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CIRCUIT SIMULATION OF ELECTRICAL BREAKDOWN IN AIR USING KIND'S EQUAL-AREA CRITERION

Запропонована спрощена схемотехнічна модель електричного пробою повітряного проміжку з використанням критерію рівної площі Кінда. Моделювання виконане за допомогою демонстраційної версії програми Micro-Cap 11. Модель дозволяє передбачити вольт-секундну характеристику різних повітряних проміжків. Модель розглядається як допоміжний засіб для студентів, що вивчають курс техніки високих напруг.

Ключові слова: *схемотехнічне моделювання, техніка високих напруг, електричний пробій, вольт-секундна характеристика, критерій рівної площі.*

1. Introduction

In recent years, the role of virtual experiment in the high voltage engineering has been continuously increasing. Physical experiments in high-voltage laboratory require considerable work for preliminary preparation, including moving large-sized equipment (high-voltage generators, current and voltage transformers, insulators, electrostatic voltmeters, voltage dividers, etc.). In addition, a large area of the high-voltage laboratory is necessary. Preliminary simulation on the personal computer allows to reduce the time to prepare the experiment in a high-voltage laboratory to a certain extent, and in some cases completely replace it. For these reasons, immediately after their appearance, various circuit simulation programs began to be used both in education and scientific activity. With the increase in the performance of personal computers and the capabilities of circuit simulation programs, the possibilities of a virtual experiment are also expanding.

The field of research in high voltage engineering is very broad. To solve some, now «classical» problems, circuit simulation programs are successfully used in education. This includes, for example, simulation of pulse current generators, high-voltage multipliers, etc. At the same time, a number of equally important problems remain practically unaffected (for example, simulation of the electrical breakdown of an air gap). The possibility of determining the discharge voltage of insulation gaps using models is important for design of high-voltage installations with air insulation. This includes a variety of electrical installations, including overhead transmission lines, the main insulation of which is atmospheric air.

2. The object of research and its technological audit

The object of research is the circuit simulation model of a streamer breakdown of a rod-rod air gap. In this case, it is necessary to solve the problem of determining the time interval of the streamer propagation. The lower bound of this interval corresponds to the beginning of the streamer propagation, and the upper bound corresponds to the time when the streamer reaches the opposite electrode. To create such model, it is not enough to take into account only the functional relationship between the breakdown voltage and the spacing between the electrodes. In this article, the authors propose to solve the posed problem using Kind's equal-area criterion [1, 2].

3. The aim and objectives of research

The main aim of the article is to demonstrate the potential possibility for modeling the electrical breakdown of air gaps using circuit simulation programs.

The following objectives were set to accomplish this aim:

1. Creation of a simplified model of electrical breakdown of a rod-rod air gap using Kind's equal-area criterion as one of the criteria for streamer breakdown in air.

Determination of the discharge times with the help of the obtained model under the action of voltage pulses of positive polarity with different amplitudes and a given shape.

3. Comparison between simulation and experimental results.

4. Research of existing solutions of the problem

The importance and applicability of circuit simulation programs for high voltage engineering was stressed long time ago [3]. Traditionally, such programs are used to explain the «classical» issues of high voltage engineering. This applies mainly to the simulation of the pulse voltage generator [4–8], the simulation of the pulse current generator [9] and the study of voltage multipliers [3]. A list of these important tasks can be expanded. In addition to these issues, circuit simulation programs can be used to simulate electrical breakdown of air gaps [10]. Obviously, considering how difficult this phenomenon is, it can talk only about simplified modeling [10]. Separately, it should be noted the trend towards the creation of virtual high-voltage laboratories [11]. In any case, if it deal with the electrical breakdown of an air gap with a highly non-uniform electric field, the volt-time characteristic of the gap must be taken into account [2, 10, 12]. In this paper, as will be shown below, this is taken into account with the help of an equal-area criterion [1, 2], which can be relatively easily taken into account in simulation modeling.

5. Materials and methods of research

To achieve objectives that were set such research method was applied: circuit simulation on personal computer. The main material in this research is the circuit simulation model of the electrical breakdown of a rod-rod air gap.

6. Research results

It was shown in [1, 2] that to determine the breakdown time of an air gap when an impulse voltage is applied to it, it is necessary to consider the area of the volt-time characteristic. For a specific electrode configuration, we can write:

$$\int_{t_1}^{t_d}\left[u(t)-U_b\right]dt = A = \text{const}, \qquad (1)$$

where $u(t)$ – applied voltage; U_b – reference voltage or breakdown voltage under prolonged application of voltage; A – constant area of the volt-time characteristic or the formation area; t_1 – time corresponding to the beginning of the streamer propagation; t_d – time at which the streamer reaches the opposite electrode.

Since the subsequent formation of the discharge channel occurs much faster, it is believed that time t_d is almost the same as the instant of voltage cutoff. The area A depends on the geometric dimensions of the electrode system and increases with increasing spacing between the electrodes s. For convenience of calculations, the concept of the relative area of the volt-time characteristic A/s is used. Table 1 [13] shows the values of A/s for some electrode configurations.

Table 1

Approximate values of the relative area A/s for some electrode configurations in the air [13]

No.	Electrode configuration	Polarity	A/s, V·s/m
1	Rod-plane	Positive	0.65
2	Rod-plane	Negative	0.40
3	Rod-rod	Positive	0.62
4	Rod-rod	Negative	0.59

Using expression (1), it is possible to construct a simplified model for calculating the breakdown time of an air gap when an impulse voltage is applied. To estimate the error of the results obtained in this model, it is necessary to compare the results of the simulation with the experimental data. As such experimental data, the volt-time characteristic of the rod-rod gap for a 1.5/40 μs wave of positive polarity, described by the following formula [14], can be used:

$$U = 4.95\cdot s\cdot\left(1+\frac{2.34}{t_d}\right), \qquad (2)$$

where s – spacing between electrodes, cm; t_d – discharge (breakdown) time, μs. In this case, the voltage U (kV) in formula (2) is determined as follows. If the discharge occurs at the tail of the wave, then the points of the volt-time characteristic relate the discharge time t_d and the pulse amplitude U_m. If the discharge occurs at front of the wave, then these points relate the discharge time t_d to the pulse voltage at the time of discharge $U(t_d)$. To describe the voltage pulse by the shape 1.5/40 μs and the amplitude U_m, authors proposed the expression (3).

$$u(t) = 1.065\cdot U_m\cdot\left(e^{-1.750\cdot10^4 t}-e^{-1.533\cdot10^6 t}\right). \qquad (3)$$

Let's consider the rod-rod gap configuration under the action of pulses with positive polarity, which corresponds to row 3 of Table 1. The spacing between the electrodes s is assumed equal to 1 m. Let's determine the reference voltage U_b for such gap. To do this, substituting the values of $s=100$ cm and $t_d=\infty$ in the formula (2), let's obtain that $U_b=495$ kV. From Table 1, for $s=1$ m, let's obtain that $A=0.62$ V·s. The electrical breakdown model of the air gap is shown in Fig. 1. Simulation was performed using the evaluation version of the Micro-Cap 11 circuit simulator, developed by Spectrum Software [15].

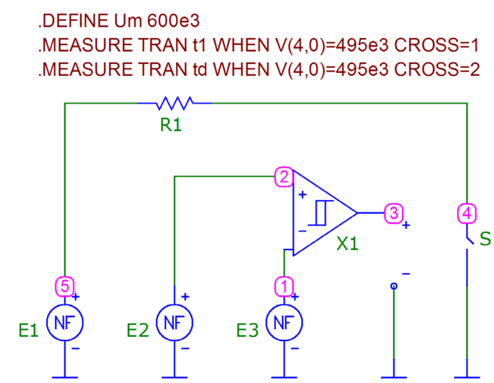

Fig. 1. Simulation of electrical breakdown of the air gap using Kind's equal-area criterion in the evaluation version of Micro-Cap 11

In Fig. 1 E_1, E_2, E_3 – functional voltage sources, the values of which are separately listed in Table 2; R_1 – damping resistor; X_1 – voltage comparator; S_1 – voltage controlled switch.

Table 2

The values of the functional voltage sources in the circuit in Fig. 1 according to the Micro-Cap syntax [15]

No.	Component	Value
1	E1	1.065*Um*(exp(-1.750e4*t)-exp(-1.533e6*t))
2	E2	SUM(v(4,0)-495e3,t,t1)
3	E3	0.62

The circuit in Fig. 1 works as follows. The voltage source E1 simulates the voltage pulse applied to the interelectrode gap. The pulse amplitude is specified by the «.DEFINE» directive. For example, «.DEFINE Um 600e3» corresponds to the value of $U_m = 600$ kV.

Source E2 simulates part of equation (1) to the left of the equal sign. In turn, the source E3 simulates part of the equation (1) to the right of the equal sign. Let's assume that the damping resistor R_1 has a typical resistance

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value of 1000 Ω. The circuit uses a voltage comparator X_1. Switch S_1 is used as a discharge channel model. The switch is controlled by voltage and operates in a hysteresis mode. The switch resistance is 100 MΩ in open state and is 1 Ω in closed one, which determines the resistance of the discharge channel in this model.

In the normal state, the switch S_1 is opened. The voltage across the gap in this state is:

$$U_{S1}=E_1\cdot\frac{R_{S1}}{R_1+R_{S1}}=E_1\cdot\frac{10^6}{10^3+10^6}=0.999001\cdot E_1\approx E_1. \quad (4)$$

As can be seen from equation (4), it can assume that all the voltage in the circuit is applied to the air gap. This is done in order to avoid modeling the pulse voltage generator when studying the breakdown process, which is not critical for this article.

The moment of activation of the switch determines the breakdown of the air gap. The switch S_1 closes when a voltage appears at the output of the comparator, that is, between nodes 3 and 0, (the grounded nodes are numbered 0, which are not shown in the circuit diagram). In turn, this can happen only when the voltage between nodes 2 and 0 becomes greater than the voltage between nodes 1 and 0. This will happen only when the curve E2 intersects with the curve E3, that is, when the Kind's equal-area criterion (1) is fulfilled. In order to determine the source E1, it is necessary to preliminarily determine the parameter t1 (Table 2) corresponding to the time at which the voltage curve across the gap intersects the straight line $U_b=495$ kV. This can be done directly in the Micro-Cap as follows. Let's demonstrate it with the example of a pulse with $U_m=600$ kV.

At first, the moment of time t_1 is unknown, therefore it is assumed that its initial value is zero. Therefore, at the first iteration let's assume that the source E2 is described by the expression «SUM(v(4,0)-495e3,t,0)». After the first run of the transient analysis mode («Transient...») this parameter will be determined and can be viewed in the «Measurements» window (Fig. 2, *a*). Now substitute this value t_1 in the last expression – «SUM(v(4,0)-495e3,t,1.026e-6)» and start the transient analysis mode («Transient...») again. After this iteration, the discharge (breakdown) time t_d becomes known, which is also displayed in the «Measurements» window (Fig. 2, *b*).

In Fig. 1 the first line with the «.MEASURE» directive is intended for t_1 calculation, and the second line is for t_d calculation.

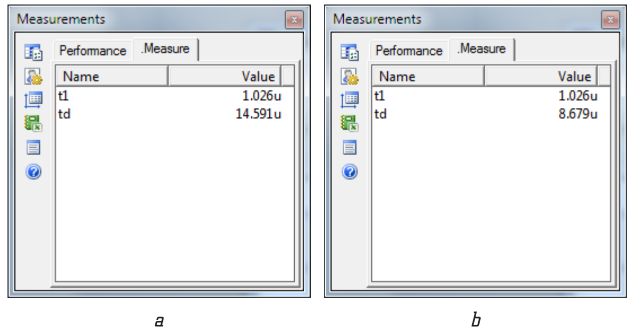

Fig. 2. Calculation results of t_1 and t_d at U_m = 600 kV: *a* – t_1 is calculated after the first iteration; *b* – t_d is calculated after the second iteration

The virtual oscillograms of the breakdown voltage, obtained in this way for different pulses, are shown in Fig. 3, 4. In Fig. 3, 4 the horizontal line shows the level of breakdown voltage with prolonged application of voltage $U_b=495$ kV. For each curve in Fig. 3, 4, the area of the figure, bounded from above by a virtual oscillogram, and from below by a horizontal line $U_b=495$ kV, is the same and equates $A=0.62$ V·s.

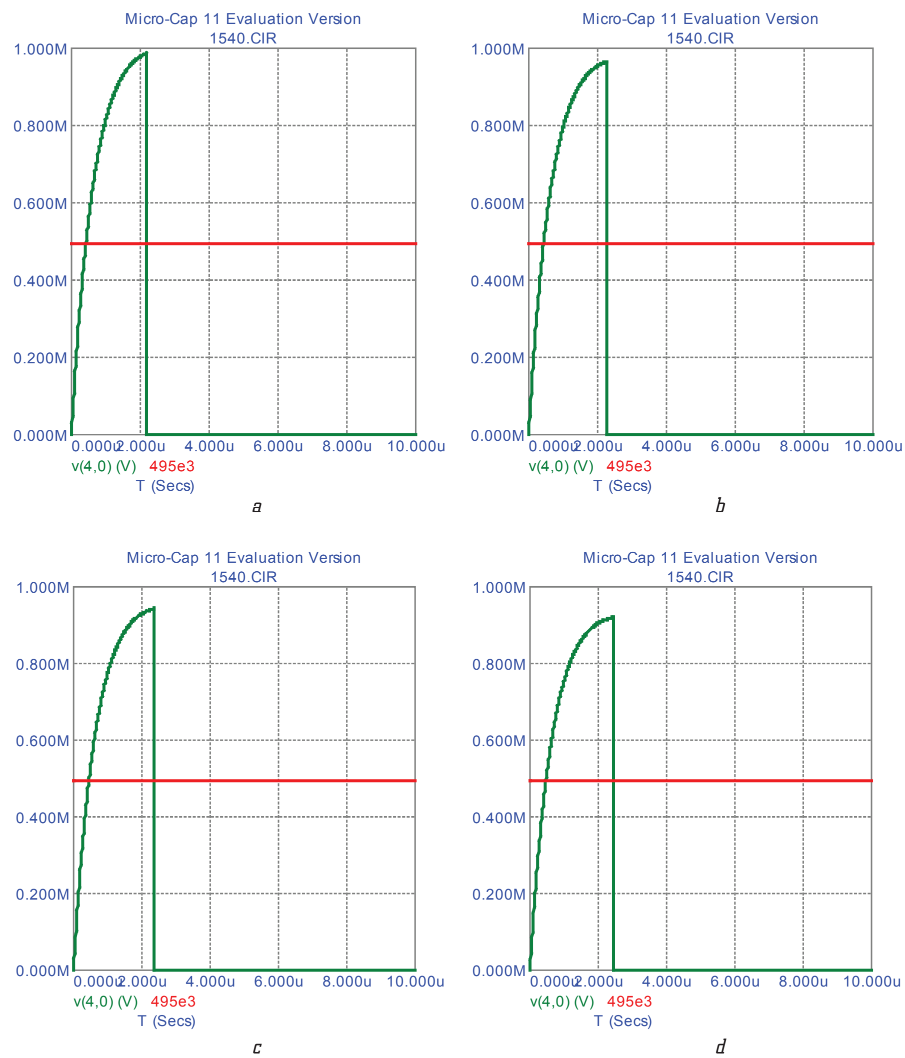

Fig. 3. Breakdown of the air gap at the front of wave, under the impulse voltage with the shape of 1.5/40 μs and amplitude of: *a* – 1000 kV; *b* – 975 kV; *c* – 950 kV; *d* – 925 kV

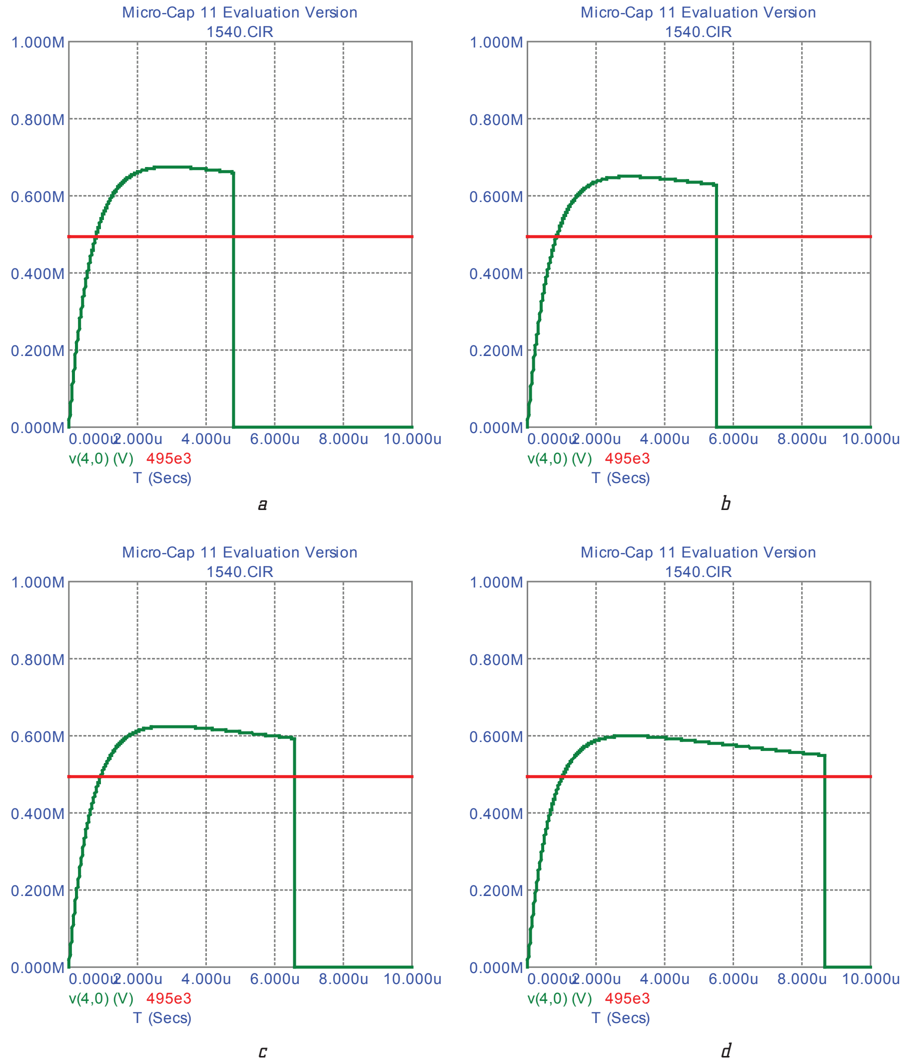

Fig. 4. Breakdown of the air gap at the tail of wave, under the impulse voltage with the shape of 1.5/40 μs and amplitude of: *a* – 675 kV; *b* – 650 kV; *c* – 625 kV; *d* – 600 kV

Thus, the curves in Fig. 3, 4 predict individual points of the volt-time characteristic of the air gap. This volt-time characteristic can be called simulated volt-time characteristic. At the same time, as was indicated above, for the given electrode configuration an experimental volt-time characteristic is known. Table 4 shows the comparison between simulated and experimental volt-time characteristics. From the curves in Fig. 3, 4, the breakdown time is determined and listed in Table 4 (on virtual oscillograms, the breakdown time corresponds to an abrupt fall of the voltage curve to zero value).

Simulation relative error in Table 4 is calculated using the following formula:

$$\xi = \frac{V'_{1.5/40} - V_{1.5/40}}{V_{1.5/40}} \cdot 100, \%, \quad (5)$$

where $V'_{1.5/40}$ – voltage defined by simulated voltage-time characteristic when subjected to a voltage pulse with shape 1.5 / 40 μs; $V_{1.5/40}$ – corresponding value defined by experimental volt-time characteristic (determined by formula (2), substituting simulated breakdown time from Table 4 in it).

As can be seen from Table 4, the simulation error makes it possible to use this model in the educational process for visual demonstration of the breakdown criterion of an air gap under the influence of voltage pulses with a given shape. The fulfilled verification of the proposed method has shown the possibility of its application for other spacing between the electrodes of the rod-rod configuration.

Table 3 shows the values of the source E2 corresponding to each curve in Fig. 3, 4, now with a calculated value of the parameter t1 (calculated after the second iteration).

Table 3

The values of the functional voltage source E2 in the circuit in Fig. 2 according to the Micro-Cap syntax [15]

No.	Amplitude of applied voltage pulse, kV	Value
1	1000	SUM(v(4,0)-495e3,t,0.417e-6)
2	975	SUM(v(4,0)-495e3,t,0.432e-6)
3	950	SUM(v(4,0)-495e3,t,0.448e-6)
4	925	SUM(v(4,0)-495e3,t,0.466e-6)
5	675	SUM(v(4,0)-495e3,t,0.790e-6)
6	650	SUM(v(4,0)-495e3,t,0.854e-6)
7	625	SUM(v(4,0)-495e3,t,0.930e-6)
8	600	SUM(v(4,0)-495e3,t,1.026e-6)

Table 4

Comparison between simulation results and experimental data

No.	Amplitude of applied voltage pulse, kV	Breakdown time, μs (simulation)	Voltage defined by voltage-time characteristic, kV (simulation)	Voltage defined by voltage-time characteristic, kV (calculation by formula (2))	Simulation relative error, % (calculation by formula (5))
1	1000	2.183	987.576	1025.600	–3.707
2	975	2.262	965.688	1007.069	–4.109
3	950	2.349	943.389	988.103	–4.525
4	925	2.446	920.659	968.549	–4.944
5	675	4.800	674.889	736.313	–8.342
6	650	5.498	649.893	705.677	–7.905
7	625	6.571	624.897	671.275	–6.909
8	600	8.679	599.901	628.460	–4.544

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7. SWOT analysis of research results

Strengths. The strengths of the proposed approach are:
– the possibility of modeling the breakdown processes with the help of circuit simulation programs. This is important, since a virtual experiment in technical education is necessary;
– all complex calculations are performed by the program, not by the user. The user needs to know only two parameters: reference voltage U_b and formation area A for considered electrode configuration.
Weaknesses. The weaknesses of the proposed approach are:
– in the proposed model, the calculation of the start time of the streamer formation t_1 and the discharge (breakdown) time t_d is determined not for one execution of the program, but for two iterations;
– the model gives somewhat underestimated values compared to the actual values of the discharge voltage of the air gap.
Opportunities. The opportunities of the proposed approach are:
– determination of the breakdown moments of various air gaps during the action of voltage pulses of all typical shapes and amplitudes, which are used in high voltage engineering;
– use of this model to determine the flashover voltage of complex insulating structures, for example, for suspension insulator strings on overhead transmission lines during lightning surges.
Threats. The model is intended for use in scientific work or in the educational process as a tool for visual demonstration of breakdown conditions of long air gaps. Unlike steady state or transient processes, circuit simulation of electric breakdown processes for high voltage engineering is a relatively new direction. At the moment, the results obtained on simplified models are only approximately equal to the results of a real physical experiment in a high-voltage laboratory.

8. Conclusions

1. The model of the electrical breakdown of the rod-rod air gap is created with a help of the evaluation version of Micro-Cap 11 circuit simulator. The model uses Kind's equal-area criterion, as one of the criteria for streamer breakdown in air.

2. Using the model, the breakdown time of the air gap is calculated under the action of voltage pulses of positive polarity with different amplitudes and shape 1.5/40 μs.

3. Simulation results are compared with experimental data. As the latter, the experimentally obtained expression for the volt-time characteristic of the rod-rod air gap is used. The simulation relative error does not exceed 10 %, which makes it possible to use this model in the educational process to visually demonstrate the conditions for the breakdown of an air gap when subjected to voltage pulses of various shapes.

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СХЕМОТЕХНИЧЕСКОЕ МОДЕЛИРОВАНИЕ ЭЛЕКТРИЧЕСКОГО ПРОБОЯ В ВОЗДУХЕ С ИСПОЛЬЗОВАНИЕМ КРИТЕРИЯ РАВНОЙ ПЛОЩАДИ КИНДА

Предложена упрощенная схемотехническая модель электрического пробоя воздушного промежутка с использованием

критерия равной площади Кинда. Моделирование выполнено с помощью демонстрационной версии программы Micro-Cap 11. Модель позволяет предсказать вольт-секундную характеристику различных воздушных промежутков. Модель рассматривается как вспомогательное средство для студентов, изучающих курс техники высоких напряжений.

Ключевые слова: схемотехническое моделирование, техника высоких напряжений, электрический пробой, вольт-секундная характеристика, критерий равной площади.

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RESEARCH OF OPERATION OF ANISOTROPIC OPTICAL THERMOELEMENT WITH LATERAL TEMPERATURE REGULATION

Розв'язано неоднорідне рівняння теплопровідності з урахуванням закону Бугера для поздовжнього перерізу круглого циліндра з термоелектрично-анізотропного матеріалу. Отримано вирази для поперечної термоЕРС та характеристик радіаційного анізотропного оптикотермоелементу (АОТЕ), що дає змогу контролювати величину потоку енергії в області оптичної прозорості матеріалу, з якого він виготовлений. Описана конструкція приладу на основі радіаційного АОТЕ з боковим термостатуванням.

Ключові слова: *радіаційний анізотропний оптикотермоелемент (АОТЕ), поперечна термо ЕРС, АОТЕ з боковим термостатуванням.*

1. Introduction

The wide use of thermoelectric devices as sources of electric energy, coolers and measuring equipment is due to their reliability, high service life, ability to work under extreme conditions and ecological purity. Thermoelectric devices are used in space and defense technology, metrology, electronics, medicine, etc.

The basis of most thermoelectric devices is a semiconductor thermocouple element, which, along with positive qualities, has drawbacks that prevent further progress in the development of thermoelectricity. The principal shortcomings of the thermocouple element include the ineffective participation of its volume in thermoelectric energy conversion, switching problems, and limitations on the Q-factor of the used materials. Therefore, the further development of thermoelectricity by searching for semiconductor materials with a higher quality factor has already almost exhausted itself.

Progress in thermoelectricity is possible with the introduction of new thermoelements (TE), which are dominated by the possibilities of thermocouple elements. Among the new promising TEs there are vortex TEs with unique properties, which are based on the use of the effect of vortex thermoelectric currents (VTC). It is possible to indicate, in particular, spiral vortex thermoelements, in which the problem of commutation and obtaining the necessary stresses is solved [1, 2].

However, the elemental base of thermoelectricity needs replenishment due to the creation of new types of thermoelements based on known thermoelectric phenomena and phenomena that have not been sufficiently studied. To known phenomena, the mechanisms of their origin have been studied, but on the basis of which TE is created, for example, the volume effects of Peltier and Bridgman can be attributed. Studies of the feasibility of creating anisotropic optical thermoelements (AOTE) on these effects on the basis of existing and hypothetical materials, as well as studying the depth of their cooling, are of current interest. Such studies could lead to the creation of AOTE for cooling or stabilizing the temperature of various kinds of microsensors and microelectronic devices, and are distinguished by a simpler design than the known ones. To the insufficiently studied phenomena from the point of view of practical application it is possible to attribute umkehr effect, VTC effect, the effect of the anisotropy of thermal conductivity on the transverse thermoelectric power.

An in-depth study of the influence of the anisotropy of thermal conductivity on the temperature field and the transverse thermoelectric power of electrically insulated AOTE and its energy would lead to a refinement of the

