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THERMAL MANAGEMENT OF A SET OF THERMOELECTRIC COOLERS CONNECTED IN PARALLEL IN AN UNEVEN TEMPERATURE FIELD

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Key words: *communication models, operating current, reliability performance, dynamic performance.*

A method of increasing the efficiency of thermoelectric system for providing thermal modes of distributed heat-loaded elements of an on-board information system is considered. It is shown that thermoelectric coolers are most susceptible to thermal effects. In accordance with the reliability model, they are connected in series with heat loaded elements and to a great extent determine their operability. The inclusion of thermoelectric coolers in the feedback loop of a thermal management system places increased demands on the dynamic performance of the coolers. However, dynamics and reliability performance are at odds with each other, requiring compromise approaches to cooler design and control. Studies have been carried out for an uneven temperature field, a typical dissipation power range, and a fixed geometry of thermocouple branches. Analytical relations for determining the relative operating current depending on the relative temperature difference at a given supply voltage, geometry of thermocouple branches and heat load value have been obtained. The range of actual values of the relative operating current in the area of relative temperature differences is determined. An analysis of relation between relative operating current and refrigerating factor, amount of consumed energy, heat dissipation capacity of a radiator, time of reaching steady-state mode and probability of no-failure operation has been carried out. The dependence of the relative failure rate, energy input, heat dissipation capacity of the heat sink and the number of thermocouples on the supply voltage has been investigated. This made it possible to determine the controlling features and to reveal the efficiency of controlling actions when the coolers are connected in parallel in an uneven temperature field. The possibility of selecting the optimum supply voltage taking into account the limiting factors for mass-size, energy, dynamic and reliability characteristics of a set of thermoelectric coolers with parallel electric connection is shown. This makes it possible to create thermoelectric systems for providing thermal modes with increased reliability while minimizing mass and dimensional characteristics.

УПРАВЛІННЯ ТЕПЛОВИМ РЕЖИМОМ КОМПЛЕКСУ ПАРАЛЕЛЬНО З’ЄДНАНИХ ТЕРМОЕЛЕКТРИЧНИХ ОХОЛОДЖУВАЧІВ У НЕРІВНОМІРНОМУ ТЕМПЕРАТУРНОМУ ПОЛІ

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Ключові слова: *моделі зв'язку, робочий струм, показники надійності, динамічні характеристики.*

Розглянуто спосіб підвищення ефективності термоелектричної системи забезпечення теплових режимів розподілених теплонавантажених елементів бортової інформаційної системи. Показано, що термоелектричні охолоджувачі найбільш схильні до впливу теплового впливу. Відповідно до моделі надійності вони з'єднані послідовно з теплонавантаженими елементами і значною мірою визначають їхню працездатність. Включення термоелектричних охолоджувачів у ланцюг зворотного зв'язку системи керування тепловими режимами висуває підвищені вимоги до динамічних характеристик охолоджувачів. Однак динаміка і показники надійності перебувають у протиріччі, що вимагає компромісних підходів до розроблення охолоджувачів та керування ними. Дослідження проведено для нерівномірного температурного поля, типового діапазону потужності розсіювання, фіксованої геометрії гілок термоелементів. Отримано аналітичні співвідношення для визначення відносного робочого струму залежно від відносного перепаду температур за заданої напруги живлення, геометрії гілок термоелементів і величини теплового навантаження. Визначено область дійсних значень відносного робочого струму в зоні відносних перепадів температур. Проведено аналіз зв'язку відносного робочого струму з холодильним коефіцієнтом, кількістю енергії, що витрачається, тепловідвідною здатністю радіатора, часом виходу на стаціонарний режим і ймовірністю безвідмовної роботи. Досліджено залежність відносної інтенсивності відмов, кількості енергії, що витрачається, тепловідвідної здатності радіатора і кількості термоелементів від напруги живлення. Це дало змогу визначити керівні ознаки та виявити ефективність керівних впливів у разі паралельного з'єднання охолоджувачів у нерівномірному температурному полі. Показано можливість вибору оптимальної живильної напруги з урахуванням обмежувальних чинників за масогабаритними, енергетичними, динамічними та характеристиками надійності комплексу термоелектричних охолоджувачів з паралельним електричним з'єднанням. Це дозволяє створювати термоелектричні системи забезпечення теплових режимів підвищеної надійності з мінімізацією масових і габаритних характеристик.

Introduction

Modern information systems are based on components with a high concentration of thermal emission per unit area. This is particularly significant for on-board systems where weight, size and energy consumption are critical. Heat-intensive components cannot function without thermal management systems, which are an essential component of information systems. One of the most promising ways of thermal management of electronic components is thermoelectric cooling, which is the most effective over a wide range of operating temperatures. Thermoelectric cooling devices (TEC) allow controlling the value of heat flow by simply changing the operating current value. The main advantages of thermoelectric cooling are high reliability and small overall dimensions, easy operation and rapid response. These advantages are inherently a consequence of the solid-state nature of such coolers, with no moving parts, pumped liquids or gases. The design features of on-board equipment include the dispersed arrangement of heat loaded elements with varying dissipation capacity. Therefore, to ensure a given thermal regime of a number of dispersed thermally loaded and temperature-dependent elements, a group arrangement system of thermoelectric coolers, located on one heat sink and connected in electrical parallel, can be used. In this case it is important to use a number of standard voltages to power the complex and determine the optimum supply voltage, taking into account the limiting factors for mass-size, power, dynamic characteristics and reliability indicators in an uneven temperature field.

Literature Overview

Thermal control systems for thermally loaded components are an essential component of modern on-board avionics [1]. Thermoelectric coolers are the most suitable for on-board systems in terms of mass-size and performance characteristics [2]. The main advantage of TEC over air and liquid cooling systems is the ease of control and high dynamic characteristics [3]. At the same time, toughening requirements to dynamics and reliability of thermally loaded equipment [4; 5], assumes their increase also for systems of providing thermal modes [6; 7]. In [8] influence of loading on reliability indices of thermoelectric coolers is investigated, however, influence of design parameters is not considered. In [9] research of influence of design parameters on reliability indicators of thermoelectric coolers is presented. In [10] a relationship between reliability indices and current operating modes of the cooler is analysed, which allowed to choose optimal operating conditions by this criterion. However, for controlling thermoelectric systems, apart from reliability indicators, dynamic characteristics are also important, the relationship between which was not considered in the cited sources [11]. It is known that dynamics unambiguously negatively affects reliability performance, which is a fundamental problem [12], in particular, linear thermal expansion of thermocouple and substrate materials leads to cracking of junction sites [13]. In [14] the relationship of dynamic performance with TEC design, in [15] with the number of thermocouples, in [16] with the current operation modes of the product, however, only for a single cascade cooler. Subsequent works [17; 18] analyzed the possibilities of optimizing thermoelectric control according to complex criteria, including both reliability and dynamics indicators. A relevant development in this direction is the control of thermoelectric coolers when they are connected in parallel in an uneven field. This is aimed at solving the problem of coordinating the reliability and dynamics indicators of operation, as applied to the management of critical systems for providing thermal modes of radio electronic equipment.

Purpose and objectives of the study

The aim of the work is to develop a thermal management model for thermoelectric coolers connected in parallel and operating in an uneven temperature field.

In order to achieve this aim it is necessary to solve tasks:

1 To develop a mathematical model of thermoelectric cooler which connects energy, dynamic, reliability and structural parameters.

2 To analyses the developed model to identify optimal modes of thermoelectric cooler operation.

Development of a thermoelectric cooler model

We will use the relations from [19] to calculate the basic parameters, reliability indicators and dynamic characteristics of the TEC.

The voltage drop on the TEC can be determined from the relation:

$$U = 2nI_{\max}R\left(B + \frac{\Delta T_{\max}}{T_0}\Theta\right), \qquad (1)$$

where n – number of thermocouples, pcs;

$I_{\max} = \frac{\bar{e}T_0}{R}$ – maximum operating current, A;

$\bar{e}$ – is the average value of the thermoelectric coefficient of the thermocouple branch, V/K;

T_0 – temperature of the absorbing junction, K;

$R = \frac{l}{\bar{\sigma}S}$ – electrical resistance of the thermocouple branch, Ohm;

l and *S* – respectively, height *l* and cross-sectional area *S* of the thermocouple branch;

$\bar{\sigma}$ – is the average conductivity value of the thermocouple branch, Sm/cm;

$B = \frac{I}{I_{\max}}$ – the relative operating current;

I – is the operating current, A;

$\Theta = \frac{T - T_0}{\Delta T_{\max}}$ – the relative temperature difference;

T – is the temperature of the fuel junction, K;

$\Delta T_{\max} = 0,5\bar{Z}T_0^2$ – maximum temperature difference, K;

$\bar{Z}$ – is the average efficiency value of the thermoelectric materials in the module, 1/K.

The value of the operating current can be determined from the expression:

$$I = BI_{\max}. \qquad (2)$$

The number of thermocouples *n* of a single stage TEC can be determined from the ratio:

$$n = \frac{Q_0}{I_{\max}^2 R\left(2B - B^2 - \Theta\right)}, \qquad (3)$$

where Q_0 – is the heat load value, W.

The refrigerating factor *E* can be calculated using the formula:

$$E = \frac{Q_0}{W}. \qquad (4)$$

The relative magnitude of the failure rate λ/λ_0 can be determined from the expression [20]:

$$\lambda\!\!\Big/\!\lambda_0 = nB^2(\Theta + C)\frac{(B + \frac{\Delta T_{\max}}{T_0}\Theta)^2}{(1 + \frac{\Delta T_{\max}}{T_0}\Theta)^2}K_T\,, \qquad (5)$$

where $C = \dfrac{Q_0}{nI_{\max}^2 R}$ – the relative heat load;

K_T – the coefficient of reduced temperatures.

The probability of no-failure operation P of the TEC can be determined from the expression:

$$P = \exp[-\lambda t]\ ; \qquad (6)$$

where t=10^4 hour – is the assigned resource.

The expression for the steady-state operation time τ can be represented as [20]:

$$\tau = \frac{m_0C_0 + \sum\limits_i m_iC_i}{K\left(1 + 2B_K\dfrac{\Delta T_{\max}}{T_0}\right)}\ln\frac{\gamma B_H(2 - B_H)}{2B_K - B_K^2 - \Theta}\,, \qquad (7)$$

where $\gamma = \dfrac{I_{\max H}^2 R_H}{I_{\max K}^2 R_K}$;

m_0C_0 – is the product of the mass and heat capacity of the cooling object. In our case $m_0C_0 \to 0$ (no object);

$\sum\limits_i m_iC_i$ – is the total value of the product of the heat capacity and mass of the constituent structural and technological elements at the heat absorbing junction of the module at a given *l/S*;

index *H* denotes the starting point in time;

index *K* is the finite point in time;

$R_{\text{н}}$ – is the electrical resistance of the thermocouple branch at the start of the cooling process, Ohm.

Relative operating current at the start of the cooling process at τ=0:

$$B_H = \frac{I}{I_{\max H}}\,. \qquad (8)$$

The expression for the relative operating current B can be obtained by substituting (1) into (3), followed by conversion:

$$B = \frac{2A - 1}{2A}\left[1 \pm \sqrt{1 - \frac{4\Theta A(A + \frac{\Delta T_{\max}}{T_0})}{(2A - 1)^2}}\right], \qquad (9)$$

where $A = \dfrac{UI_{\max}}{2Q_0}$ – is a relative value depending on the voltage drop U, the heat load value Q_0, the cooling level temperature T_0 and the geometry of the thermocouple branches (*l/S* ratio).

For a cooling system consisting of *M* independent elements (TEC), the probability of failure of the *i*-th element is $P_i(t)$, then the total probability of system failure is [19]:

$$P_\Sigma(t) = P_1(t)\cdot P_2(t)\ldots P_M(t) = \prod_{i=1}^{M} P_i(t)\,. \qquad (10)$$

Calculations of basic parameters, reliability indices and dynamic characteristics of the complex TEU with parallel electric connection in an uneven temperature field have been carried out. Results have been received for temperatures from T_0 = 295K to T_0 = 250K at various thermal loading from Q_0 = 0.5 W to Q_0 = 15 W, standard values of a supply voltage from U = 6.0 V to U = 24 V, the set geometry of branches of thermoelements *l/S*, *T*=300K and are presented in the form of graphic dependences.

Model analysis

As the supply voltage U of the TEC complex increases with total heat load $Q_{0\Sigma}$ =35 W in an irregular temperature field:

– the value $A = \dfrac{UI_{\max}}{2Q_0}$ (Fig. 1) for different thermocouple branch geometry *l/s* increases.

As the *l/s* ratio increases, the value *A* decreases for a given supply voltage *U*:

– the number of thermocouples *n* increases (Fig. 2 p. 1);

– the total operating current I_Σ decreases (Fig. 2 item 2);

– the refrigerating factor *E* decreases (Fig. 2 item 3);

– the amount of consumed energy *N* increases (Fig. 3 item 1);

– the required heat dissipation capacity of the heat sink increases *αF* (fig. 3 item 2);

– the ramp-up time *τ* increases (Fig. 3 item 3);

– the relative failure rate λ/λ_0 increases (Fig. 4 item 1);

– the probability of no-failure operation *P* decreases (Fig. 4 item 2).

The analysis of results of investigation of basic parameters of the complex TEC at application of standard voltages *U* has shown the necessity of application of current operation modes close to the mode Q_0=0 (*b*<0). This leads to an increase in the number of thermocouples n, dimensions and mass of the TEC complex even when using the geometry of thermocouple branches (ratio *l/s* = 4.5). Therefore, in the following we will consider the possibility of applying the characteristic current modes of operation of the TEC complex for different geometry of thermocouple branches (ratio *l/s* = 4.5, 10, 20) for the values of supply voltage obtained by calculation.

Calculations of basic parameters, dynamic characteristics and reliability indicators of TEC complex, consisting of 6 elements of radio-electronic equipment were performed. Used power dissipation power from Q_0=0.5W to *Q0*=15W, different level of tem-

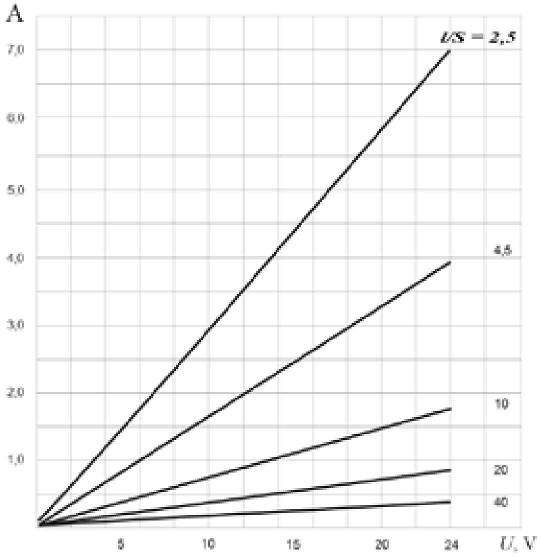

Fig. 1. Dependence of averaged value $A = \frac{UI_{\max}}{2Q_0}$ of TEC complex on supply voltage *U* for different geometry of thermocouple branches (*l/s* ratio) for *T*=300 K, Q_0=34,5W

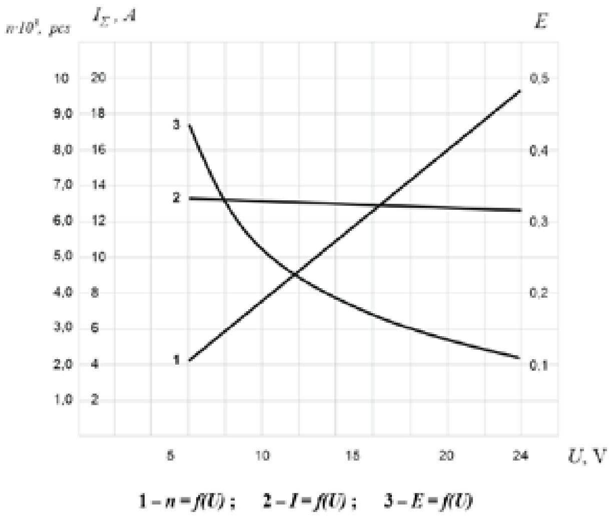

Fig. 2. Dependence of the number of thermocouples *n*, the total value of the operating current I_Σ, the refrigerating factor *E* of the TEC complex with parallel electric connection in the uneven electric field on the supply voltage *U* at *T*=300K, *l/s*=4.5

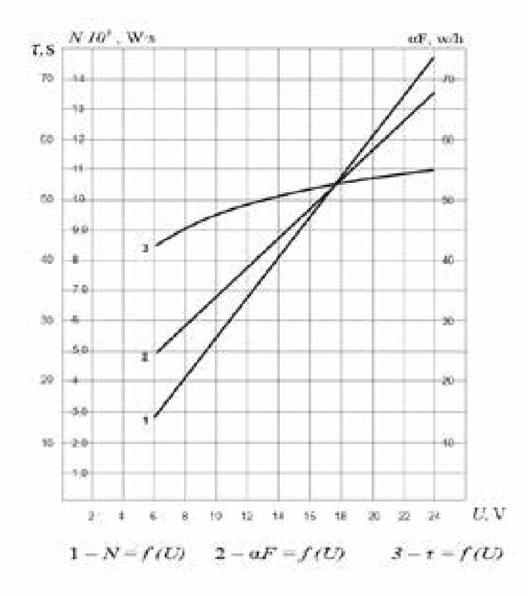

Fig. 3. Dependence of steady-state operation *τ*, amount of energy expended *N*, heat dissipation capacity *αF* of the heat sink of the TEC complex with parallel electric connection in an uneven temperature field on the supply voltage *U* at *T*=300K *l/s* = 4.5

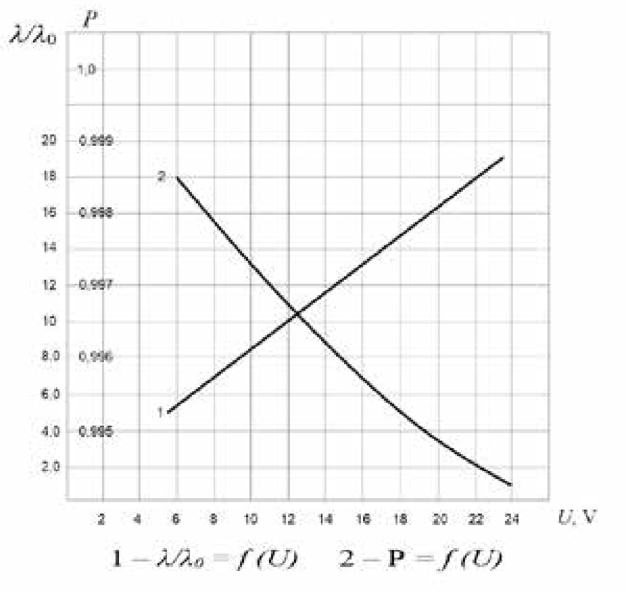

Fig. 4. Dependence of the relative failure rate λ/λ_0 of the probability of failure-free operation *P* of a complex of TECs with parallel electric connection in an uneven temperature field on the supply voltage *U* at *T*=300K *l/s* = 4.5

perature cooling from T_0=295K to T_0=250K, different characteristic current operation modes, different geometry of thermoelement branches (ratio *l/s* =4.5, 10, 20). Graphical dependencies were plotted and the analysis was carried out.

As the average operating current *B* of the TEC complex increases for different thermocouple branch geometries (*l/s* ratio) and characteristic current operating modes:

– the value of the operating current *I* increases (Fig. 5). As the *l/s* ratio increases, the operating current *I* decreases with a fixed relative operating current *B* (for the different characteristic current operating modes);

– the number of thermocouples *n* decreases (Fig. 6). As the *l/s* ratio increases, the number of thermocouples *n* increases with a fixed relative operating current *B*;

– the functional dependence of voltage drop *U=f(B)* on the relative operating current *B* has a minimum at *B* = 0.52 (mode $(nI)_{min}$ for different geometry of thermocouple branches (*l/s* ratio) (Fig. 7). As the *l/s* ratio increases, the voltage drop *U* increases at a fixed relative operating current *B*;

– the functional dependence of the refrigerant *E=f(B)* on the relative operating current *B* has a maximum at *B* = 0.32 for the current mode $(nI\,\lambda/\lambda_0\,\tau)_{min}$ and is independent of the geometry of the thermocouple branches (*l/s* ratio) (Fig. 8);

– the functional dependence of the heat dissipation capacity of the heat sink *αF = (B*) on the relative operating current *B* has a minimum at *B* = 0.32 in the mode $(nI\,\lambda/\lambda_0\,\tau)_{min}$ and is independent of the geometry of the thermocouple branches (*l/s* ratio) (Fig. 9);

– the steady-state time *τ* decreases (Fig. 10). As the *l/s* ratio increases, the steady-state time *τ* decreases at a fixed relative operating current *B*. The minimum steady-state time τ_{min} is achieved at Q_{0max};

– the functional dependence of the amount of spent energy *N=f(B)* on the relative operating current *B* has a minimum at *B* = 0.52 in $(nI)_{\min}$ mode (Fig. 11). As the *l/s* ratio increases, the amount of energy expended *N* decreases at a fixed relative operating current *B*;

– the relative failure rate λ/λ_0 increases (Fig. 12). As the l/s ratio increases, the relative failure rate λ/λ_0 at a fixed relative operating current *B*;

– the probability of failure-free operation *P* decreases (Fig. 13). As the ratio *l/s* increases, the probability of failure *P* decreases for a fixed relative operating current *B*.

Discussion of the results of the analysis

For clarity and ease of comparative analysis, all calculated data are shown in Table 1.

When selecting nominal supply voltage for the complex with parallel electric connection of TEC it is necessary to take into account the limiting requirements: for operating current *I*, number of thermoe-

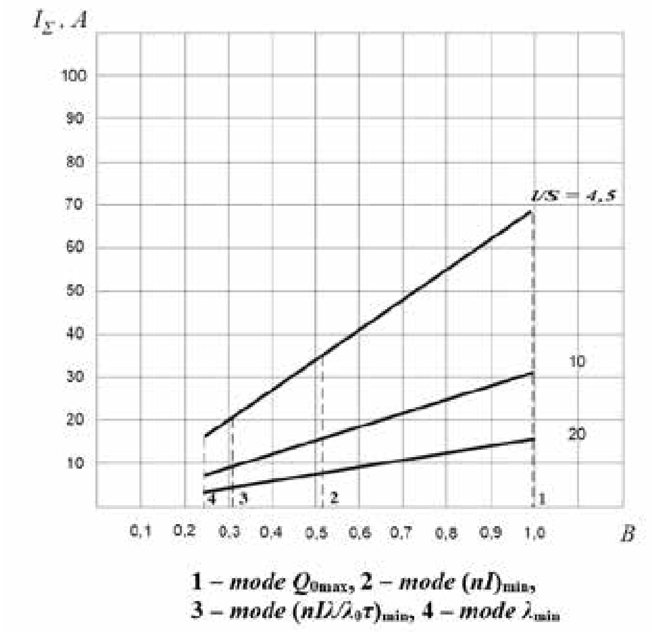

Fig. 5. Dependence of total operating current I_Σ on the averaged relative operating current *B* for different geometry of thermocouple branches *l/s* and current operating modes at *T* = 300 K, Q_0 = 34.5 W

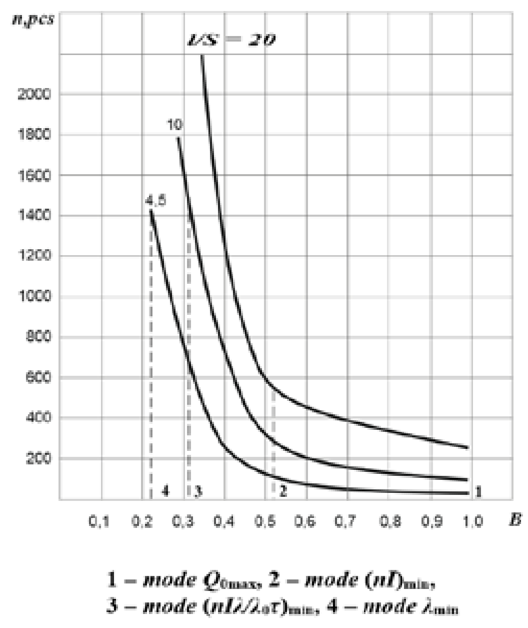

Fig. 6. Dependence of the number of thermocouples *n* in the TEC complex on the averaged relative operating current *B* for different geometry of thermocouple branches *l/s* and current operating modes at *T* = 300 K, Q_0 = 34.5 W

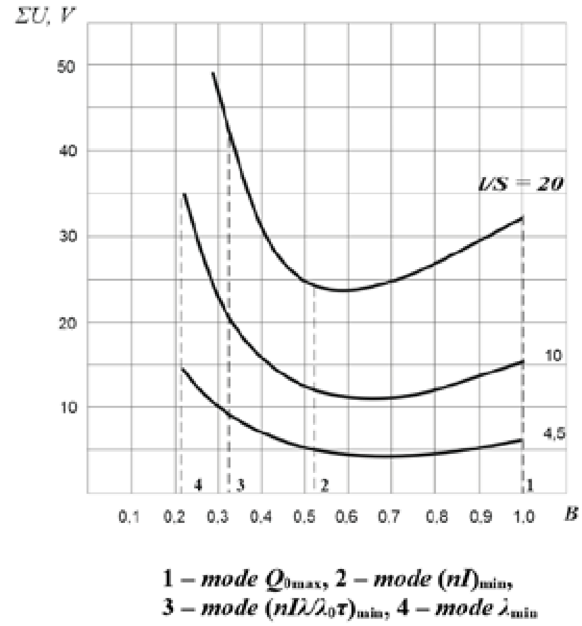

Fig. 7. Dependence of the total voltage drop U_Σ of the TEC complex on the averaged relative operating current B for different geometry of thermocouple branches l/s and current operating modes at T = 300 K, Q_0 = 34.5 W

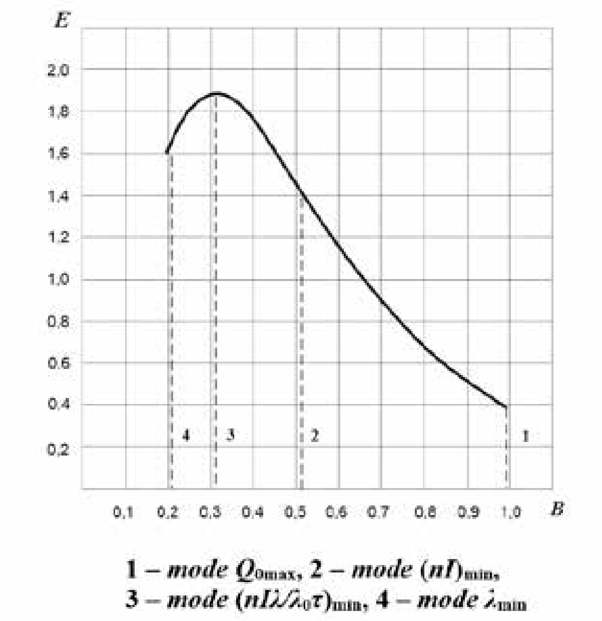

Fig. 8. Cooling coefficient E of the TEC complex from the averaged relative operating current B for different geometry of thermocouple branches l/s and current operating modes at T = 300 K, Q_0 = 34.5 W

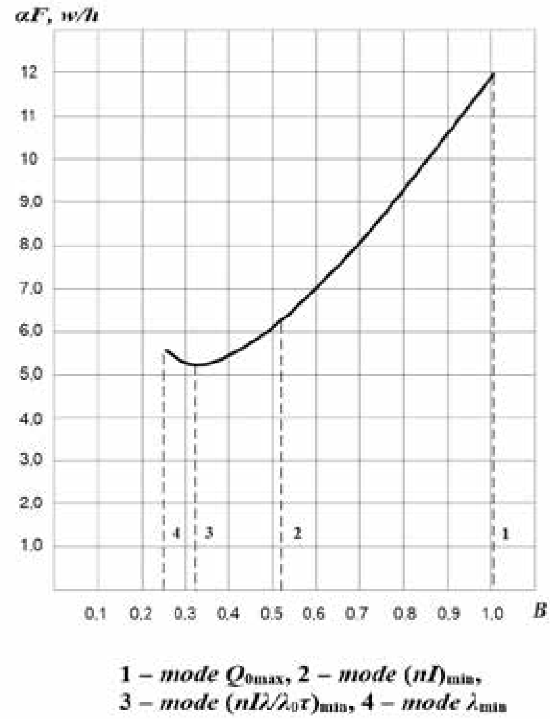

Fig. 9. Dependence of heat dissipation capacity αF of the TEC complex on the averaged relative operating current B for different geometries of thermocouple branches l/s and current operating modes at T = 300 K, Q_0 = 34.5 W, T-T_c=10 K

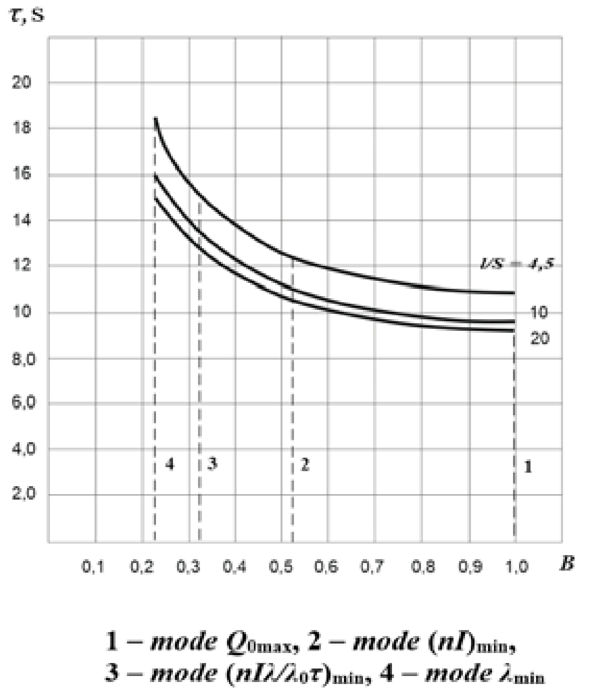

Fig. 10. Dependence of time to steady-state operation τ of TEC complex on the averaged relative operating current B for different geometries of thermocouple branches l/s and current operation modes at T = 300 K, Q_0 = 34.5

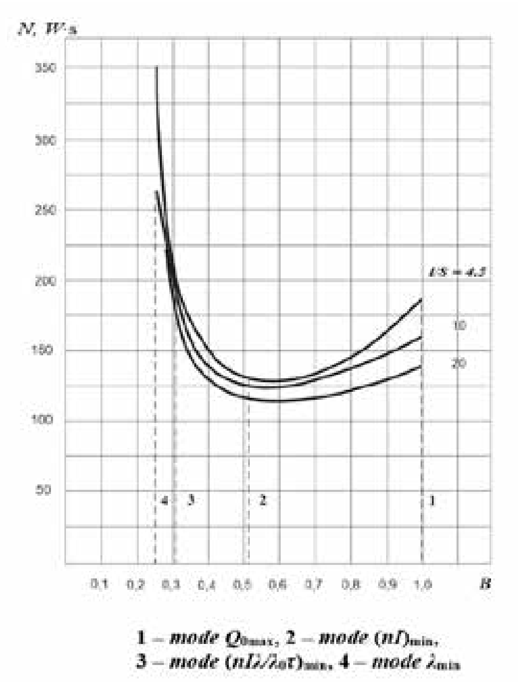

Fig. 11. Dependence of amount of consumed energy *N* of TEC complex on the averaged relative operating current *B* for different geometries of thermocouple branches *l/s* and current operating modes at *T* = 300 K, Q_0 = 34.5 W

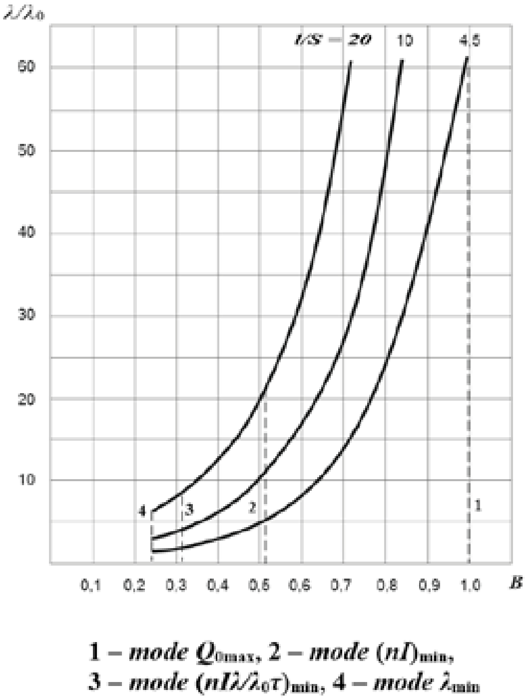

Fig. 12. Dependence of relative failure rate λ/λ_0 of TEC complex on the averaged relative operating current *B* for different geometries of thermocouple branches *l/s* and current operating modes at *T* = 300 K, Q_0 = 34.5 W, λ_0=3·10^{-8} 1/h

lements *n*, cooling factor *E,* power consumption *W*, and, therefore, dimensions and weight of heat sink *αF*, failure rate λ/λ_0 and dynamics of operation *τ*.

At the same time, it is necessary to estimate the weighting of each of the limiting factors and choose an acceptable variant of the complex design. The proposed approach allows a rational design of the TEC complex with selection of the most acceptable variants.

Conclusions

A model of thermal mode support system based on a set of thermoelectric coolers with parallel electric connection has been developed to control the thermal mode of a number of temperature-dependent elements of radio electronic equipment. The model is designed to operate with different power dissipation in an uneven temperature field for different supply voltages and thermocouple vertex geometries.

Comparative analysis of basic parameters, reliability indices and dynamic characteristics of thermoelectric cooler complex for different supply voltages has been carried out.

Analysis of the results has shown the possibility of selecting the supply voltage rating taking into account the limitations on mass-size, energy, dynamic and reliability characteristics for different geometries of thermocouple vertebrae.

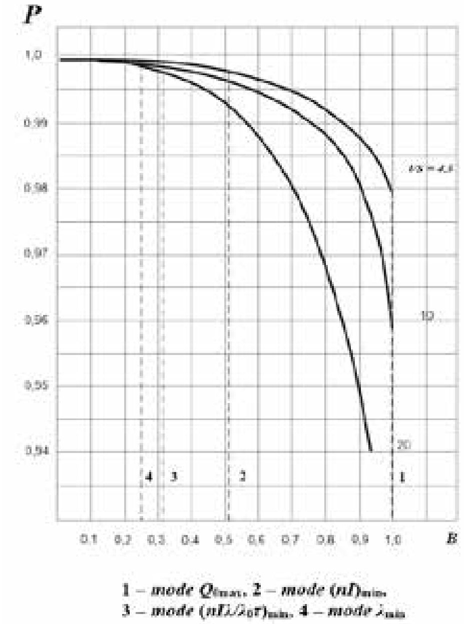

Fig. 13. The dependence of probability of no-failure operation *P* of TEC complex on the averaged relative operating current *B* for different geometries of thermoelement branches *l/s* and current operation modes at *T* = 300 K, Q_0 = 34.5 W, λ_0=3·10^{-8} 1/h, t = 10^4 h.

Table 1

Comparative analysis of basic parameters and indicators at $Q_{0\Sigma}$ =34.5W, $T-T_0$ =10K

Mode	l/s	U, **V**	n, **pcs**	I, **A**	W, **W**	E	αF **W/K**	**τ, s**	N, **W·s**	$\frac{\lambda}{\lambda_0}$	$\lambda 10^8$, h^{-1}	P
Q_{0max}	10	16.0	137	31.0	87.0	0.40	12.2	10	190	138	413	0.9595
$(nI)_{min}$	4.5	5.1	126	35.0	25.4	1.40	6.1	12	133	4.8	14.5	0.9986
	10	12.0	283	16.0	26.0	1.30	6.0	11	126	11.1	33.3	0.9967
	20	24.0	563	8.0	26.0	1.35	6.0	11	120	21.5	64.5	0.9936
$\left(nI\frac{\lambda}{\lambda_0}\tau\right)_{min}$	4.5	9.4	690	21.0	18.2	1.9	5.3	15	200	1.8	5.3	0.99947

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