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SUBSTANTIATION FOR THE SELECTION OF PARAMETERS FOR ENSURING ELECTROTHERMAL PROTECTION OF SOLAR BATTERIES IN SPACECRAFT POWER SYSTEMS

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A relevant scientific-practical issue related to the sustainable development of outer space is the selection of optimal parameters of solar panels for the uninterrupted supply of energy in the power plants of spacecraft. It has been determined that advancing energy-efficient technologies is a prerequisite for ensuring stable space activities. The decision-making process regarding the choice of alternative options for ensuring the electrothermal protection of solar panels in the power plants of spacecraft occurs under the conditions of uncertainty and various risks.

A methodical approach to assessing the effectiveness of options for building electrothermal protection systems for solar panels in the power plants of spacecraft has been devised. The hierarchical structure of the problem about approving of the choice of electrothermal protection of solar panels has been constructed on the basis of the method of analytical hierarchical process, which makes it possible to derive a set of optimal options.

Five alternative options for electrothermal protection of solar panels have been chosen, which, unlike existing ones, take into consideration the phases of the life cycle, namely, the period of active operation. The selection of criteria for choosing the parameters of electrothermal protection of solar panels in the power installations of spacecraft has been substantiated: ensuring the smooth operation of solar panels; availability of service in emergencies; the life cycle of solar panels; the cost of solar panels; technical safety; mass-size indicators.

It is argued that the chosen optimal alternative "Solar panels with protection on the basis of self-resetting fuses" could prolong the active life cycle and, as a result, reduce the number of repairs (current and overhaul) of solar panels in space activities. Owing to the use of this option, positive results could be achieved such an increase in the active life cycle by 20 %, as well as an increase in technical safety by 24 %

Keywords: solar butterfly, electrothermal protection, posistor polymer nanocomposite, dark current, efficiency of switching elements

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1. Introduction

The rapid development of solar energy generation leads to the large number of offers of various solar panels (SPs) in the market, with the appropriate parameters of operation. At the same time, the main issue is to choose optimal parameters for solar panels that would meet the requirements of all alpha stakeholders, first of all, consumers.

This issue is especially acute when choosing the optimal parameters for solar panels in the power plants of spacecraft. Sustainable development of space activities is possible only when space users implement technologies and practices that can ensure the application of energy-efficient technologies [1].

The increase in the number of countries and private operators exploiting space systems in geostationary orbit significantly actualizes the problem of long-term energy sustainability of space activities due to the large increase in energy demand.

One of the most effective sources of energy in space activities is the use of solar energy. The functioning of solar panels in space, in the cosmos where there are no atmosphere, clouds, no changes in day and night, makes it possible to obtain much more solar energy than on the Earth's surface [2]. However, extreme factors in the functioning of solar panels in space necessitate a thorough justification of the parameters of their selection. This renders relevance to the scientific search in the area of devising energy-efficient technologies.

First of all, it is necessary to develop electro-thermal protection of solar panels in spacecraft power plants in order to increase the reliability and efficiency of switching elements. The intensification of the search for innovative ways to protect solar panels leads to the emergence of less expensive and easy to maintain elements of electrical protection and reduce weight and size. The introduction of these scientific advancements will ensure the effective functioning of solar panels over an operational period in space for 15–20 years [3].

The insufficient level of the scientific principles for choosing the optimal parameters of the functioning of solar panels remains an unresolved issue related to energy development of the technological platform in many countries of the world. Thus, further substantiation of procedures for choosing the optimal parameters for selecting the electrothermal protection of solar panels in the power plants of spacecraft (SC) is important scientifically and practically. To provide energy for space activities in the world, this is a relevant scientific and practical issue that must be further clarified and resolved.

2. Literature review and problem statement

When determining the parameters for choosing the protection of solar panels in the power plants of spacecraft, it is necessary to take into consideration the types of operational risks of SPs. Of particular importance is to ensure the electrothermal protection of solar panels.

Work [4] emphasizes that one of the reasons for SP deformation is thermal shocks due to the deep cooling of the structure in shaded areas of the orbit, heating on the illuminated ones, and vice versa. This phenomenon destroys the fastening of individual panel elements, the connection between them. However, the issue of determining the typical and emergency events of SP functioning in space has not been resolved.

Thus, the authors of paper [5] emphasize that the thermal shock is a typical event for photovoltaic cells in space when, while moving from the illuminated part of the orbit to the earth-shaded one, the temperature changes by more than 300 °C in a few minutes. However, the scientific apparatus of the research is insufficiently substantiated – the analysis of the complete list of typical events for SP deformation is not carried out.

In work [6], it is thoroughly analyzed that electrical discharge processes in solar panels lead to undesirable consequences. The authors determine how the surface materials destroyed, first of all, optical and thermoregulating coatings, glass, and how the resource of solar cells (photo converters) is reduced. However, it is impossible to consider only the destruction of surface materials without analyzing changes in the structure of solar cells. Only an integrated approach could resolve the issue of protection of solar panels in the power plants of spacecraft.

Work [7] identifies the need to take into consideration magnetospheric perturbations for ensuring the electrothermal protection of solar panels in power plants of SC. At the same time, the influence of the solar wind on the functioning of SP under space conditions is determined. However, the "Schwabe-Wolf cycle" was not taken into consideration, which significantly increases the impact of magnetospheric perturbation on SP operation.

In support of this theory, a thorough study was carried out in [8]. The paper analyzes the deformation of SP when the Sun reaches maximum solar activity. In particular, upon reaching the peak of solar activity, dielectric materials of geostationary artificial satellites of the Earth acquire an excess surface charge from the flux of electrons with energy up to 100 keV. As a result, there is a possibility that this could lead to the creation of a primary trigger discharge on the electrical contacts of the solar cell. However, possible ways to protect solar panels in the power plants of spacecraft under the conditions of influence of the Sun's processes are not sufficiently substantiated.

It is expedient to consider the thesis discussed in all the above studies [4–8] that the electrothermal protection of solar panels in the power plants of spacecraft is a key element of their effective functioning. It is necessary to consider the basic techniques of electrothermal protection of solar panels of our time. First of all, through the use of the following technical means: melting fuses; shunt diodes; self-resetting fuses; shunting and bypass diodes; voltage limiters and automatic fuses.

Solar panels are protected by melting fuses. In study [9], it is argued that in the electrical ac and dc circuits, to prevent the currents of overloads and short circuiting, various protection devices are used. The authors separate two types: melting fuses and circuit breakers. However, the advantages and disadvantages of these technical devices are not highlighted. Work [10] considers the features of the functioning of melting fuses as devices for protective disconnection of a single action. However, the use of such devices in space is ineffective. First of all, due to inaccessibility in service in typical and emergency events. Paper [11] states that the more effective device for protecting electrical circuits of photovoltaic systems from pulse drops are circuit breakers. Circuit breakers, unlike melting fuses, are designed for multiple operation. However, the features of using a technical device in typical and emergency events are not specified.

Solar panels are protected by shunt diodes. Paper [12] proposes the design of new diodes – new multilayer switching buses of diodes based on molybdenum, owing to which diodes can withstand more than seven hundred thermal shocks. However, the analysis of these structures in space in an extreme situation is not carried out – when the Sun achieves maximum solar activity. It is in work [13] that such an emergency is mathematically modeled. Thus, the use of a specially designed multilayer dielectric crystal insulation allows the diode to withstand a reverse voltage of up to 1.1 kilovolts. Owing to this, a new generation of protective diodes can be used with the most effective of the existing photovoltaic converters. However, it is necessary to devise a comprehensive methodology for protecting solar panels in the power plants of spacecraft, which takes into consideration all possible cases of SP deformation.

Solar panels have protection elements based on self-resetting fuses. In [14], it is proved that existing techniques for resolving issues related to protection against the occurrence of electrical overloads and local overheating (the appearance of "hot spots") are not technically reliable enough in maintenance, and costly at that. Study [15] proposes the use of solid-state combined structures based on varistor ceramics, materials with critical thermally resistive properties, posistor polymer nanocomposites with phase transition. That could improve the reliability of switching elements that would prevent the destruction of solar cells, which occurs when heated with dark current ("hot spots", fire hazards). However, this proposal does not take into consideration changes in the parameters of protection of solar panels in the power plants of spacecraft in space.

Solar panels are protected by shunt and bypass diodes. In [16] it was argued that the term of active operation of the solar cell of spacecraft increases to 15.5 years, provided the technology of shunt and bypass diodes is applied. Study [17] states that the diode can be stored on Earth for 5 years after exploitation in space. Thus, the total warranty period of operation of new generation diodes is 20.5 years. However, in accordance with existing standards/guidelines of international organizations in the field of space sustainable activity [18], the maximum service life of equipment in orbit up to 2000 km should not exceed 25 years. Therefore, it is necessary to devise techniques for the electrothermal protection of SPs, which would prolong the period of active operation of diodes to 25 years. Thus, work [19] confirmed, by independent resource test, the high reliability of devices, during which diodes withstood more than 7 thousand thermocycles. That exceeds 25 years of SP operation. However, this is a significantly costly technical advancement that requires additional calculations of the reported payback period during operation and maintenance (O&M).

Solar panels are protected by voltage limiters and automatic fuses. In work [20], it is determined that circuit breakers are the main thermal protection for excess current. The electromagnetic switch is designed to save from short circuit and is triggered by current. However, it is not specified how automatic fuses could ensure the smooth operation of solar panels in a fire event. This issue is addressed in [21]. The heat switch (bimetallic plate) operates at a temperature, and the higher the current, the higher the heating of the plate, and the faster the trigger time. When the current flowing through the machine is equal to its rated value, the machine should work for an hour, depending on the temperature. However, there is no interdependence of the increase in the temperature of SP and the period of enabling an automatic fuse.

However, the above studies into determining the parameters for choosing the electrothermal protection of solar panels in the power plants of spacecraft are fragmentary. Namely, there is no single integrated approach to solving the problem of defining the parameters of the choice of solar panels in the power plants of spacecraft. Each technology under consideration is focused on protecting individual parameters of the electrothermal protection of solar panels in the power plants of spacecraft. The technology described in works [16–19] focuses on increasing the active life of SPs in space. The technology that was analyzed in [20, 21] is aimed at ensuring the necessary time for triggering the protection against SP deformation. It should be noted that the unified technology that is considered in [14, 15] can take into consideration a more complete range of parameters for the electrothermal protection of SPs. In particular, such as technical safety, service life, cost, etc.

In addition, the considered techniques for the electrothermal protection of SPs can be conditionally divided into three groups of a protection event: typical [9–11], non-standard [12, 13, 16–19], and combined (typical–non-standard) [14, 15, 20, 21]. Undoubtedly, the most effective are the techniques of electrothermal protection, which are able to work in a combined event of SP operation. At the same time, it is necessary to take into consideration the full list of causes of emergencies in space.

All this gives grounds to assert that it is expedient to conduct a study on the substantiation of the choice of parameters for ensuring the electrothermal protection of solar panels in the power plants of spacecraft using modern scientific toolset.

3. The aim and objectives of the study

The purpose of this work is to devise a methodical approach to determining the parameters for ensuring the electrothermal protection of solar panels in the power plants of spacecraft. This will make it possible to improve the efficiency of solar panels in power plants under the non-standard modes of spacecraft operation.

To accomplish the aim, the following tasks have been set:

– to define the criteria for choosing parameters for ensuring the electrothermal protection of solar panels in the power plants of spacecraft;

– to perform a multicriterial analysis of enabling the electrothermal protection of solar panels in the power plants of spacecraft.

4. The study materials and methods

The object of our research is the decision-making process regarding the choice of alternative options for ensuring the electrothermal protection of solar panels in the power plants of spacecraft.

The main hypothesis of this study is the statement that the chosen option for providing electrothermal protection of solar panels in the power plants of spacecraft is effective. It will provide a significant reduction in the mass-size of solar panels and the possibility of their reusability. This justifies ensuring the smooth operation of solar panels in power plants in space in emergencies.

The proposed scientific method underlying the choice of alternative variants of solar panels in the power plants of spacecraft is the method of hierarchy analysis (MHA). This multicriteria analysis procedure is proposed in [22].

Solving the problem is the process of gradual formation of priorities [23]. At the first stage, the most important elements of the problem are identified, at the second stage – the best way to check statements and evaluate parameters. The entire process is subject to verification and rethinking until it is established that it has covered all the important characteristics of solving the problem of choosing solar panels in the power plants of spacecraft.

The choice of the optimal option for electrothermal protection of solar panels in the power plants of spacecraft is carried out using the appropriate structure (Fig. 1).

Thus, the first step of the method of hierarchy analysis is to decompose and represent the problem in a hierarchical form [24]. We consider the dominant hierarchies that are built from the top (aim – from the point of view of management) through intermediate levels (the criteria on which the following levels depend) to the lowest level, which is usually a list of alternatives. A hierarchy is considered complete if each element of a given level functions as a criterion for all elements of the level below. That is, the hierarchy can be divided into sub-hierarchies that share the highest element. The law of hierarchical continuity requires that lower-level elements be compared in pairs with items of the next level to the top of the hierarchy.

At the second stage, we justify the choice at each level using the expert matrix by T. Saati according to the pairwise comparison rule [24]:

$$\begin{cases} P_1 = 2P_2, P_1 = 5P_3, \\ 2P_2 = 5P_3 \vee P_2 = 5/2P_3 \rightarrow \\ \rightarrow P_3 = 2/5P_2, \\ \dfrac{P_2}{P_3} = \dfrac{5}{2}, \dfrac{P_3}{P_2} = \dfrac{2}{5}, \end{cases} \quad (1)$$

where P_i is the i-th value of the comparative criterion.

After calculations based on (1), a matrix of pairwise comparisons is constructed in tabular form. Then, for the subsequent assembly of the scalar chain, the factor that receives the maximum number of points in the Matrix of paired comparisons is determined.

The procedure of the analytical hierarchical process method has a built-in criterion for the quality of parameter selection – consistency index (CI). It provides information on the degree of violation of the numerical (cardinal) and transitive (ordinal) consistency of judgments. The consistency index of the Matrix of pairwise comparisons is determined from [22]:

$$CI = \frac{\lambda - n}{n - 1}, \quad (2)$$

where CI is the consistency index;

λ is the natural number;

n is the number of comparable criteria.

The objectivity of the evaluation of criteria is determined by the consistency ratio (CR) [22]:

$$CR = \frac{CI}{AC} \times 100\,\%, \quad (3)$$

where CR is the consistency ratio;

AC – average consistency for random matrices of different orders.

For example, the value of the AC matrix 6×6 is 1.24.

According to [22], the condition must be met: $CR \leq 10\,\%$.

The global priorities (P^G) of the criteria for choosing options is determined from [24]:

$$P^G = \sum_{i=1}^{n} V_{norm} \times V_e, \quad (4)$$

where P^G is the global priority of the criteria for choosing options;

V_{norm} is the normalized assessment of criteria priority vectors;

V_e is the evaluation of the component of criterion of eigenvector.

An alternative option is chosen that meets the condition: $P^G \rightarrow \max$.

The information base for calculating the criteria for the effectiveness of choosing options for ensuring the electrothermal protection of solar panels is the data acquired from the experimental work that we performed. The experimental study was carried out at the NDL of problems of reliability of technical devices of renewable energy sources in the Research Institute of Energy Efficient Technologies and Materials Science at the Dnipro National University named after OlesHonchar. According to the results of our study, the following technical solutions were chosen:

– $A1$. Solar panels without protection.

– $A2$. Solar panels that are protected by melting fuses.

– $A3$. Solar panels with the protection based on self-resetting fuses.

– $A4$. Solar panels that are protected by shunt diodes.

– $A5$. Solar panels that are protected by shunt and bypass diodes.

– $A6$. Solar panels that are protected by voltage limiters and automatic fuses.

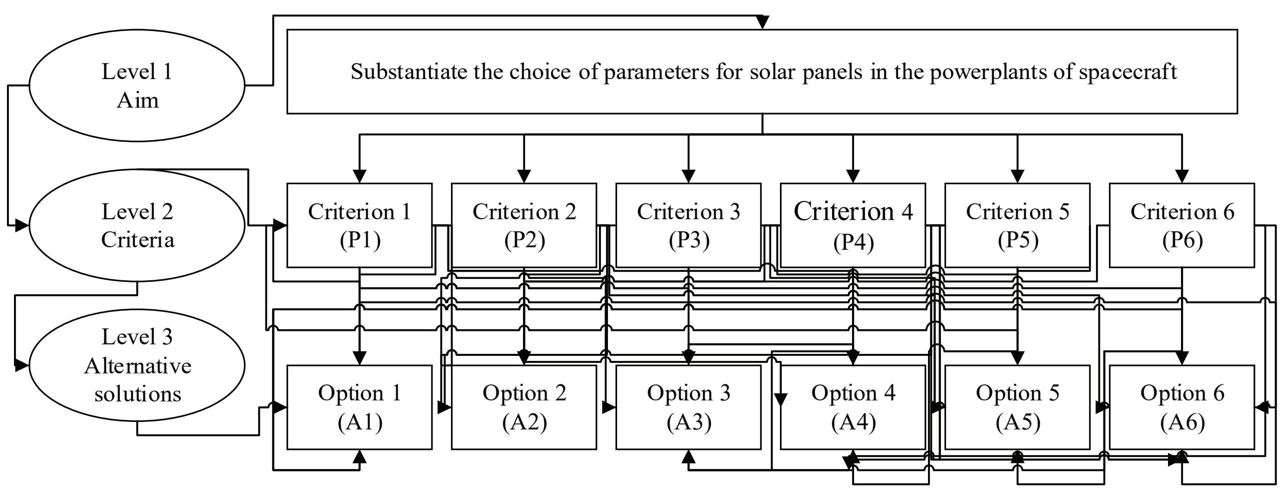

Fig. 1. Hierarchical structure of the problem of deciding on the choice of electrothermal protection of solar panels in the power plants of spacecraft

5. The results of research into substantiating the choice of electrothermal protection of solar panels in the power plants of spacecraft

5. 1. Selection of criteria for selecting parameters for ensuring the electrothermal protection of solar panels in the power plants of spacecraft

When analyzing and selecting solar panels according to the results of our study, it is advisable to take into consideration the following criteria (*P*1–*P*6):

– *P*1. Ensuring the smooth operation of solar panels provides an opportunity for high-quality uninterrupted generation of stable output current. Continuous operation of the device without losing maximum power. This is determined through the following indicators: ensuring frequency stability, the absence of harmonic distortions and jumps in voltage.

– *P*2. Affordability of service in emergencies. Emergencies in the operation of solar panels in space are include a failure to unfold panels, a fire, a deformation (exposure to space weather, solar cycles, meteorites), etc. The inability to repair solar panels, especially solar farms on the International Space Station (ISS), completely/partially leaves spacecraft without energy. It is the additional provision of electrothermal protection of solar panels that makes it possible to ensure maximum manufacturability of service under various operating conditions.

– *P*3. The life cycle of solar panels. While solar panels on Earth have a lifespan of 3–5 years, monocrystalline solar panels in space have a lifespan of 15–20 years [25]. In the economic aspect, it is necessary to take into consideration the given payback period in changes in cost in operation and maintenance (O&M). Namely, the period of active operation of solar panels. It is believed that the additional provision of electrothermal protection of solar panels makes it possible to prolong the period of energy-generating activity.

– *P*4. The cost of solar panels. The cost of design can be determined by summing up the cost of manufacturing (the cost of fabrication, testing, and assembling), operation and maintenance (O&M). The calculation is carried out on the basis of the postulates of the methodology given in [26].

– *P*5. Technical safety. Technical safety is manifested in increasing the reliability of the technical characteristics of the components of photovoltaic modules due to the total increase in reliability: solar cells, protection elements, switching elements, and engineering structures.

– *P*6. Mass-size indicators. The main desirable results of providing electrothermal protection of solar panels are ensuring a significant reduction in the mass-size indicators; ensuring maximum electrical power per unit of mass. Since solar panels are delivered to earth's orbit by shuttle, there is a problem of the existence of the value of the payload mass of SC. It is the use of energy-efficient technical means of electrothermal protection that is based on their functional ability to significantly reduce the mass-size indicators of solar panels and the possibility of their reusability.

Table 1 gives the basic criteria for choosing options for solar panels in the power plants of spacecraft based on the selected options and indicators.

It should be noted the following in relation to indicators. The criteria *P*1 and *P*2 acquire linguistic meanings "Yes"/"No". That is, when determining the priorities of constructing parameter matrices, "1"/"0" will be put.

The criteria *P*4–*P*6 are determined by such a postulate. Option *A*1 "Solar panels without protection" is basic; if additional means of electrothermal protection of solar panels are used, these are variants *A*2–*A*6. As a basic option, *A*1 acquires a value of *P*4–*P*6 criteria of 1. Changes in the *A*2–*A*6 variants are the sum of the basic version and changes in the corresponding indicators. Analytically, it can be represented as follows: 1±change in share. For example, if the criterion *P*4 changes by 10 %, then in the final form: 1+0.1=1.1 (share).

Table 1

Criteria for choosing options for solar panels in the power plants of spacecraft

No. of entry	Criterion	Designation	Variants of solar panels in the power plants of spacecraft					
			A1	A2	A3	A4	A5	A6
1	Ensuring uninterrupted operation of solar panels	*P*1	Yes	Yes	Yes	Yes	Yes	Yes
2	Affordability of service in emergencies	*P*2	Yes	Yes	Yes	Yes	Yes	Yes
3	Service life of solar panels, years	*P*3	15	15	20	18	18	17
4	The cost of solar panels, USD/sq.m.	*P*4	105	107	125	130	140	120
5	Technical safety, share	*P*5	1.0	1.05	1.24	1.1	1.15	1.1
6	Mass and size indicators, share	*P*6	1.0	1.1	1.15	1.2	1.25	1.3

5. 2. Multicriterial analysis of the provision of electrothermal protection of solar panels in the power plants of spacecraft

Limiting the long existence of space technology in near-Earth orbits requires solving a multicriterial analysis of determining the criteria for choosing options for the electrothermal protection of solar panels in the power plants of spacecraft.

The results of the construction of a matrix of criteria for choosing options for the electrothermal protection of solar panels in the power plants of spacecraft are given in Table 2. The calculation is based on (1).

We shall rank the criteria for choosing options for the electrothermal protection of solar panels in the power plants of spacecraft. Rank 1 – *P*5 (0.3824); rank 2 – *P*4 (0.2362); rank 3 – *P*6 (0.1299); rank 4 – *P*1(0.1246); rank 5 – *P*2 (0.1061); rank 6 – *P*3 (0.0207). It should be noted that the criteria "The cost of solar panels" and "Mass-size indicators" in optimum acquire a minimum value. The other four criteria are the maximum value.

Table 2

Matrix of criteria for choosing options for the electrothermal protection of solar panels in power plants of spacecraft

Criterion	*P*1	*P*2	*P*3	*P*4	*P*5	*P*6	Evaluation of the component of eigenvector	Normalized assessment of priority vectors
*P*1	1	9	3	0.333	0.333	0.5	1.0696	0.1299
*P*2	0.111	1	0.125	0.111	0.111	0.143	0.1704	0.0207
*P*3	0.333	8	1	0.333	0.25	2	0.8734	0.1061
*P*4	3	9	3	1	0.3333	2	1.9445	0.2362
*P*5	3	9	4	3	1	3	3.1479	0.3824
*P*6	2	7	0.5	0.5	0.333	1	1.0260	0.1246
Total							8	*X*

Let's analyze the objectivity of the assessment of the criteria for selecting options for electrothermal protection of solar panels in the power plants of spacecraft. The matrix consistency index, calculated from (2), is 0.116, then the consistency ratio calculated from (3) is 9.33 %. The condition is met: 9.33 %<10 %.

The results of determining the global priorities of the criteria for choosing options for the electrothermal protection of solar panels in the power plants of spacecraft are given in Table 3. The calculation is based on (4).

We shall rank the choice of alternative options for the electrothermal protection of solar panels in the power plants of spacecraft. Rank 1 – "*A*3" (0.2707); rank 2 – "*A*2" (0.1863); rank 3 – "*A*4" (0.1587); rank 4 – "*A*6" (0.1567); rank 5 – "*A*1" (0.1261); rank 6 – "*A*5" (0.1016).

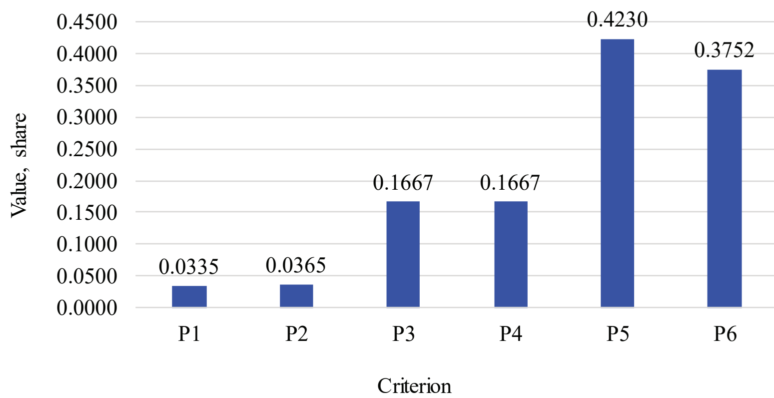

Fig. 3. Histogram of choice of criteria for optimal alternative (*A*3) of the electrothermal protection of solar panels in power plants of spacecraft

Table 3

Determining the global priorities of the criteria for choosing options for the electrothermal protection of solar panels in the power plants of spacecraft

Alternative	Parameter						Global priority
	*P*1	*P*2	*P*3	*P*4	*P*5	*P*6	
	Numerical value of the priority vector						
	0.1299	0.0207	0.1061	0.2362	0.3824	0.1246	
A1	0.1791	0.1047	0.1667	0.1667	0.0820	0.0984	0.1261
A2	0.0961	0.1047	0.1667	0.1667	0.2355	0.1968	0.1863
A3	0.0335	0.0365	0.1667	0.1667	0.4230	0.3752	0.2707
A4	0.1034	0.1128	0.1667	0.1667	0.1604	0.1968	0.1587
A5	0.0580	0.0633	0.1667	0.1667	0.0612	0.0984	0.1016
A6	0.5300	0.5780	0.1667	0.1667	0.0379	0.0344	0.1567

It should be noted that the criteria "The cost of solar panels" and "Mass-size indicators" in optimum acquire a minimum value. The other four criteria are the maximum value.

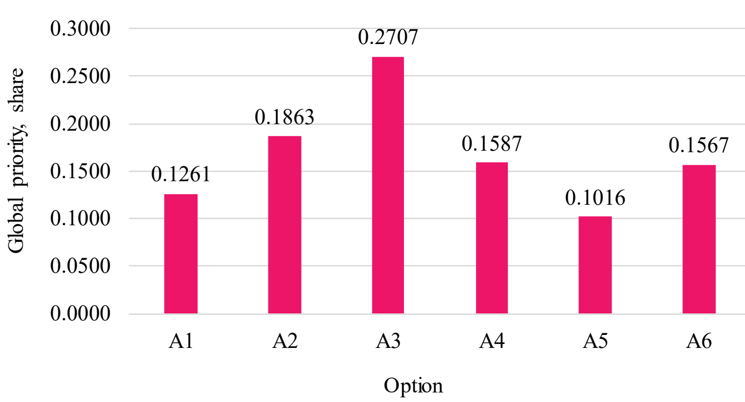

Fig. 2. Histogram of the choice of options for solar panels in the power plants of spacecraft

The results of calculating the choice of solar panels in the power plants of spacecraft are shown in Fig. 2.

As noted, the best option for choosing the electrothermal protection of solar panels in the power plants of spacecraft is the *A*3 option. Consider in detail the criteria for selecting thermal protection of solar panels in power plants of spacecraft (Fig. 3).

Our ranking of the criteria for choosing the *A*3 variant of solar panels in the power plants of spacecraft showed the following results. Rank 1 – P5(0.423); rank 2 – *P*6 (0.3752); rank 3 – two parameters *P*3 (0.1667) and *P*4 (0.1667); rank 4 – *P*2 (0.0365); rank 5 – *P*1 (0.0335). That is, according to the constructed matrix of parameters for choosing options for solar panels in the power plants of spacecraft (Table 2), it corresponds to the correspondence of ranks according to the following criterion: rank 1 – "Technical safety". This is indeed a priority criterion when choosing a variant of solar panels in the power plants of spacecraft.

The resulting same rank 3 is due to the fact that the criteria *P*1 and *P*2 acquire a linguistic meaning "Yes" – the same matrices for choosing a variant of solar panels in the power plants of spacecraft.

At the same time, the quantitative gap by criteria according to the data in Tables 2, 3 (the best option is *A*3) is: *P*5+0.406; *P*6+0.2453; *P*3+0.146; *P*4–0.0695; *P*2–0.0699; *P*1+0.0128. The total criteria gap is +0.6707. This indicates that the parameters for choosing the A3 variant of solar panels in the power plants of spacecraft showed the results that significantly exceed the normalized estimates of priority vectors.

6. Discussion of results of substantiating the choice of the electrothermal protection of solar panels in the power plants of spacecraft

Unlike [10–21] where the choice of electrothermal protection of SPs is fragmentarily considered, our result of choosing the parameters for the electrothermal protection makes it possible to determine the plane of alternative projects and build a common vector of the optimal option. This becomes possible due to the use of the method of analytical hierarchical process with the possibility of multicriterial analysis of the parameters for the electrothermal protection of solar panels in the power plants of spacecraft. Fragmentation implies a single choice, without comparisons, of the electrothermal protection of solar panels in the power plants of spacecraft.

The justification for the choice of the electrothermal protection of solar panels in the power plants of spacecraft can be carried out in accordance with the built hierarchical structure of the problem based on the MHA method (Fig. 1). The choice of options for the electrothermal protection of solar panels in the power plants of spacecraft can be determined using parameters in Table 1. They are selected on the basis of the postulates of the concept of the life cycle of solar panels, namely, the period of active operation.

The constructed matrix of criteria for the parameters of choosing options for the electrothermal protection of solar panels in the power plants of spacecraft (Table 2, (1)) makes it possible to carry out a normalized assessment of priority vectors. The matrix (2) consistency index is 0.116, then the consistency ratio (3) is 9.33 %. Determining the global priorities of criteria for parameters of choice of options for the electrothermal protection of solar panels in power plants of spacecraft ((4), Table 3, Fig. 2) makes it possible to choose the optimal alternative A3 "Solar panels with protection based on self-resetting fuses". The built histogram of the choice of criteria for the optimal alternative to the electrothermal protection of solar panels in the power plants of spacecraft (Fig. 3) determines the ranking according to the selected criteria.

Our results could be used in the design of optimal options for the electrothermal protection of solar panels in the power plants of spacecraft. Also, taking into account the specificity of the operating conditions of solar panels – in the operation of mobile devices for defense that use SB.

The limitations of our study are based on the principle of Ceterisparibus. Namely, under the same conditions, there is a choice of alternative options for solar panels. The main conditions are technical, physicochemical, climatic, etc. For example, the existence of an 11-year cycle of solar activity ("Schwabe cycle" or "Schwabe-Wolf cycle"). Thus, according to NASA scientists, the next peak of solar activity will be observed in July, 2025 [3].

The main disadvantage of our study when using the MHA method is the use of transitivity for qualitative indicators. The ratio of transitivity is expedient when all the characteristics of the studied system can be given a numerical value. However, as soon as this becomes impossible, the requirement of transitivity is most often at odds with the logic of the researcher. That requires the connection of additional procedures, for example, pulse modeling.

The present study could be advanced by devising scenarios for the functioning of solar panels in the power plants of spacecraft based on changes and interaction of parameters (concepts) using pulse and agent modeling. We believe that this will ensure the introduction of the necessary mechanisms to prevent the reduction of operational reliability of solar panels in spacecraft power plants, in emergencies.

7. Conclusions

1. We have defined the criteria for selecting parameters of the electrothermal protection of solar panels in power plants of spacecraft: ensuring the smooth operation of solar panels; availability of service in emergencies; the life cycle of solar panels; the cost of solar panels; technical safety; mass-size indicators. The choice of alternative systems of the electrothermal protection of solar panels in the power plants of spacecraft is proposed to be carried out on the basis of the method of analytical hierarchical process. Owing to its use, it is possible to obtain a set of alternative options for the electrothermal protection of solar panels in the power plants of spacecraft in accordance with the principles of sustainable space development.

2. A multicriterial analysis of the provision of electrothermal protection of solar panels in the power plants of spacecraft, namely solar panels with protection based on self-resetting fuses, has been carried out. We ranked the calculated criteria for selecting parameters and determined the quantitative gap in global priorities. This allows for an in-depth assessment of the priority level of alternative options with their subsequent gradation based on the results obtained. Owing to the use of solar panels with protection based on self-resetting fuses, it is possible to achieve positive results of SP functioning: an increase in active operation by 20 % and an increase in technical safety by 24 %.

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