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Original Article

Implementation of Thermoelectric Batteries for Power Supply of Compensating Devices and Relay Protection Elements

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Abstract - *The work presents for the first time the results of a study on the implementation of thermoelectric current converters in the manufacturing industry to replace traditional power supply circuits for capacitor banks with an alternative current source called a thermoelectric converter of thermal energy into electrical energy. The importance and cost-effectiveness of thermopiles in installations with heat-generating technologies are substantiated. The sequence of technology for producing thermoelectric substances and developing thermoelectric batteries for the power supply of compensating devices of industrial enterprises intended for the power supply of the operational current circuit of the relay protection system is outlined. The results of measurements and experimental studies of the parameters of the branches of thermoelectric materials with electronic and hole conductivity are presented. The procedure for creating the design and the results of charging the capacitor bank are outlined.*

Keywords - *Semiconductors, Substances, Thermopile, Power supply, Capacitor bank, Power supply, Efficiency.*

1. Introduction

The widespread use of each developed device primarily depends on finding suitable materials and technologies for their manufacture, efficiency and versatility. Thermoelectric Batteries (TB) have been used in many engineering and technology fields until today [1, 2]. However, the possibilities of using them in other, even additional, production structures have not yet been sufficiently developed and researched.

The last task is becoming very relevant today. This is due to many reasons, which are not worth listing in full. One of the reasonable answers may be the vigorous interest of researchers and power engineers in alternative sources of electrical energy. The gifts of nature have not always been used for practical purposes.

In addition, very little attention has been paid to thermal energy losses. In our opinion, not limiting ourselves to persistent research into solar semiconductor converters, it is necessary to expand the research areas into other types of non-traditional sources of electrical energy.

Researchers have remained a little out of sight of thermoelectric converters in recent years, even in developed countries. Some countries practically do not do this. Directing attention to using thermoelectric sources of electric current in production is associated with intriguing considerations [3-5].

Firstly, this type of converter can be classified as an environmentally friendly energy source (if it is not used on carbon fuel).

Secondly, it can successfully convert waste thermal energy into electrical energy, which helps save energy.

Thirdly, they are mechanically robust compared to solar converters and have relatively simple manufacturing technology.

Such advantages include the economic benefit of obtaining one kilowatt of electricity and the possibility of operating it with any heat source, ranging from solar to heat obtained due to the decay of radioactive isotope substances [6, 7].

In the studied foreign and domestic literature, there is data on their use in the automotive industry, medicine, space technology, and household devices [8-11].

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There are works [9] in which they were successfully used as a constant energy source for clock mechanisms, using the human body's energy. At the initial stage of introducing thermoelectric converters, special attention was paid to their use as cooling devices [12]. The Peltier effect was well suited for this from a physics point of view.

Moreover, thanks to this, Peltier converters are now widely used in industry (as a cooler for electronic devices) and on sale. Despite this, there is still no work in using them in industrial enterprises where there is a need for DC sources of low and medium power. This task is also urgent because generating direct electricity is more expensive than alternating current.

In addition, traditional energy relies on the consumption of natural resources, which has recently begun to have a catastrophic effect on the supply of fossil fuels, the ecology of the environment, and changes in the climatic conditions of the globe. Therefore, we have carried out work on introducing thermoelectric current sources into industry, where their use solves several problems.

Our theoretical research and analysis show that the solution to these problems on a large scale is facilitated by the additional use of waste heat energy, uselessly emitted cooling refrigerants, natural solar energy, and the like. In a word, you can see the benefits of this work with the naked eye. To accomplish this task, the correct choice of technology for producing semiconductor materials is required [13]; for this purpose, to create an installation, assemble and install a thermopile, and conduct tests at a specific facility of an industrial enterprise.

This requires solving complex problems related to the properties of enterprises, their technological problems, air pollution on the territory of the enterprise, and so on.Depending on the listed factors, you should choose the material of the thermoelectric converter, the type of heat source and the unit's design.

The study of the properties of direct current electrical energy consumers showed the relevance of introducing thermopiles as a source of operational current for elements and relay protection devices of power systems. Electricity production depends on reliable and selective operation. Any unprotected energy system cannot operate for a long or short time [14, 15, 19].

The danger of emergencies constantly exists. Let us note that such research works have not yet been found in the scientific literature. Based on the above considerations, this paper presents the results of a study on introducing heat energy from industrial waste, which was used to cool chemical reaction tanks, to produce electrical energy for low-power DC consumers.

2. Problem Statement

It was said that, in our opinion, the issues of introducing thermoelectric batteries for the power supply of capacitor banks and their use as power sources for operational circuits of devices and relay protection elements are being studied for the first time. The analysis of foreign and domestic literature on TB research to introduce it into many branches of engineering and technology showed a lack of work in this direction [16].

Some studies have shown the ineffectiveness of some thermoelectric materials when functioning as an electricity generator [16]. It is well known [2] that thermoelectric materials, depending on operating temperatures, are divided into three groups. If you do not consider the temperature regime, the converter's efficiency will deteriorate sharply and not yield the expected result.

Therefore, to positively resolve this issue, it is necessary to think through all aspects of the creation, development and selection of the location of thermoelectric batteries in industry. In addition, the converter should be made from suitable semiconductor thermoelectric materials [13], which have high thermoelectric figures of merit Z among materials with the same operating conditions [2].

It is also essential to choose the technology for manufacturing half-legs of thermo elements. Of course, there are many technologies for producing thermoelectric compounds [13]. However, as you know, one of the requirements of the economy of the entire country is the simplicity of technology, the relative cheapness and quality of the resulting product. Let us note that a good result for the new work we recommend depends on the high-quality fulfilment of the listed conditions.

Therefore, we tested and analysed the varieties of manufacturing technology of existing methods for obtaining substances, and finally, we chose the zone melting method using a resistance electric furnace. Among the many semiconductor thermoelectric materials in the region of low temperatures and substances, alloys based on bismuth and antimony telluride were considered the most effective [13].

According to foreign literature, these materials' thermoelectric figure of merit was achieved up to a value of $Z=8.0\text{-}10^{-3}$ $\deg^{-1}$ [16]. Unfortunately, a detailed description of such technology has not yet been published in the open press. Although our technology gives relatively low results, it encourages the possibility of using them in proposed experiments and practice. The main task of researching materials and manufacturing technology of thermoelectric energy converters was creating an operational direct current source for charging capacitor banks of relay protection, automation elements, and electrical power systems.

Because such a question, until now, has practically not been considered in science. Since microprocessor-based security elements have become typical in recent years [17], studying and obtaining specific results in this direction is becoming relevant. Confirmation of this situation is the relatively low value of their power consumption and their operation on direct current.

3. Materials and Methods

According to the planned work on developing thermoelectric batteries for industrial enterprises, ternary alloys based on Bismuth and Antimony Telluride (BiTeSb-BiTeSe) were selected as the primary materials [13]. This choice is explained by these compounds' relatively good thermoelectric properties at low-temperature operating conditions.

A preliminary analysis of flowing water coming out of the cooling system of chemical tanks showed that the average temperature of technical wastewater lies in the range of 70-75 ℃. Let us consider that at the beginning of the water flow, it reaches over one hundred degrees Celsius. We can fully hope for a favourable operating mode for thermoelectric batteries as a current source. Moreover, the water flow has a stationary flow, the density is almost constant, and the temperature is stable during operation.

Two methods for producing thermoelectric materials were chosen to obtain the p- and n-branches of thermo elements: the powder pressing method and the zone melting method [18]. According to the first method, we carried out the process in two stages. First, pressing was carried out at cold temperatures under a 5.7 t/cm2 pressure. Then, raising the temperature to 350 ℃ and the pressure of 4.5 t/cm^2, the talc substance was maintained for five minutes.

A comparison of the results of the obtained samples showed that the thermoelectric figure of merit of the p-type half-branch is very close; that is, it lies within the range $z = 3\text{-}3.2 \cdot 10^{-3}$ deg^{-1} [13]. However, such a coincidence was not observed in our samples' n-type solid solution obtained by these methods. There is a noticeable scatter in the Z values between the results for cast samples $Z=2.8\text{-}3.2 \cdot 10^{-3}$ deg^{-1} and pressed samples $Z=2 \cdot 10^{-3}$ deg^{-1}. This can be explained by the improvement of the structure and the increase in the mobility of current carriers. It can also be assumed that p-type alloys are less sensitive to structural perfection than n-type crystals.

In addition, the anisotropy of low-temperature materials plays a significant role. Based on the experiments conducted, the importance of additional heat treatment was established since the thermoelectric properties are stabilized after such treatments, and their values remain constant during operation. This result is because the heat treatment process helps to equalize the composition and some additional dissolution of components that did not enter the lattice during crystallization. The latter affects the change in thermoelectric properties.

Figure 1 shows an installation diagram for fusing thermoelectric materials under pressure. Half of the branches of thermo elements of the thermopile were made from the obtained substances. The cutting of the substance into thermo element branches was carried out using an electric spark-cutting installation. This setup provided precise cutting with relatively few defects. Since each crack or deformation of the substance leads to a sharp deterioration in the parameters of the branch and a decrease in the values of the output characteristics, we paid maximum attention to the quality of the resulting alloy.

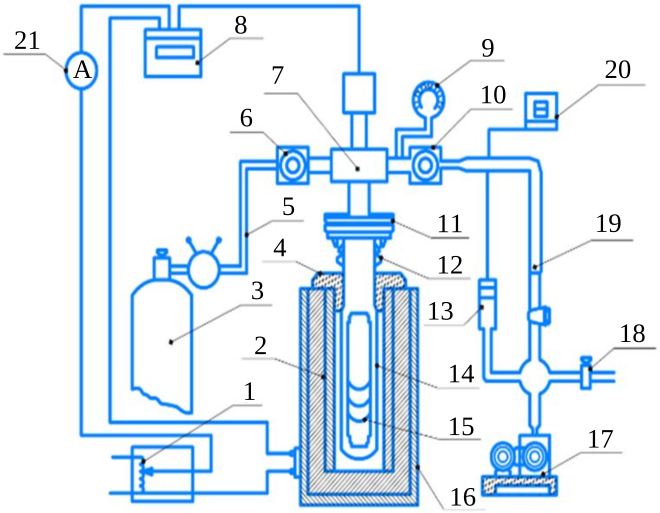

Fig. 1 Scheme of an installation for fusion of thermoelectric materials under inert gas pressure: 1-transformer, 2-insulating layer of the cylinder, 3-argon gas cylinder, 4-fireclay cover, 5-argon guide tube, 6-valve, 7-distributor, 8-temperature controller, 9-manometer, 10-valve with bellows, 11-flange, 12-coil, 13-thermocouple lamp LT-2, 14-sleeve, 15-quartz crucible, 16-furnace (T=1000 ℃), 17-fore vacuum pump, 18-cock for air inlet, 19-exhaust air passage, 20-vacuum gauge VIT-2, and 21 ammeter.

When working on an electric spark cutting installation, cutting is carried out with a minimal diameter wire, passing an electric current through it. When the semi-conductor thermoelectric substance being cut approaches, an electric discharge occurs between the wire and the substance. Cutting occurs due to the thermal energy released due to this discharge. This helps prevent any cracks and deformations. After manufacturing half-leg thermo elements, assembly and installation were carried out using the technology.

3.1. Thermal Converter for Charging Capacitor Banks

The thermal converter consisted of forty thermo elements. The TE branches had the following geometric dimensions: 4x4x7mm^3. The hot-side switching plates of the thermo elements were made of iron. The cold side of the p-type and n-type half-branches was switched with nickel plates. Then, the joint surface of the thermopile was combined with a ceramic plate of Beryllium Oxide (BeO) with good thermal conductivity. The thermal expansion coefficients of iron and ceramics are very close, so no parasitic effects were observed during the experiment. The cold ends of the TB were cooled by running tap water.

The hot side of the thermopile is attached to the surface of a fuel-dumping pipe shaped like a coil. The diameter of the pipe was about 9.8 mm. The load for the TB was a capacitor bank. Traditionally, this installation was charged from an alternating current network through relatively large and expensive current and voltage instrument transformers. To obtain direct current at the input of the capacitor bank, rectifier units were used. In our case, we considered the circuit for connecting this source of the operational DC circuit in the traditional way and replacing it with a thermoelectric converter. In the first case, a capacitor bank with a power of 120 kbar was connected to the network for the operational power supply of relay protection elements (Figure 2).

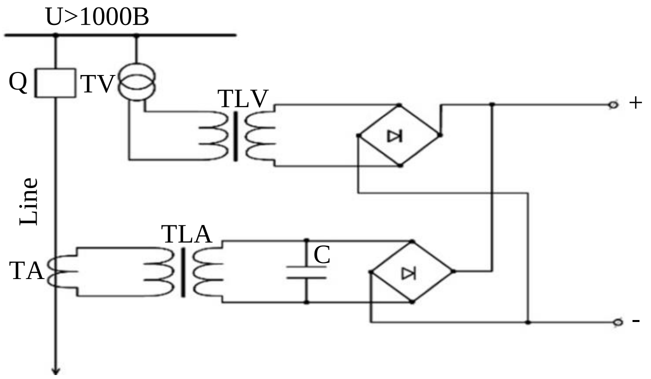

Fig. 2 Charging a capacitor bank and protection elements from measuring trans rectifier formatters

As the figure shows, a rectifier unit and a voltage-measuring transformer are required to supply DC power to a capacitor bank. Replacing this equipment not only reduces the number of necessary devices but also saves network energy and allows waste heat energy from production technologies (Figure 3). In addition to connecting a thermoelectric current source through a measuring current transformer, Figure 3 shows that it can be connected autonomously.

That is, directly to the operational circuit of relay protection elements. In this case, it is necessary to calculate so that the electric current from the TB circuit is sufficient to start the relay and other electricity consumers connected to this circuit. In this case, switching on a capacitor bank ensures against energy shortages. Note that TB, as a current source for the capacitor and other consumers of electricity, should be used for an operating process plant with a heat source. As experience shows, in the event of a shutdown or failure of a fuel-generating unit, the TB ceases its energy activity.

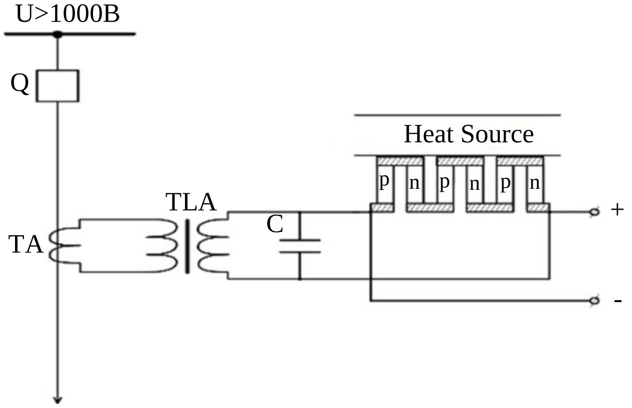

Fig. 3 Charging a capacitor bank and protection elements from thermoelectric batteries

As a result, electrical energy disappears, and the consequences for protective devices can be catastrophic. To avoid being exposed to such a phenomenon, TB must be used for protection only for that installation; when it was stopped, the need for relay protection and automation of this particular installation ceased.

4. Results and Discussion

The branches of thermo elements intended for the manufacture of a thermoelectric generator were subjected to examination. Electro physical parameters such as electrical conductivity σ, thermal conductivity χ and term electromotive force coefficient α for electron and hole conductivity branches were measured. The results of the study of these parameters at the corresponding temperature differences between the hot and cold junctions are shown in Table 1.

As the table shows, the resistivity value increases with the increasing temperature of the hot junction; the thermal conductivity of the electronic conduction branch first decreases to T_h = 333K, and then an increase in this parameter is observed. The parameter α for this branch first increases, and later, from T_h = 353K, it begins to fall. In this case, the increase in the electrical conductivity of the sample is essential. The nature of the dependence of these electrical properties of hole conductivity material is slightly different.

Here, the thermal conductivity increases, and the thermoelectric coefficient is also growing. Although the last parameter exhibits saturation, there is no decline. This positive effect was achieved by the zone melting technology we used. The thermal conductivity of the p-type branch first decreases, then increases.

Table 1. Parameters for corresponding temperature differences between hot and cold junctions

T	**n-type**			**p-type**		
(TO)	$\rho \cdot 10^3$ (Ohm cm)	α (μV/deg)	$\chi \cdot 10^3$ (W/.cm deg)	$\rho \cdot 10^3$ (Ohm cm)	α (μV/deg)	$\chi \cdot 10^3$ (W/.cm deg)
193	0.82	196	16.8	0.629	164	18.5
213	0.909	207	15.9	0.73	182	17.4
233	0.99	218	15.2	0.826	198	16.6
253	1.087	227	14.6	0.934	209	16
273	1.205	234	14.1	1.031	218	15.3
293	1.333	241	13.6	1.176	226	14.7
313	1.45	245	13.2	1.333	234	14.4
333	1.59	250	13.1	1.538	239	14.6
353	1.724	253	13.2	1.695	245	15.1
373	1.852	252	13.6	1.82	248	16
393	1.886	250	14.1	1.886	250	17.1
413	1.852	246	15.4	1.923	250	18.6

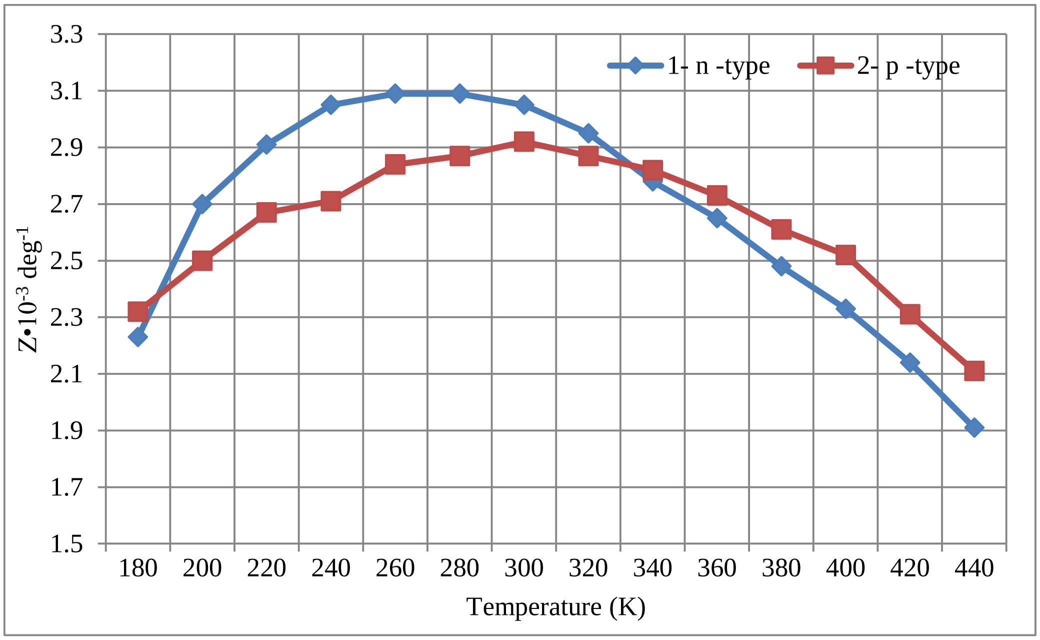

Fig. 4 Dependence of thermoelectric figure of merit of branches on temperature, 1-n-type, 2-p-type

Figure 4 shows the result of processing measurement data in the form of thermoelectric figures of merit Z, p- type and n-type thermoelectric materials we obtained as a processed final indicator in the form of thermoelectric figure of merit. Theoretically, this parameter can be determined by the formula.

$$Z = \propto^2 \sigma/\chi \qquad (1)$$

However, in addition to theoretical calculations, we also studied the thermopile's quality factor separately on a special installation, allowing a temperature difference along the thermo element branches up to 120-130℃. Then, based on this, the results were compared, and a conclusion was made about the possibility of using it in the intended task. The maximum value of the dependence of the thermoelectric figure of merit of the ternary alloy is achieved at different temperatures. As can be seen from the figure, it should be noted that the general pattern of the temperature dependence of the thermoelectric figure of merit obtained by us is preserved, and the measurement results coincide with the work results [3, 13]. The substances manufactured by us have an excellent thermoelectric figure of merit for the p-type (about $3.1*10^{-3}$ deg^{-1}).

This parameter for n-type is slightly lower (i.e. $2.9*10^{-3}$ deg^{-1}). Operating parameters are very close to the results of laboratory tests. Such Z values allow us to solve the power supply problem for charging capacitors and rechargeable batteries of the relay protection operational current circuit. Depending on the capacitor's or battery's power, producing thermoelectric batteries of varying power is naturally possible. To do this, the number of thermocouples should be calculated considering the geometric dimensions of the thermo element branches.

A significant influence of the geometric dimensions of the FC branches on the output electrical parameters. This dependence is due to the mismatch between the values of the optimal and operating currents flowing along the branch of thermo elements. The connection of capacitor banks to the thermoelectric converter circuit was carried out without unnecessary problems. During the experimental study, a full battery charge was achieved in 1 hour 47 minutes (when charging the battery with zero charge!).

After the protection was triggered, charging lasted only 13 minutes since the capacitor did not use up all the accumulated energy. It can be assumed that it will not take less than three minutes to trigger the protection again, or even if it is needed, the residual energy will be enough to trigger the protection devices two or three times. In the experimental design, we provided for automatic disconnection of the TB from the capacitor bank network after a full charge. In this case, to efficiently use the energy from the thermoelectric converter, you can install the switch to another consumer of direct current electricity.

5. Conclusion

In this work, for the first time, the possibilities of using thermoelectric generators as a source of operational current for relay protection and automation elements have been theoretically and experimentally studied. Based on the results of the studies, the following were established.

In our opinion, thermoelectric substances from semiconductor ternary compounds based on bismuth and antimony telluride are so far the only semiconductors that allow solving the problem in the low-temperature region of the operating range (from Th= -20℃ to Th=+20℃ and up to Th=100-120℃). They must be operated under the importance of working with the same fuel installation. This guarantees constant protection without emergencies.

We have produced prototypes of thermopile connected to the power system circuit, allowing the TB to operate effectively as a source of constant operating current. They can supply power to protection circuits around the clock without consuming electrical energy from the electrical network. Their use due to the heat supplied from the reservoir of the cooling system of chemical reactions makes them economical and compact.

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