Technical Physics, 2023, Vol. 68, No. 2

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Statistical evaluation of the characteristics of damaged solar panels of spacecraft

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Received May 4, 2022
Revised November 27, 2022
Accepted December 16, 2022

The change in the characteristics of a solar battery as a result of a random abrupt change in the properties of individual solar cells, which occurred as a result of a single or systematic impact of adverse factors in near-Earth outer space, is considered. The choice of the calculation scheme for constructing a model of a single solar cell is substantiated. For this situation, analytical mathematical models of typical connections of solar cells have been developed. Using the developed models, the current-voltage and volt-watt characteristics of the solar battery are analyzed in the case of an abrupt decrease in the photocurrent of solar cells with different probabilities. A statistical analysis of the characteristics of damaged solar cells was carried out using simplified logical-analytical models with the introduced circuit loss coefficient. Estimates of the values of the coefficient of circuit losses for typical schemes for connecting solar cells are given.

Keywords: solar cell, voltage characteristic, functioning model, damaged solar battery.

DOI: 10.21883/TP.2023.02.55480.121-22

Introduction

Under the influence of various factors of near-Earth space, a significant degradation of solar batteries (SB) of spacecrafts is observed. In this regard, both at the design stage and during the operation of the spacecraft, a tool is needed to predict the technical state of the SC, which adequately considers the degradation processes of the SS components, i.e. solar cells (SC).

During spacecrafts operation two types of processes of degradation of individual elements of the SB can be observed: a smooth change in the properties of the SC as damages accumulate as a result of the unfavorable factors (UF) action or a stepwise change in the SC properties. The methodological apparatus that allows simulating the process of SB operation with a smooth change in the SC properties is sufficiently developed [1–9], however, there are no models that describe the process of SB operation in the case of stepwise change in the SC properties. The list of SC characteristics, causes and examples of their stepwise changes are presented in the paper [10]. Therefore, the purpose of this paper is to develop methods that allow one to evaluate the characteristics of damaged SBs of spacecraft power supply systems under conditions of uncertain characteristics of SCs due to the random nature of degradation of their properties as a result of exposure to NF.

1. Simulation of SB individual elements operation

Prediction of SB state can be performed based on the results of calculating the integral characteristics of SB based on the characteristics of its constituent elementary fragments. Here, SB elementary fragment is such a part of the battery, within which its degradation can be assumed to be uniform. It is expedient to consider SC as SB elementary fragments. This is due to the fact that the SC has rather stable characteristics over the entire area. Besides, there is the possibility to execute experimental studies of the UF effect on its properties.

The integral characteristic of the SB should be understood as the SB statistical characteristic as a whole calculated on the basis of the characteristics of damaged elementary fragments, which determines its properties when functioning as part of the spacecraft power supply system.

When simulating the SB operation under the UF effect, it is advisable to choose an universal current-voltage characteristic (CVC) of the battery, which determines its ability to generate electricity under various modes. It is expedient to include individual CVC of SC in the composition of this model:

$$I^{SB}(U) = f^{SB}_{VAC}\left(I^{SC}_{\langle n\rangle}(U)\right), \tag{1}$$

where $I^{SC}_{\langle n\rangle}(U)$ is the set of CVC of SCs included in SB; n is the number of SCs that make up the SB; f^{SB}_{VAC} is a function that links the SC characteristics with the entire SB characteristics.

The choice of an equivalent scheme and a set of assumptions for SC description is carried out depending on the problem being solved. A rather complete overview of the problems to be solved and the cell models suitable for their solution is presented in the papers [1–9]. To build a model (1) during the study of SC operation under external effects that can lead to the occurrence of damage of various types, the equivalent scheme shown in Fig. 1 is well suited.

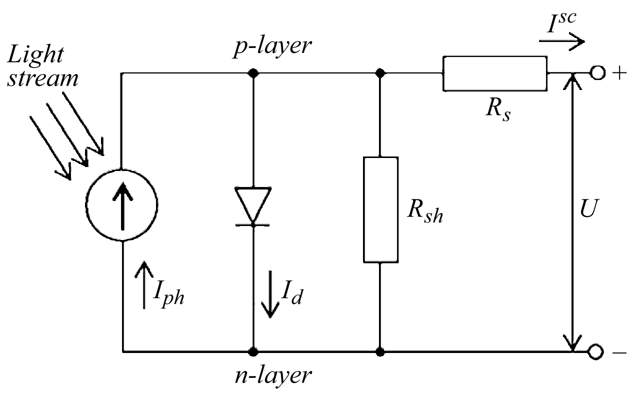

Figure 1. Equivalent scheme of SC.

The mathematical model for this equivalent scheme can be represented by the expression [1]:

$$I^{SC} = I_{ph} - I_{rev}\left(e^{\frac{q_e(U+I^{SC}R_s)}{AkT}} - 1\right) - \frac{U}{R_{sh}}, \qquad (2)$$

where I^{SC} — load current or SC output current; I_{ph} — photocurrent generated by light of minority carriers; I_{rev} — reverse saturation current; $q_e = 1.60217653 \cdot 10^{-19}$ C — electron charge; U — SC output voltage; R_s — SC series resistance; A — experimentally obtained coefficient, taking values from 1 to 5; $k = 1.3806505 \cdot 10^{-23}$ J/K — Boltzmann's constant; T — SC temperature; R_{sh} — SC shunt resistance.

If modern heterostructural SCs are reviewed, the model (2) can be supplemented by the corresponding terms [5,7–10].

To determine the parameters included in the equation (2), it is possible to use an approach based on the plotting of a normalized CVC [1,10].

Another important integral characteristic of SC and SB — volt-watt characteristic (VWC):

$$N^{SC}(U) = I^{SC}(U) \cdot U.$$

The SB power is the sum of the output powers of individual SCs. The SB output current in the battery is determined by the number of cells connected in parallel, and the output voltage — by the number of cells connected in series. For the convenience of analyzing the SB operation it is advisable to present it in the form of SCs connected in series and parallel.

When SCs are connected in parallel, all the cells combined into an elementary circuit generate an electric current at the same operating voltage:

$$I^{C}(U) = \sum_{i=1}^{m} I_i^{sc}(U), \quad N^{C}(U) = I^{C}(U) \cdot U,$$

$$N^{C}_{\max} = I^{C}(U^{C}_{opt}) \cdot U^{C}_{opt}, \qquad (3)$$

where $I^{C}(U)$ — CVC of m SCs connected in parallel; $N^{C}(U)$ — VWC of m SCs connected in parallel; $N^{C}_{\max}$ — the maximum electrical power that m SC connected in parallel can generate under design conditions; U^{C}_{opt} — the optimal voltage at which the parallel connection generates the maximum power.

When connected in series into an elementary circuit, SCs with different CVC generate electricity at the same current value:

$$U^{S}(I) = \sum_{i=1}^{n} U_i^{SC}(I), \quad N^{S}(I) = U^{S}(I) \cdot I,$$

$$N^{S}_{\max} = U^{S}(I^{S}_{opt}) \cdot I^{S}_{opt}, \qquad (4)$$

where $U^{S}(I)$ — CVC of n SCs connected in series; $N^{S}(I)$ — VWC of n SCs connected in series; $N^{S}_{\max}$ — the maximum electrical power that n SCS connected in series can generate under design conditions; I^{S}_{SC} — the optimal current at which the series connection of the SCs generates the maximum power.

The operating voltage vs. the SC generated current for the model used can be plotted from the solution of equation (2) with respect to voltage:

$$U^{SC} = R_{sh}\left(I_{ph} - I - I_{rev}\left(e^{\frac{q_e(U^{SC}+IR_s)}{AkT}} - 1\right)\right). \qquad (5)$$

Thus, in order to obtain integral characteristics of SBs, which in electrical terms are various combinations of serial and parallel connections of a large number of SCs, it is necessary to obtain the CVC of the SB as a whole.

2. Simulating the damaged SBs operation in the event of a random change in properties of individual cell

Under the conditions of the uncertainty of SC characteristics due to the random nature of degradation of their properties as a result of the UF effect, a consistent estimate of the mathematical expectations of the CVC values of the battery can be formed by a statistical analysis of the results of numerical experiments [11], based on the mathematical model of the battery made using the relations (2)–(5):

$$\tilde{I}^{SB}(U) = \frac{\sum_{i=1}^{n} \hat{I}_i^{SB}(U)}{n},$$

where $\hat{I}_i^{SB}(U)$ — random implementation of CVC of the SB during the i-th experiment; n — number of experiments.

With a smooth change in the SC properties depending on the UF parameters, the characteristics scattering of the neighboring cells in most cases will be insignificant due to the fact that when connecting SBs in elementary chains of series and parallel connection of SCs, the manufacturer selects cells with similar characteristics. In this case, in the SC models (2) and (5), their average values can be used as parameters, the consistent estimates of which are their mathematical expectations:

$$I^{SC} = M(I_{ph}) - M(I_{rev}) \left(e^{\frac{q_e\left(U + I^{SC} M(R_s)\right)}{M(A)kT}} - 1 \right) - \frac{U}{M(R_{sh})},$$

$$U^{SC} = M(R_{sh}) \left(M(I_{ph}) - I - M(I_{rev}) \left(e^{\frac{q_e\left(U^{SC} + IM(R_s)\right)}{M(A)kT}} - 1 \right) \right), \tag{6}$$

where $M(I_{ph})$, $M(I_{rev})$, $M(R_s)$, $M(R_{sh})$, $M(A)$ — mathematical expectations of the SC parameters after NF effect.

The use of experimentally obtained functions of mathematical expectations of the parameters of damaged SCs for various values of the UF parameters $\lambda_{\langle m \rangle}$, $h_{I_{ph}}$, $h_{I_{rev}}$, h_{R_s}, $h_{R_{sh}}$, h_A, in place of the corresponding mathematical expectations in the expression (6) allows you to calculate the CVC of the SB at the values of the UF parameters leading to a smooth degradation of SC properties:

$$I^{SC}(U|\lambda_j) = h_{I_{ph}}(\lambda_j) - h_{I_{rev}}(\lambda_j) \left(e^{\frac{q_e\left(U + I^{SC} h_{R_s}(\lambda_j)\right)}{h_A(\lambda_j) kT(\lambda_j)}} - 1 \right) - \frac{U}{h_{R_{sh}}(\lambda_j)},$$

$$U^{SC}(I|\lambda_j) = h_{R_{sh}}(\lambda_j) \cdot \left(h_{I_{ph}}(\lambda_j) - I - h_{I_{rev}}(\lambda_j) \times \left(e^{\frac{q_e\left(U^{SC} + I h_{R_s}(\lambda_j)\right)}{h_A(\lambda_j) kT(\lambda_j)}} - 1 \right) \right), \tag{7}$$

where $T(\lambda)$ is the dependence of the SC temperature on the NF parameters.

The SC temperature can change after exposure to UF, if as a result of the exposure the optical characteristics of the front or back surfaces of the SC change, as well as due to ohmic heating of unprotected SCs and their assemblies.

Further, CVCs of individual SCs, once calculated using the model (6) at certain values of the UF parameters, are used to calculate serial and parallel connections of SB fragments using models (3), (4) to obtain the CVC of the battery as a whole.

In the case of an abrupt change in the SC parameters as a result of the UF effect in models of elementary connections containing a large number of SCs, instead of random values of the SC parameters, their average values can be used only in cases when these parameters are included in equations (2) or (5) in the form of terms in the first degree. For example, to calculate the CVC of series connection of n SCs, the model (4) taking into account (5) in the general case will take the form:

$$U^G(I) = \sum_{i=1}^{n} U_i^{SC}(I) = \sum_{i=1}^{n} \left(R_{sh_i} \left(I_{ph_i} - I - I_{rev_i} \times \left(e^{\frac{q_e\left(U_i^{SC} + IR_{s_i}\right)}{A_i kT_i}} - 1 \right) \right) \right) = \sum_{i=1}^{n} (R_{sh_i} I_{ph_i}) - I \sum_{i=1}^{n} R_{sh_i} - \sum_{i=1}^{n} \left(R_{sh_i} I_{rev_i} \left(e^{\frac{q_e\left(U_i^{SC} + IR_{s_i}\right)}{A_i kT_i}} - 1 \right) \right). \tag{8}$$

Model (8) represents a system of n transcendental equations, each of which must be solved several times to obtain the CVC of each SC in the range of parameters of interest. However, if as a result of the analysis of the UF effect mechanism it turns out that for the considered values of the parameter of the factor λ_j only the value of one of SC parameters — R_{sh}, I_{ph}, I_{rev} changes stepwise, or several parameters change simultaneously, then the model (8) can be significantly simplified. For example, if only the value of the generated photocurrent for each element undergoes a stepwise change:

$$\widetilde{U^G}(I|\lambda_j) = nR_{sh} \left(\overline{I_{ph}}(\lambda_j) - I + I_{rev} - I_{rev} \overline{E}(I|\lambda_j) \right),$$

$$\overline{I_{ph}}(\lambda_j) = \frac{\sum_{i=1}^{n} I_{ph_i}}{n} \approx I_{ph_1}(\lambda_j) M \left(\frac{\hat{r}_G - 1}{n} \right) + I_{ph_3}(\lambda_j) M \times \left(\frac{n - \hat{r}_G + 1}{n} \right) = I_{ph_1}(\lambda_j)\left(1 - F_\lambda^{SC}(\lambda_j)\right) + I_{ph_3}(\lambda_j) F_\lambda^{SC}(\lambda_j),$$

$$\overline{E}(I|\lambda_j) = \frac{\sum_{i=1}^{n} e^{\frac{q_e\left(U_i^{SC} + IR_s\right)}{AkT}}}{n} \approx e^{\frac{q_e\left(U_1^{SC} + IR_s\right)}{AkT}} M \left(\frac{\hat{r}_G - 1}{n} \right) + e^{\frac{q_e\left(U_3^{SC} + IR_s\right)}{AkT}} M \left(\frac{n - \hat{r}_G + 1}{n} \right) = e^{\frac{q_e\left(U_1^{SC} + IR_s\right)}{AkT}} \left(1 - F_\lambda^{SC}(\lambda_j)\right) + e^{\frac{q_e\left(U_3^{SC} + IR_s\right)}{AkT}} F_\lambda^{SC}(\lambda_j), \tag{9}$$

where I_{ph_1} is the value of the photocurrent generated by the SC in the absence of stepwise change of the parameter as a result of UF effect; I_{ph_3} — values of the photocurrent generated by the SC in case of stepwise change of the parameter as result of UF effect; U_1^{SC}, U_3^{SC} is voltage generated by damaged SC with a current I flowing through it, if the generated photocurrent of SC is I_{ph_1} or I_{ph_3} respectively; $\hat{r}_G$ — rank of the first element of the group of values of characteristics of damaged elementary fragments in the series of characteristics of all SCs, ordered from I_{ph_1} to I_{ph_3}. Then $\hat{r}_G - 1$ corresponds to the number of elementary fragments of the connection for which there was no stepwise change in properties after exposure to UF; $F_\lambda^{SC}(\lambda_j)$ is the distribution function of the critical value of the UF at which there is stepwise change of SC properties.

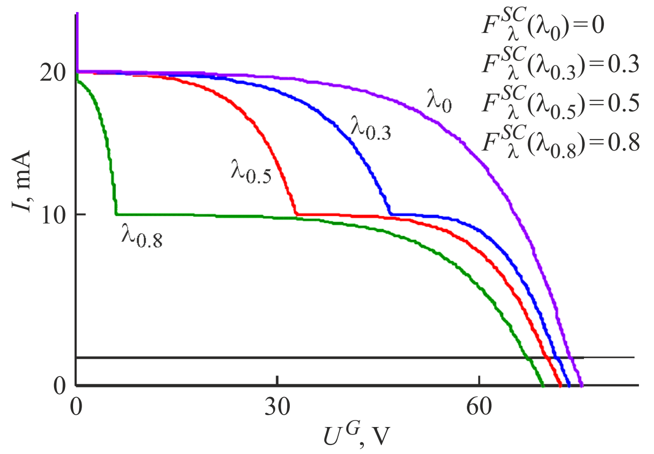

Figure 2. CVC of group of series-connected SCs with stepwise decreasing by two times of SC photocurrent with different probability.

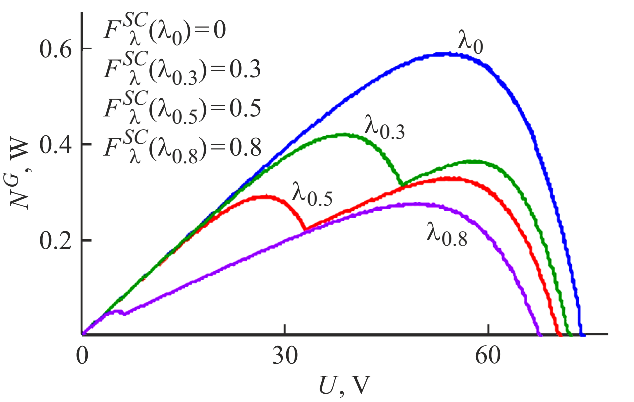

Figure 3. VWC of group of series-connected SCs with stepwise fold decreasing by two times of SC photocurrent with different probability.

The SC parameters in the model (9) can be replaced by the functions of their mathematical expectations from NF parameters $h_{I_{ph}}$, $h_{I_{rev}}$, h_{R_s}, $h_{R_{ph}}$, h_A, which will allow us to form a degradation model of the SC series connection at different levels of exposure to UFF λ_j:

$$\widetilde{U_G}(I|\lambda_j) = nh_{R_{sh}}(\lambda_j)\Big(\overline{I_{ph}}(\lambda_j) - I + h_{I_{rev}}(\lambda_j)\big(1-\overline{E}(I|\lambda_j)\big)\Big),$$

$$\overline{I_{ph}}(\lambda_j) = h^1_{I_{ph}}(\lambda_j)\big(1-F_{\lambda}^{SC}(\lambda_j)\big) + h^3_{I_{ph}}(\lambda_j)F_{\lambda}^{SC}(\lambda_j),$$

$$\overline{E}(I|\lambda_j) = e^{\frac{q_e\left(U_1^{SC}+Ih_{R_S}(\lambda_j)\right)}{h_A(\lambda_j)kT(\lambda_j)}}\big(1-F_{\lambda}^{SC}(\lambda_j)\big)$$
$$+\, e^{\frac{q_e\left(U_3^{SC}+Ih_{R_S}(\lambda_j)\right)}{h_A(\lambda_j)kT(\lambda_j)}}F_{\lambda}^{SC}(\lambda_j). \quad (10)$$

Figs 2 and 3 show the results of CVC and VWC calculation of series connection of 100 SCs.

Calculations were performed using the model (10). Comparison of the estimates obtained with the results of calculations using exact models [9] shows that the calculation error is within the limits of the confidence interval for voltage corresponding to the sample size. Similarly, characteristics can be obtained for the case of change of any other parameter.

In the case of a simultaneous stepwise change of several SC parameters, which is a consequence of one physical process occurring as a result of the UF effect, the estimates of the voltage values of CVC of the series or parallel connection of SCs can be obtained by adding two CVCs for a separate cell. For serial connection of SCs:

$$\widetilde{U^G}(I|\lambda_j) = n\Big(U_1^{SC}(I|\lambda_j)\big(1-F_{\lambda}^{SC}(\lambda_j)\big) + U_3^{SC}(I|\lambda_j)F_{\lambda}^{SC}(\lambda_j)\Big), \quad (11)$$

where $U_1^{SC}(I|\lambda_j)$ — CVC of the SC that was not subjected to stepwise change of parameters as a result of the UF effect; $U_3^{SC}(I|\lambda_j)$ — CVC of SC, with a stepwise change of the parameters of the converter as a result of the UF effect.

For parallel connection of cells:

$$\widetilde{I^C}(U|\lambda_j) = n\Big(I_1^{SC}(U|\lambda_j)\big(1-F_{\lambda}^{SC}(\lambda_j)\big) + I_3^{SC}(U|\lambda_j)F_{\lambda}^{SC}(\lambda_j)\Big), \quad (12)$$

where $I_1^{SC}(U|\lambda_j)$ — CVC of the SC that was not subjected to stepwise change of parameters as a result of the UF effect; $I_3^{SC}(U|\lambda_j)$ — CVC of the SC, with stepwise change of the parameters of the converter as a result of the UF effect.

CVC of the SC represent a solution of the equation (7) corresponding to the type of connection with the corresponding sets of functions of the mathematical expectations of the SC parameters from the exposure parameters.

In the case of a sufficiently large number of SCs as part of parallel and series electrical connections of lower-level cells, when simulating the SB operation, it is permissible to use estimates (11), (12). Otherwise, if the required accuracy of simulation is not provided, then the CVC should be plotted on the basis of statistical simulation of damage to the connection cells of the lower level and the use of random realizations of their CVC in models (3), (4).

To generate the number of damaged elements in the low-level electrical connection, the binomial distribution law [11] is used, in which the probability of a successful occurrence of the event p uses the value of the distribution function of the UF critical value corresponding to the level of the influencing factor, at which there is an stepwise change of the SC properties $F_{\lambda}^{SC}(\lambda_j)$:

$$B(k|\lambda_j) = \frac{n!}{(n-k)!k!}F_{\lambda}^{SC}(\lambda_j)^k\big(1-F_{\lambda}^{SC}(\lambda_j)\big)^{n-k}.$$

All presented SB models are made with the expectation that there are serviceable blocking and shunting protective elements in the SCs connection scheme. Losses on modern protective elements are much lower than losses as a result of SC damage and are not taken into account in the models. This approach is admissible in cases when the protective elements, which have a small area and safer placement, do not change their characteristics when exposed to UF. Otherwise, the protective elements must be included in the SB model [10].

3. Statistical analysis of damaged SB characteristics using simplified logical-analytical models

When simulating damaged SBs, it is often required to obtain only one point of the CVC. This point can correspond to the maximum electrical power of the SB, or to a certain voltage that the battery is capable to supply to the onboard network of the spacecraft. In this case, the SB characteristic can be determined based on the calculation of the corresponding characteristics of individual SCs, taking into account circuit losses that arise due to differences in the parameters of individual SCs [10]. For example, the expression for the maximum power of the SB can be written as follows:

$$N_{\max}^{SB} = k_{CL} \sum_{i=1}^{n_{SB}} N_{\max_i}^{SC}, \tag{13}$$

where $N_{\max_i}^{SC}$ is the maximum electrical power generated by i-th SC at its optimal CVC point; n_{SB} — number of SCs in SB; k_{CL} — circuit loss factor.

The circuit loss factor is unique for each combination of the SB switching circuit and the UF damaging action mechanism. Fig. 4 shows the calculation of the circuit loss coefficient for parallel connection of SCs, which, as a result of the UF effect, stepwise lose their ability to generate electrical energy, while keeping the same values of their other parameters.

For comparison, Fig. 5 shows the calculation of the circuit loss coefficient for series connection of SCs, which, as a result of the UF effect, can stepwise decrease by two times the photocurrent, while keeping the unchanged values of their other parameters.

In most cases, the dependence of the circuit loss coefficient on the probability of SC damage has an extremum, the presence of which is explained by the fact that circuit losses appear only if there is a difference in the values of the battery cell characteristics, and its position can change

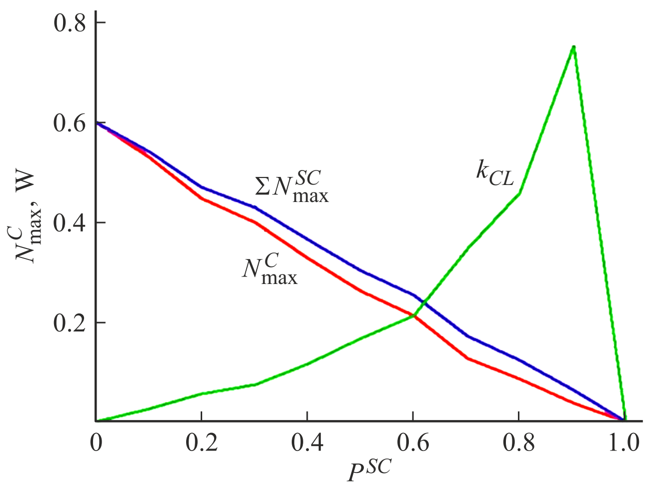

Figure 4. Circuit loss coefficient vs. probability of stepwise degradation of SC properties when cells are connected in parallel.

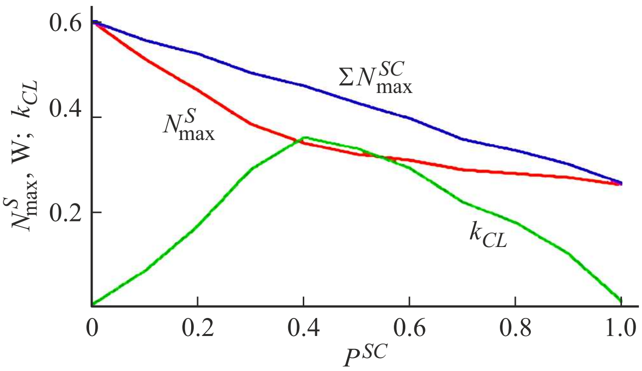

Figure 5. Circuit loss coefficient vs. probability of stepwise degradation of SC properties when cells are connected in series.

depending on the ratio of the absolute values of the losses and the battery power.

It is obvious that the circuit loss coefficient is a function of the probability of the stepwise change of the SC characteristics P^{SC}, which in turn depends on the parameters of the acting UF $\lambda_{\langle m\rangle}$. Since, at stepwise change of SC parameters, each value λ_j can be associated with two values of the maximum power of SC, expression (13) can be represented in a form that is more convenient for calculation:

$$\widetilde{N}_{\max}^{SB}(\lambda_j) = k_{CL}\big(F_\lambda^{SC}(\lambda_j)\big) \cdot \Big(N_{\max_1}^{SC}(\lambda_j)\big(1 - F_\lambda^{SC}(\lambda_j)\big) + N_{\max_3}^{SC}(\lambda_j) F_\lambda^{SC}(\lambda_j)\Big),$$

$$N_{\max_i}^{SC}(\lambda_j) = I_i^{SC}\big(U_{opt_i}^{SC}(\lambda_j)\big|\lambda_j\big) \cdot U_{opt_i}^{SC}(\lambda_j), \quad i = 1, 3,$$

where $I_1^{SC}(U|\lambda_j)$ — CVC of the SC that was not subjected to stepwise change of parameters as a result of the UF action; $I_3^{SC}(U|\lambda_j)$ — CVC of the SC, with stepwise change of the parameters of the converter as a result of the UF effect; $U_{opt_i}^{SC}(\lambda_j)$ — optimal voltage at the SC output with the i-th CVC corresponding to the maximum electric power generated by the converter.

CVCs of the SC are solutions of the equation (7) with the corresponding functions of mathematical expectations of the SC parameters. The optimal voltage at SC output is determined by its state and is different not only for cases when there is stepwise change of the SC parameters, but also, in the general case, for different values of the UF parameters, leading to smooth degradation of the SC properties.

In turn, the circuit loss coefficient is determined on the basis of the results of a computational experiment:

$$\tilde{k}_{CL}\big(F_\lambda^{SC}(\lambda_j)\big) = \frac{1}{m} \sum_{i=1}^{m} \frac{\widehat{N}_{\max_i}^{SB}(\lambda_j)}{\sum_{s=1}^{n_{SB}} \widehat{N}_{\max_{si}}^{SC}(\lambda_j)}, \tag{14}$$

where m — number of computational experiments performed; $\widehat{N}_{\max_{si}}^{SC}(\lambda_j)$ — random implementation of the maximum power of the s-th SC in i-th experiment; $\widehat{N}_{\max_i}^{SB}(\lambda_j)$ —

random implementation of the maximum power of SB, calculated using the mathematical model of the SB based on the SC generated parameters.

With a large number of SC in the SB, the sum of the maximum powers of individual SCs can be replaced by its estimate:

$$\sum_{s=1}^{n_{SB}} \widehat{N}^{SC}_{\max_{si}}(\lambda_j) \approx N^{SC}_{\max_1}(\lambda_j)\left(1 - F^{SC}_{\lambda}(\lambda_j)\right) + N^{SC}_{\max_3}(\lambda_j)F^{SC}_{\lambda}(\lambda_j).$$

Expression (14) in this case will take the form

$$\tilde{k}_{CL}\left(F^{SC}_{\lambda}(\lambda_j)\right) = \frac{\sum_{i=1}^{m} \widehat{N}^{SB}_{\max_i}(\lambda_j)}{m\left(N^{SC}_{\max_1}(\lambda_j)\left(1 - F^{SC}_{\lambda}(\lambda_j)\right) + N^{SC}_{\max_3}(\lambda_j)F^{SC}_{\lambda}(\lambda_j)\right)}.$$

In this case, the required number of computational experiments for each value λ_j is calculated based on the required accuracy of obtaining the estimate of the mathematical expectation of the coefficient [10]:

$$m \geq \left(\frac{\tilde{\sigma}_{k_{CL}}\left(F^{SC}_{\lambda}(\lambda_j)\right)}{\varepsilon_M} t_{\beta,m-1}\right)^2,$$

$$\tilde{\sigma}^2_{k_{CL}}\left(F^{SC}_{\lambda}(\lambda_j)\right) = \frac{\sum_{i=1}^{m}\left(k_{CL_i}\left(F^{SC}_{\lambda}(\lambda_j)\right) - \frac{\sum_{s=1}^{m} k_{CL_s}\left(F^{SC}_{\lambda}(\lambda_j)\right)}{m}\right)^2}{m-1},$$

$$k_{CL_i}\left(F^{SC}_{\lambda}(\lambda_j)\right) = \frac{\widehat{N}^{SB}_{\max_i}(\lambda_j)}{N^{SC}_{\max_1}(\lambda_j)\left(1 - F^{SC}_{\lambda}(\lambda_j)\right) + N^{SC}_{\max_3}(\lambda_j)F^{SC}_{\lambda}(\lambda_j)}.$$

The presented method for determining the SB characteristics using the circuit loss coefficient is, in fact, the only way to use the results of experimental studies of the SC resistance to the effects of unfavourable factors, previously performed without highlighting the area of the stepwise change of the SC properties and the corresponding statistical processing of the results. To use these results, it is sufficient to conduct individual experimental and theoretical studies to determine the SC degradation mechanisms and the required number of numerical experiments on models of SCs of interest to determine the circuit loss coefficient.

Conclusion

Of the many possible situations of NF effect on the spacecraft SB, the cases are considered, in which it is possible to use a simplified logical-analytical model of the SB, which makes it possible to significantly reduce the laboriousness of statistical simulation of the processes of the spacecraft operation under the effect of space factors:

— when stepwise change of individual SC parameters is due to the same physical processes occurring under the NF effect, it is permissible to assume that the stepwise change of all parameters, each of which is a random event, occurs simultaneously. Then, each SC that is part of the SB will correspond to one of the two possible CVCs, and the process of simulation of SB operation will be reduced to their addition in accordance with the connection models presented in the paper;

— when one characteristic point of the CVC of the SB is sufficient to simulate the operation of the power supply system of spacecraft, a simplified model with the proposed circuit loss coefficient can be used for statistical simulation of the SC operation, which allows calculation of the parameters of the CVC characteristic point of the SB from the CVC characteristic points of the SC. The proposed approach, in particular, can be applied to use the results of earlier experimental studies of the effect on SC.

Conflict of interest

The authors declare that they have no conflict of interest.

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