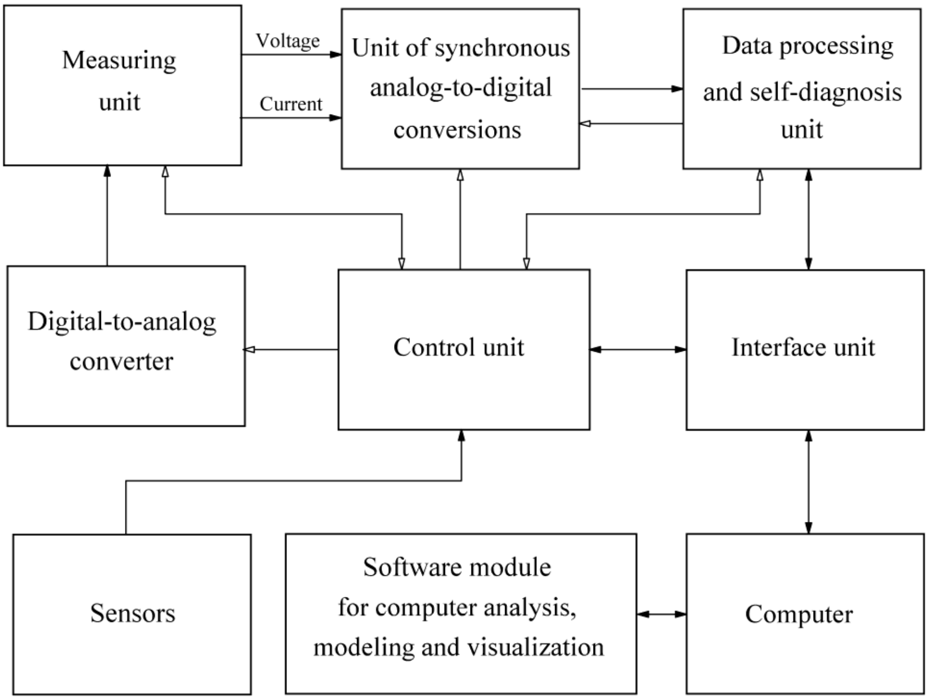


Fig. 2. Block diagram of a specialized software and hardware system for the study of thermoelectric properties and rapid diagnostics of thermoelectric modules of energy conversion. Painted arrows - information, and transparent arrows - control.

Depending on the objects under study, various options for implementing the control and data processing unit of such a specialized computer system are possible. A prototype of a specialized computer system was implemented based on the STM32F303 microcontroller and the DAC and ADC built into it for 5 MSPS. Two independent ADCs with the possibility of hardware synchronization from the timer, admit synchronously digitize voltage and current, greatly simplify the algorithms for determining the phase shift between them. The speed of ADCs provided measurements at frequencies up to 350 kHz, which turned out to be sufficient for research and rejection of thermoelectric modules and films up to 500 nm. At a frequency of about 350 kHz, we get 14 counts per period. To study thermoelectric films of the nanometer range of thicknesses, it is already necessary to develop a specialized computer system based on a high-speed FPGA, for example, by Xilinx. The main task of fast digitizing an analog signal is solved using a high-speed analog-to-digital converter, for example, the AD9238, which has two independent high-quality sample-and-hold devices up to 65 MSPS and an integrated voltage reference. Generation of a signal of the desired frequency, filtering, and mathematical data processing are implemented on the FPGA. The 32-bit microcontroller is selected for communication with a computer, control of switching, and operation of amplifiers.

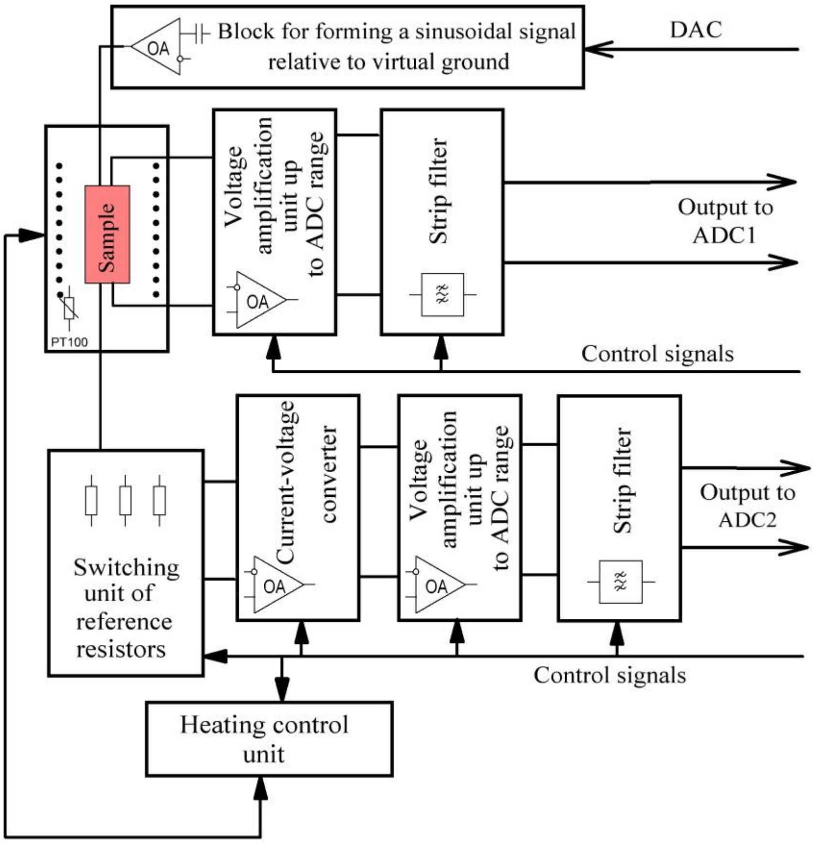


Fig. 3. Block diagram of the measurement unit.

The main algorithm for measuring impedance is shown in Fig. 4. It consists of 4 steps. First, the period corresponding to a given frequency is divided into an even number of uniform intervals n, usually of the power 2 and a sin tabulation function with an interval of 2π/n, since using an array of sine values significantly reduces the processor load. Then, a sinusoidal signal is generated, the current and voltage across the sample is measured, if necessary, switching the shunt and changing the gain of the operational amplifiers. Finally, the count values are accumulated in arrays and the real Re (Z) and imaginary Im (Z) components of the complex impedance are determined.

With the synchronous measurement of the voltage drop across the resistor and on the sample, the complex voltage and current are calculated as the sum of the products of the measured values by the sine or cosine value. Instead of calculating cosines, shift the array of the obtained values by the number of samples corresponding to a quarter of the period was made. This provides speeding up the calculations.

Since the value of the internal resistance of thermoelectric transducers for bulks can be 10 mOhm and for thin-film thermoelectric material up to 100 kOhm, the circuit of switching of a current shunt with an analog switch is applied. This solution is a compromise as it somewhat reduces the accuracy and requires the recording of calibration factors for each shunt but provide expanding the range of measurements. And PGA113 is the main operational amplifier with software-controlled gain.

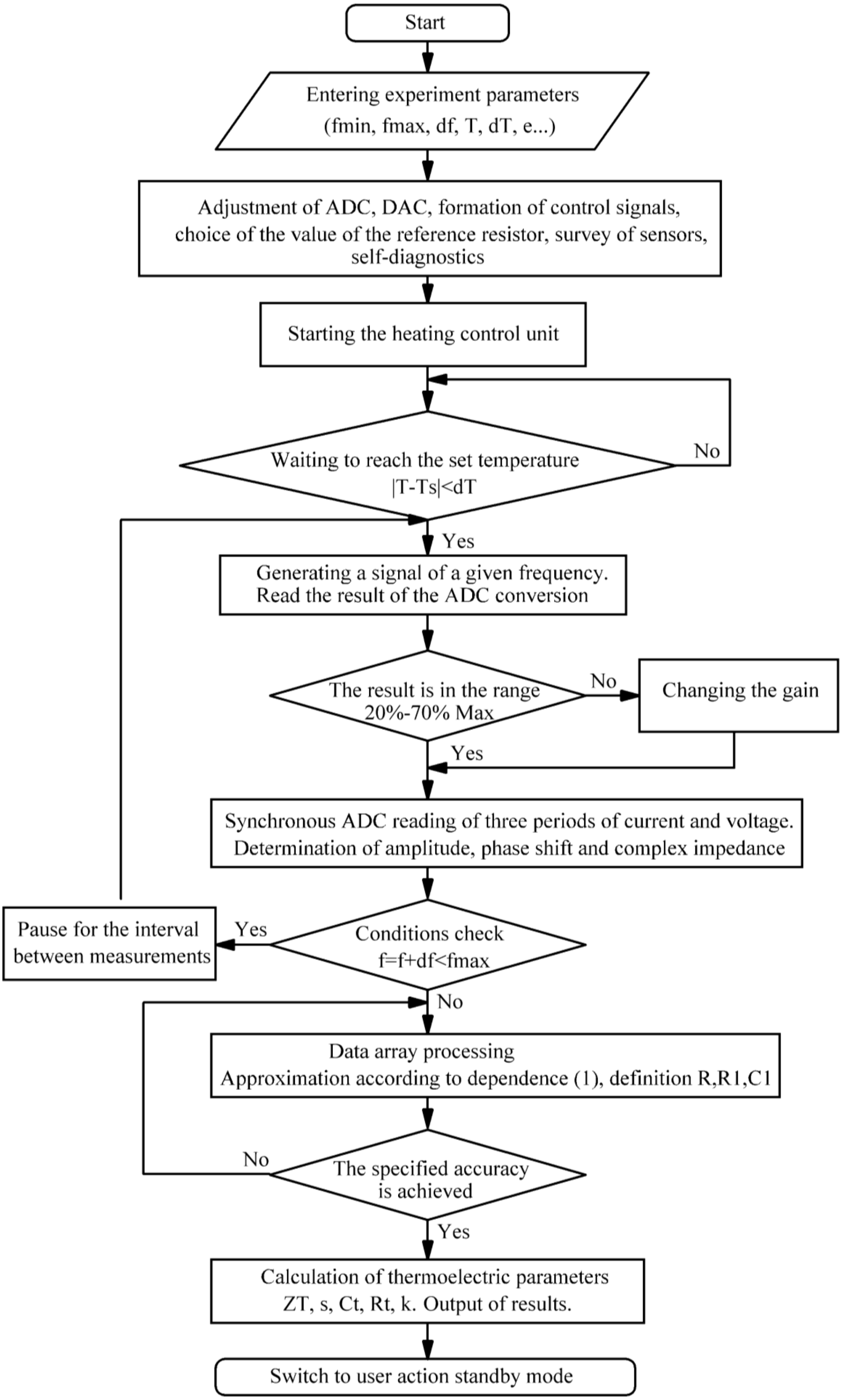
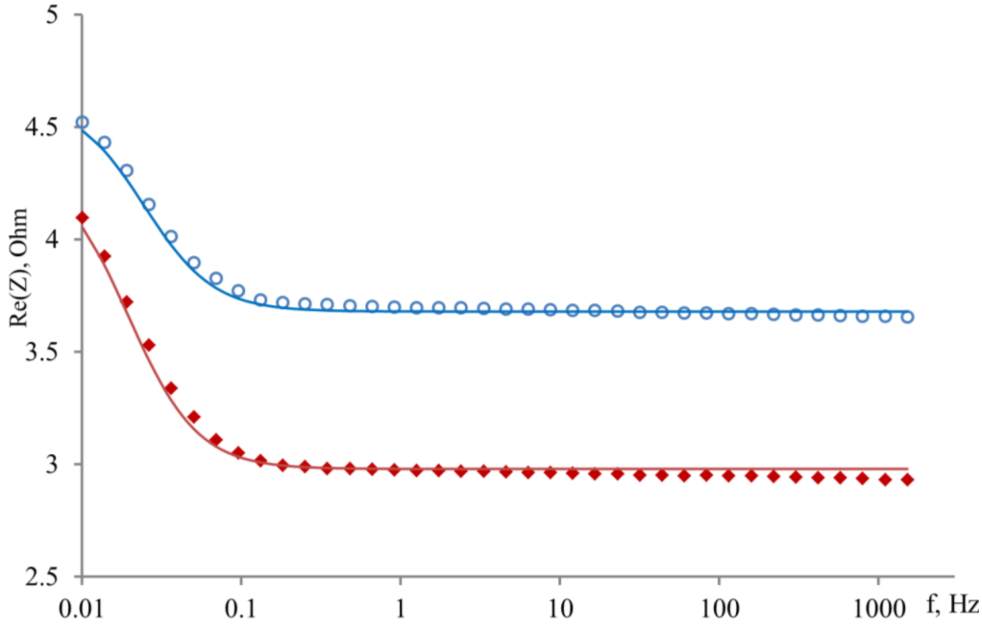
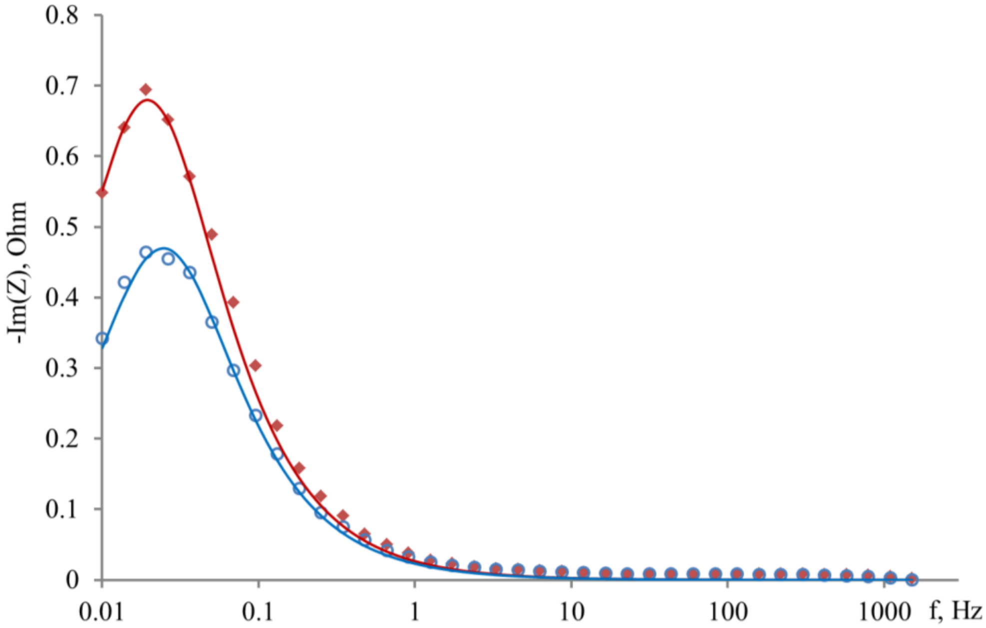


Fig. 4. A possible implementation of the algorithm for determining thermoelectric characteristics based on impedance measurements.

The software and hardware complex provide automated modes of operation necessary for measuring the complex impedance at different temperatures, software processing of the obtained spectra. In fig. 5. the obtained impedance spectra for industrial thermoelectric modules SP1848 and TEC1 based on Bi_2Te_3 are given. Similar dependence for the obtained by the method of thermal evaporation in the vacuum of a thin film of PbTe : In on the mica substrate is shown in Figure 6. The film thickness is 0.5 μm.



a



b

Fig. 5. Complex impedance spectra for industrial thermoelectric modules SP1848 (♦) and TEC1 (•) based on Bi_2Te_3 a) real component, b) imaginary component.

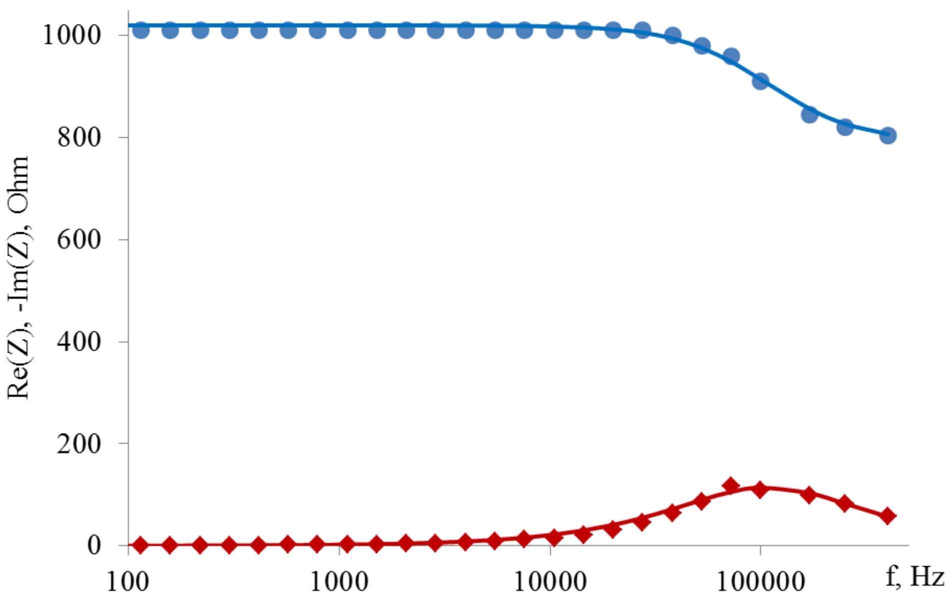


Fig. 6. Complex impedance dependence for a thin film based on PbTe: In ● - real component, ♦ - imaginary component.

In the software analysis of these dependencies, first, from the frequency dependence of the imaginary component of the complex impedance, according to expression (1), the values of the parameters C1, R1 were found, and from the real component, the parameter R was estimated. The approximation was performed using the least-squares method. The solution to the problem of minimizing the function of two variables presented in the sum of squares of deviations was carried out by the quasi-Newtonian method using the Levenberg-Marquardt algorithm. The approximation results are shown in Fig. 5 and Fig. 6 as a solid line.

For thermoelectric modules, the calculated data are given in Table 1. For a film sample, a sufficiently low thermoelectric figure of merit ZT = 0.29 was obtained, which is most likely due to the large influence of the thermal conductivity of the substrate and heat losses to the environment. The specific electrical conductivity is 74 Ohm^{-1} cm^{-1}, the heat capacity is 0.22 W/K.

Table 1. Thermoelectric parameters of the studied modules.

Parameter	SP1848	TEC1
Seebeck coefficient, V/K	0.042	0.05
Number of elements	254	
Seebeck coefficient per element, μV/K	165	197
Thermoelectric figure of merit ZT at 300 K	0.46	0.26
Element length, cm	0.14	
Element area, cm^2	0.01	
Specific conductivity, $Ohm^{-1}cm^{-1}$	1193	966
Thermal resistance, K/W	2.57	1.25
Thermal conductivity, W/m K	2.14	4.39
Heat capacity, W/K	3.17	5.17

The obtained results coincide well with the previous studies of the other authors by the method of direct measurements on samples obtained from the same material under an identical deposition method. The relative difference between them does not exceed 3-5%. The program provides convenient control of the measurement process and automated comparative analysis for a series of identical samples for rapid detection of defective specimens.

6. Conclusions

1. Models and basic parameters have been determined to obtain important electrical and thermal characteristics of a thermoelectric energy converter from impedance spectra.
2. The method, algorithm, block diagram, software, and hardware for automated measurement and processing of impedance spectra are developed, considering the models of physical processes that determine the performance of semiconductor material, which significantly reduces the time spent on conducting and processing the experiment.

3. Using the developed tools experimental research of thermoelectric modules and thin-film samples are carried out. Thermoelectric figure of merit and other basic electric and thermal characteristics which define their operational properties are defined. The high efficiency of the developed software and hardware for carrying out similar researches is shown.

7. Acknowledgments

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8. Conflict of Interests

Conflict of interest while writing, preparing, and publishing the article as well as mutual claims by the co-authors is absent.

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