UDC 620.92
Doi: 10.31772/2587-6066-2018-19-4-651-657

For citation: Chernaya M. M. [Method for calculating the energy characteristics and solar battery parameters of high-voltage power supply systems]. *Siberian Journal of Science and Technology.* 2018, Vol. 19, No. 4, P. 651–657. Doi: 10.31772/2587-6066-2018-19-4-651-657

Для цитирования: Черная М. М. Методика расчета энергетических характеристик и параметров солнечных батарей высоковольтных систем электропитания космических аппаратов // Сибирский журнал науки и технологий. 2018. Т. 19, № 4. С. 651–657. Doi: 10.31772/2587-6066-2018-19-4-651-657

METHOD FOR CALCULATING THE ENERGY CHARACTERISTICS AND SOLAR BATTERY PARAMETERS OF HIGH-VOLTAGE POWER SUPPLY SYSTEMS

M. M. Chernaya

Tomsk State University of Control System and Radio Electronics
40, Lenina Av., Tomsk, 634050, Russian Federation
E-mail: cmm91@inbox.ru

One of the main tasks arising in power supply systems (PSS) of spacecraft (SC) design is the determination of rational structure in terms of providing consumers with electricity of the required quality. At the same time, a reasonable consumption of power generated by solar batteries (SB) and accumulator batteries (AB) should be realized in PSS. The choice of the PSS structure is based on the calculation and comparative analysis of PSS options, taking into account the adopted system performance criteria, the main ones being the energy and weight-dimension characteristics. For this purpose, the process of energy flows distribution in the PSS by forming a mathematical description of the PSS operating modes is carried out. In order to obtain the graphs of the SB generated power and to calculate SB parameters during the service life, a mathematical model of the SB based on the use of initial and experimental parameters of its photovoltaic elements of any area was developed. The SB model provides the required accuracy of I-V and V-W characteristics calculation for any given values of illumination and temperature.

In the article the method for calculating the energy characteristics of PSS and SB parameters taking into account the possibility of its limitation at the maximum or minimum level was described. It is shown that the method allows to determine the ways of rational redistribution of energy flows in the systems being designed to improve its weight-dimension characteristics by reducing the maximum design power of energy-converting equipment (ECE), which is achieved by forming a rational logic for applying the SB maximum power point tracking mode, in particular, when the spacecraft leaves the Earth's shadow. Energy balance in PSS is provided by applying correction coefficients. The calculation results obtained by the method are the basis for requirements for ECE and SB design in PSS and can be used by developers and manufacturers of onboard and ground PSS.

Keywords: spacecraft, power supply system, mathematical model of the solar battery, energy characteristics, maximum power point tracking mode.

МЕТОДИКА РАСЧЕТА ЭНЕРГЕТИЧЕСКИХ ХАРАКТЕРИСТИК И ПАРАМЕТРОВ СОЛНЕЧНЫХ БАТАРЕЙ ВЫСОКОВОЛЬТНЫХ СИСТЕМ ЭЛЕКТРОПИТАНИЯ КОСМИЧЕСКИХ АППАРАТОВ

М. М. Черная

Томский государственный университет систем управления и радиоэлектроники
Российская Федерация, 634050, г. Томск, просп. Ленина, 40
E-mail: cmm91@inbox.ru

Одной из основных задач проектирования систем электропитания (СЭП) космических аппаратов (КА) является определение их рациональной с точки зрения обеспечения потребителей электроэнергией заданного качества структуры. При этом в системе должно быть реализовано обоснованное потребление генерируемых солнечными (БС) и аккумуляторными батареями мощностей. Выбор структуры СЭП основывается на проведении расчета и сопоставительного анализа их альтернативных вариантов с учетом принятых критериев эффективности системы, основными из которых являются энергетические и габаритно-массовые характеристики СЭП. Для этого проводится исследование процессов распределения потоков энергии в системе путем формирования математического описания режимов работы СЭП. С целью получения графиков ге-

нерируемой БС мощности и для расчета ее параметров в течение срока эксплуатации разработана математическая модель БС, которая основана на использовании основных и экспериментальных параметров их фотоэлектрических элементов любой площади. Модель БС обеспечивает требуемую точность расчета вольт-амперных и вольт-ваттных характеристик для любых заданных значений температуры и освещенности. Описана методика расчета энергетических характеристик СЭП и параметров БС с учетом возможности их ограничения по максимальному либо минимальному уровню. Показано, что методика позволяет определять пути рационального перераспределения потоков энергии в системах с целью улучшения их габаритно-массовых характеристик за счет уменьшения максимальной расчётной мощности их энергопреобразующей аппаратуры (ЭПА), что достигается путем формирования рационального алгоритма применения режима экстремального регулирования мощности БС, в частности, при выходе КА из тени Земли. Энергобаланс в СЭП при этом обеспечивается за счет применения поправочных коэффициентов. Полученные по методике результаты являются основой ряда требований по проектированию ЭПА и БС в СЭП и могут быть использованы разработчиками и производителями бортовых и наземных СЭП.

Ключевые слова: космический аппарат, система электропитания, математическая модель солнечной батареи, энергетические характеристики, экстремальное регулирование мощности.

Introduction. Ensuring the long term of the spacecraft (SC) active lifetime (TAL) is one of priority scientific, technical and economic tasks which solution demands a comprehensive fundamental approach during the development and creation of SC power supply systems (PSS).

The main primary energy source in SC PSS are solar batteries (SB) designed on the basis of Si or GaAs solar cells having non-linear I-V and V-W characteristics with a pronounced maximum of the generated power, determined by an operating voltage level that proves the expediency of maximum power point tracking (MPPT) mode of SB in PSS application [1–4]. Due to the increase of output voltage of the SC load power bus up to 100 V, new technical requirements to the ways of coordination and service conditions of energy sources in PSS have been created. This is due to the possibility of electrostatic discharges between photodiodes chains and current collection elements of the SB and, as a result, to the need for the maximum level of SB open circuit (OC) voltage operation limitation reached when the SC leaves the orbit shadow areas [5–7]. Application of other solar cells types in PSS is possible in case of feasibility of their use realized by means of calculation of the generated by SB capacities during TAL providing an energy balance in PSS, rational distribution of energy flows and prevention of PSS work emergency operation.

The developed technique provides the reduction in calculation time of power characteristics and the SB parameters of high-voltage SC PSS which is obtained by the decrease in the number of iterations directly proportional to the quantity of correction factors to be calculated. The technique can be applied when calculating options of ground and onboard PSS with various load curves and service conditions for the purpose of realization of energy flows in PSS rational redistribution and to impose its ECE and SB design requirements.

Mathematical model of solar battery. The SB electric parameters during SC service change significantly. The considerable influence on SB I-V and V-W characteristics is rendered by temperature and illumination. So, in low-orbit SC the SB panels temperature changes in the range from –90 to +80 ^{0}C, herewith the SC can have the sharp-variable load curve and the significant number of shadow areas on the orbit. Therefore for the correct planning of PSS target equipment operation it is expedient to carry out the calculation of SB generated power in all operating modes of SC PSS during TAL.

The SB current parameters, taking into account the graphs of their illumination F and temperature t, are calculated on the experimental solar cells I-V characteristics of any area provided by their manufacturers. The SB mathematical model set by three points is the basis for the developed mathematical model: of an open circuit (OC) voltage U_{OC}, short circuit (ShC) current I_{ShC}, optimum values of SB current I_{MPP} and voltage U_{MPP} [8]. The SB mathematical model depending on temperature t and illumination F is described as

$$I_{SB}(U_{SB},t,F)=I_{ShC}(t,F)\times$$

$$\times\left[1-\left(1-\frac{I_{MPP}(t,F)}{I_{ShC}(t,F)}\right)^{\frac{U_{OC}(t,F)-U_{SB}}{U_{OC}(t,F)-U_{MPP}(t,F)}}\right], \qquad (1)$$

where U_{SB} – current value of SB voltage; $I_{ShC}(t,F)$ – SB short circuit current; $I_{MPP}(t,F)$ – optimum value of SB current on I-V characteristics at SB MPPT mode in PSS; $U_{MPP}(t,F)$ – optimum value of SB voltage on I-V characteristics at SB MPPT mode in PSS; $U_{OC}(t,F)$ – SB open circuit voltage.

The SB open circuit voltage depending on t and F is calculated by the formula

$$U_{OC}(t,F)=k_{Un}\cdot U_{OC}(t_1,F_1)\cdot(1+0{,}01\cdot\beta)^{(t-t_1)}, \qquad (2)$$

where k_{Un} – the correction coefficient of voltage determined by SB I-V characteristics abscissa axis, considering its illumination influence; F_1 – SB nominal illumination value; $U_{OC}(t_1,F_1)$ – SB open circuit voltage at nominal values t_1 and F_1; β – temperature coefficient of SB open circuit voltage.

The SB short circuit current depending on t and F is determined by the formula

$$I_{ShC}(t,F)=k_{In}\cdot I_{ShC}(t_1,F_1)\cdot(1+0{,}01\cdot\alpha)^{(t-t_1)}, \qquad (3)$$

where k_{In} – the correction coefficient on current determined by SB I-V characteristics ordinate axis, considering its illumination influence; $I_{ShC}(t_1,F_1)$ – SB short circuit current at nominal values t_1 and F_1; α – temperature coefficient of SB short circuit current.

The optimum value of SB current is calculated taking into account t and F as follows

$$I_{MPP}(t,F) = \frac{k_{In} \cdot I_{MPP}(t_1,F_1) \cdot (1+0{,}01 \cdot \lambda)^{(t-t_1)}}{(1+0{,}01 \cdot \nu)^{(t-t_1)}}, \qquad (4)$$

where $I_{MPP}(t_1,F_1)$ – optimum value of SB current at t_1 and F_1; λ – temperature coefficient of SB maximum generated power, i. e. power in an optimum point (MPPT mode); ν – temperature coefficient of the optimum value of SB voltage.

The optimum value of SB voltage taking into account t and F is calculated according to the formula

$$U_{MPP}(t,F) = k_{Un} \cdot U_{MPP}(t_1,F_1) \cdot (1+0{,}01 \cdot \nu)^{(t-t_1)}, \qquad (5)$$

where $U_{MPP}(t_1,F_1)$ – value of SB optimum voltage on I-V characteristics at t_1 and F_1.

Correction coefficient of voltage k_{Un} is determined as follows:

1. On the experimental solar cells I-V characteristics of any single area (fig. 1), obtained at different illumination levels $F_1 \ldots F_n$ of solar cells and at some nominal temperature t_1, values of solar cells open circuit voltages $U_{OC1}(t_1,F_1)$ … $U_{OCn}(t_1,F_n)$ are determined by the abscissa axis.

2. The correction coefficients $k_{U1} \ldots k_{Un}$, reflecting the relative change of solar cells open circuit voltage which is in the range between $U_{OCn}(t_1,F_n)$ and $U_{OCn+1}(t_1,F_{n+1})$ depending on levels of their illumination are calculated according to the formula:

$$k_{Un} = \frac{U_{OCn+1}(t_1,F_{n+1})}{U_{OC1}(t_1,F_1)} + \left[\left(\frac{\dfrac{U_{OCn}(t_1,F_n)}{U_{OC1}(t_1,F_1)} - \dfrac{U_{OCn+1}(t_1,F_{n+1})}{U_{OC1}(t_1,F_1)}}{F_n - F_{n+1}}\right) \cdot (F - F_{n+1})\right]. \qquad (6)$$

Correction coefficient of current k_{In} is determined in the same way by an abscissa axis of the experimental solar cells I-V characteristics and taking into account the use of solar cells short circuit current values:

$$k_{In} = \frac{I_{ShCn+1}(t_1,F_{n+1})}{I_{ShC1}(t_1,F_1)} + \left[\left(\frac{\dfrac{I_{ShCn}(t_1,F_n)}{I_{ShC1}(t_1,F_1)} - \dfrac{I_{ShCn+1}(t_1,F_{n+1})}{I_{ShC1}(t_1,F_1)}}{F_n - F_{n+1}}\right) \cdot (F - F_{n+1})\right]. \qquad (7)$$

Calculation method of spacecrafts high-voltage power supply systems. Calculation of SB parameters begins with the choice of SC PSS structure and formation of the mathematical description of PSS operation modes taking into account the ECE coefficients of energy efficiency (CE) by researching the processes of energy flows in PSS distribution depending on a ratio of generated by energy sources and power consumption load [9–11]. For example, for parallel-serial (PS) PSS the current values of SB power (P_{SB}), AB charge power (P_{AB_C}), AB discharge power (P_{AB_DC}) and load power (P_{VR}) are calculated according to tab. 1.

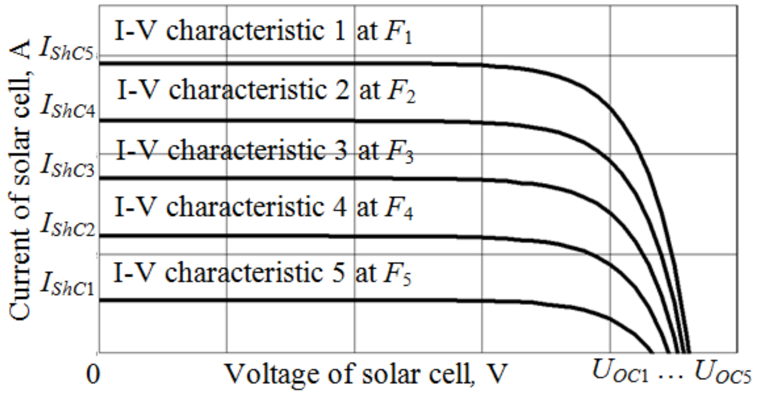

Fig. 1. I-V characteristics of the solar cell

Рис. 1. Вольт-амперные характеристики ФЭ

Table 1

Current values of SB, AB and load power in PSS

Load power supply mode from SB (VR)	$P_{LOAD} = P_{SB} \cdot \eta_{VR}$
Load power supply mode from SB and AB charge (VR + C)	$P_{SB} = \frac{P_{LOAD}}{\eta_{VR}} + \frac{P_{AB\_C}}{\eta_C}$
Load power supply mode from SB and AB discharge (VR + DC)	$P_{LOAD} = P_{SB} \cdot \eta_{VR} + P_{AB\_DC} \cdot \eta_{DC} \cdot \eta_{AB}$
Load power supply mode from AB (DC)	$P_{LOAD} = P_{AB\_DC} \cdot \eta_{DC} \cdot \eta_{AB}$

The following designations are introduced in tab. 1: η_{VR} – voltage regulator CE, η_C – charger CE, η_{DC} – discharger CE, η_{AB} – AB efficiency. The load curve of SC for some given period of time of T which, as a rule, has a cyclic character is formed. Calculation of total energy W_{LOAD_sum} consumed by load during T is carried out according to the formula:

$$W_{LOAD\_sum} = \sum_{i=1}^{n} d\tau_i \cdot P_{LOAD}(\tau_i)\,, \tag{8}$$

where n – the number of areas on T, during which the current value of load power $P_{LOAD}(\tau_i)$ is invariable; i – ordinal value of T n-area; $d\tau_i$ – is a time period on T during which $P_{LOAD}(\tau_i)$ remains invariable.

Load curves of SB illumination $F(\tau_j)$ and temperature $t(\tau_j)$ are formed. Initial values of solar cells parameters of any single area at nominal parameters of temperature and illumination are introduced: $I_{MPP}(t(\tau_1), F(\tau_1))$, $U_{MPP}(t(\tau_1), F(\tau_1))$, $U_{OC}(t(\tau_1), F(\tau_1))$ and $I_{ShC}(t(\tau_1), F(\tau_1))$, α, ν, λ и β.

Further calculation of solar cells parameters current values taking into consideration SB $F(\tau_j)$ and $t(\tau_j)$ curves according to formulas (2)–(7) is carried out and calculation of total value of the solar cells generated energy $W_{solar\ cell\_sum}$ during T is similar to W_{LOAD_sum} computational method.

The current values of the SB generated power on condition of equality of the consumed load and the SB generated power according to the formula (9) by determination of correction coefficient k_W as the ratio of W_{LOAD_sum} to $W_{solar\ cell\_sum}$ are calculated. The k-areas on the T period corresponding to their invariable current values are defined

$$P_{SB}(t(\tau_k), F(\tau_k)) = P_{solar\,cell}(t(\tau_k), F(\tau_k)) \cdot k_W\,. \tag{9}$$

Calculation of an energy balance in SC PSS is carried out by calculation of the current and total values of energy and discharge $Q_{AB\_DC\_sum}$ and charge $Q_{AB\_C\_sum}$ power of AB calculated taking into account PSS ECE CE, and determination of correction coefficient k_{AB} providing proportional increase in the current values of SB power for each k-rea on T, on which the current values of SB generated power are more than zero. The total value of SB generated energy (W_{SB_sum}) is calculated similarly to computational method W_{LOAD_sum}.

For example, for PSS PS equation for energy balance calculation is as follows

$$Q_{AB\_DC\_sum} = Q_{AB\_C\_sum} =$$

$$= \sum_{b=1}^{r} \left(\frac{\dfrac{P_{LOAD}(\tau_b)}{\eta_{DC}(\tau_b)\cdot\eta_{AB}(\tau_b)} - P_{SB}(t(\tau_b), F(\tau_b)) \times \dfrac{\eta_{VR}(\tau_b)\cdot k_{AB}(\tau_b)}{\eta_{DC}(\tau_b)\cdot\eta_{AB}(\tau_b)}}{U_{AB\_DC}(\tau_b)} \cdot d\tau_b \right) =$$

$$= \sum_{c=1}^{s} \left(\frac{P_{SB}(t(\tau_c), F(\tau_c))\cdot k_{AB}(\tau_c)\cdot\eta_C(\tau_c) - \dfrac{P_{LOAD}(\tau_c)\cdot\eta_C(\tau_c)}{\eta_{VR}(\tau_c)}}{U_{AB\_C}(\tau_c)} \cdot d\tau_c \right), \tag{10}$$

where r – the number of areas on T, in which PSS operates in modes VR + DC or DC; $b = 1\ldots r$ – r-area ordinal number on T; $U_{AB\_DC}(\tau_b)$ – AB discharge voltage in modes VR + DC or DC; s – the number of areas on T, in which PSS operates in VR + C or VR modes; $c = 1\ldots s$ – s-area ordinal number on T; $U_{AB\_C}(\tau_c)$ – AB voltage in the charge mode.

AB power characteristics, including the current values of AB charge and discharge currents and AB nominal power, counted taking into consideration the accepted maximum AB charge depth, are calculated [1; 4; 11].

If discharge/charge currents of AB do not meet the technical requirements to AB, ECE and PSS in general, then their correction is implemented at the given level by calculation of correction coefficient k_{W2} which provides proportional change of $P_{SB}(t(\tau_k),F(\tau_k))$ on T areas with SB maximum generated power for the purpose of providing PSS energy balance.

In this case, calculation values of SB current power is carried out on condition:

$$\sum_{k=1}^{p} d\tau_k \cdot P_{SB}(t(\tau_k), F(\tau_k)) = \sum_{e=1}^{f} d\tau_e \cdot P_{SB}(t(\tau_e), F(\tau_e)) +$$

$$+ \sum_{h=1}^{q} d\tau_h \cdot P_{MPP}(t(\tau_h), F(\tau_h)) \cdot k_{W2}, \tag{11}$$

where p – total number of k-reas on T; f – the number of areas on T without SB MPPT realization in PSS; $e = 1\ldots f$ – f-area ordinal number on T; $d\tau_e$ – time period on T, during which the current value of SB generated power $P_{SB}(t(\tau_e),F(\tau_e))$ remains invariable in PSS without SB MPPT realization; q – the number of areas with SB MPPT realization in PSS on T; $h = 1\ldots q$ – q-area ordinal number on T; $d\tau_h$ – time period on T, during which current optimum value of SB generated power $P_{MPP}(t(\tau_h),F(\tau_h))$ remains invariable in PSS with SB MPPT.

The SB parameters in PSS are calculated. The coefficient of proportional increase in the solar cells initial parameters is calculated [11]

$$k_{IU} = \sqrt{k_W \cdot k_{AB} \cdot k_{W2}}\,. \tag{12}$$

For restriction of SB actual value of current or voltage level on T the value of the restricted level of the actual parameter value is set, and also the level of illumination and temperature at which this level of restriction should not be broken and the correction coefficient of restriction k_{lim} is calculated.

For example, in high-voltage SC PSS on the condition of the maximum SB OC voltage level $U_{OC\_\max}$ restriction the coefficient of restriction k_{lim} is calculated as:

$$k_{lim} = \frac{U_{OC}(t(\tau_k), F(\tau_k)) \cdot k_{IU}}{U_{OC\_\max}}\,, \tag{13}$$

where $U_{OC}(t(\tau_k), F(\tau_k))$ – current value of solar cells OC voltage at minimum values of t and F.

Solar cells initial parameters are corrected taking into account k_{IU} and k_{lim}, what allows to calculate SB parameters and their I-V and V-W characteristics accounting $F(\tau_j)$ and $t(\tau_j)$ curves by application of the developed SB mathematical model. At the same time solar cells non-restricted parameters are multiplied by k_{IU} and k_{lim}. The k_{lim} placement in the denominator means the SB parameter restriction. It is also necessary to consider coherence of solar cells parameters change. For example, at restriction of the allowed maximum level of SB OC voltage reached at a minimum temperature of its panels the level of SB optimum voltage is also corrected.

Results of mathematical modeling of the spacecraft high-voltage power supply system. Calculation of SB power characteristics and parameters was executed for high-voltage parallel-serial SC PSS (100 V) with SB MPPT [10] operating either in the mode of a simultaneous power supply load from the SB and the AB charge, or in the mode of a simultaneous power supply load from SB and the AB discharge.

Arbitrarily composed SC load curve $P_{LOAD}(\tau)$ and the solar cells generated power curve obtained by using the developed mathematical model of SB taking into account solar cells initial parameters at t_1 = 25 ^{0}C: $I_{ShC}(t_1,F_1)$ = = 5.83 A, $U_{OC}(t_1,F_1)$ = 46.2 V, $I_{MPP}(t_1,F_1)$ = 5.43 A, $U_{MPP}(t_1,F_1)$ = 37.7 V, β = –0.3, λ = –0.39, α = 0.04, ν = –0.4 and SB temperature $t(\tau)$ and illumination $F(\tau)$ curves are shown in fig. 2.

During the calculation it was obtained that $W_{solar\ cell\_sum}$ = 314.33 W·h. For providing an energy balance in PSS at W_{LOAD_sum} = 9883.33 W·h and taking into account the restriction of allowed maximum level of SB OC voltage reached at a SC exit from the Earth's shadow is 180 V, the correction coefficient k_W = 31.443, the correction coefficient k_{AB} = 1.158, the coefficient of proportional increase in solar cell initial parameters k_{IU} = 36.403 and the correction coefficient k_{lim} = 2.097. The current values of the SB generated capacities P_{BS_cur} are shown in tab. 2.

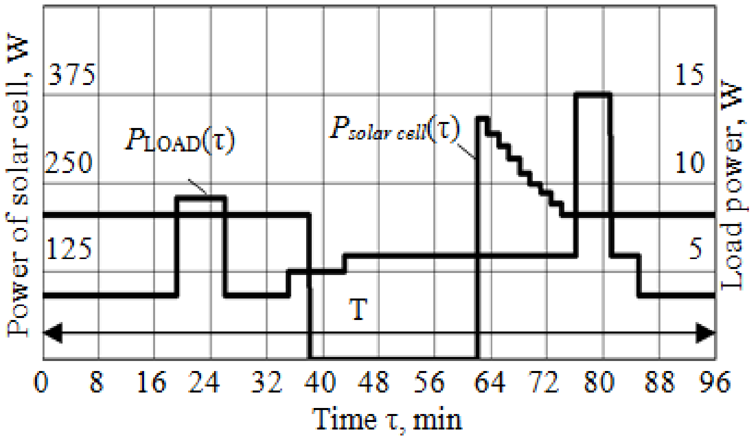

Fig. 2. The load curve $P_{LOAD}(\tau)$ and the solar cell generated power curve $P_{solar\ cell}(\tau)$ in the SC PSS with the MPPT

Рис. 2. Графики нагрузки $P_{Н}(\tau)$ и генерируемой ФЭ мощности $P_{ФЭ}(\tau)$ в СЭП КА с ЭРМ БС

Table 2

Parameters of the solar battery of the spacecraft high-voltage power supply system

τ_k, minute	P_{LOAD_cur}, W	$P_{solar\ cell\_cur}$, W	P_{BS_cur}, W	$U_{OC}(t,F)$, V	$I_{MPP}(t,F)$, A	$U_{MPP}(t,F)$, V
0	4000	247.37	9005.03	121.90	93.76	96.04
19	10000	247.37	9005.03	121.90	93.76	96.04
26	4000	247.37	9005.03	121.90	93.76	96.04
35	5500	247.37	9005.03	121.90	93.76	96.04
38	5500	0.00	0.00	–	–	–
43	6500	0.00	0.00	–	–	–
62	6500	254.79	14944.29	180	92.55	161.47
63.5	6500	256.32	14096.72	172.09	92.69	152.08
64	6500	257.85	13297.24	164.53	92.83	143.24
65	6500	259.33	12543.09	157.30	92.97	134.92
66.5	6500	260.98	11603.68	148.15	93.15	124.57
68	6500	261.54	10945.59	141.64	93.29	117.33
69.5	6500	260.83	10324.81	135.42	93.43	110.51
71	6500	257.78	9737.02	129.45	93.57	104.06
74	6500	247.37	9005.03	121.90	93.76	96.04
76	16500	247.37	9005.03	121.90	93.76	96.04
81	6500	247.37	9005.03	121.90	93.76	96.04
85	4000	247.37	9005.03	121.90	93.76	96.04

The maximum rated power of a voltage regulator in the channel of energy transformation from the SB and an AB charger are defined by the SB maximum generated power value on *T* and are equal to 14.94 kW. The maximum rated power of the discharger is defined by the SC maximum power of load, depends on the discharger CE and is equal to 17.37 kW.

PSS mass decrease is reached by the development of new circuit realization of SC PSS ECE with the increased values of CE [12–15] and by the research of ways of energy flows rational distribution in PSS. For example, the change of SB MPPT mode use algorithm at the SC exit from shadow areas on the orbit, will allow to reduce the ECE maximum rated power, and, as a result, the mass of PSS in general.

Conclusion. The developed solar battery mathematical model is based on the values of initial and experimental parameters of photoelectric cells use and provides calculation of SB I-V and V-W characteristics taking into account arbitrary assigned values of illumination and temperature regardless of their manufacture technology.

The offered method of calculation of SB power characteristics and parameters in PSS based on the use of correction coefficients provides calculation and the possibility of energy flows redistribution in the system for the purpose of PSS weight-dimension characteristics decrease, and allows to obtain SB initial parameters, on condition of ensuring an energy balance in PSS, accounting the given service conditions and load curves of the SC. Based on calculation results, carried out according to the developed technique, the requirements for solar batteries and PSS energy-converting equipment designing can be formulated and imposed.

The developed method of SB initial parameters calculation allows defining the requirements to their design in PSS taking into consideration the limitation of the actual values of SB currents and/or voltage maximum or minimum level.

Acknowledgements. The research was made to implement decree of the Government of the Russian Federation of 9 April, 2010 No. 218 and contract between ISS JSC and the Ministry of Education and Science of the Russian Federation of 01 December 2015 No. 02.G25.31.0182.

Благодарности. Работа выполнена в рамках реализации Постановления Правительства РФ № 218 от 09.04.2010 г. и договора между АО «ИСС» и Минобрнауки РФ от 01.12.2015 г. № 02.G25.31.0182.

References

1. Soustin B. P., Ivanchura V. I., Chernyshev A. I., Islyaev Sh. N. *Sistemy elektropitaniya kosmicheskikh apparatov* [Power supply systems of space crafts]. Novosibirsk, Nauka Publ., 1994, 318 p.

2. *Elektronnye i elektromekhanicheskie sistemy i ustroistva* [Electronic and electromechanical systems and devices]. Tomsk, Polytechnic University Publ., 2016, 512 p.

3. Dontsov O. A., Ivanchura V. I., Krasnobaev Yu. V., Post S. S. [Autonomous electric power supply system with extreme regulation power tracker of primary energy sources]. *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*. 2016, Vol. 327, No. 12, P. 35–44 (In Russ.).

4. Chebotaev V. E., Kosenko V. E. *Osnovy proektirovaniya kosmicheskikh apparatov informatsionnogo obespecheniya* [Basics of design of information space vehicles]. Krasnoyarsk, SibSAU Publ., 2011, 515 p.

5. Chernaya M. M., Shinyakov Y. A., Osipov A. V. [Spacecraft power system]. *17 Mezhdunarodnaja konferencija molodyh specialistov po mikro/nanotehnologijam i jelektronnym priboram* [17th International conference of young specialists on micro/nanotechnologies and electron devices. Proc. of the 17th International conference]. Erlagol, 2016, P. 589–593.

6. Lesnykh A. N., Sarychev V. A. [The research of high-voltage power supply systems for space crafts with boost converter]. *Vestnik SibGAU*. 2006, No. 6 (13), P. 63–66 (In Russ.).

7. Akishin A. I. [Impact of electrical discharges on solar panels] *Nauchno- issledovatel'skii institut yadernoi fiziki imeni D.V. Skobel'tsyna MGU*. 2008, No. 4, P. 68–71 (In Russ.).

8. Privalov V. D., Nikiforov V. E. *Otsenka effektivnosti primeneniya ekstremal'nogo regulyatora v avtonomnykh SEP* [Estimation of the effectiveness of the application of the extreme regulator in autonomous PSS]. Kuibyshev, KPI Publ., 1981, 16 p.

9. Osipov A. V., Shinyakov Yu. A., Shkol'nyi V. N., Suntsov S. B., Chernaya M. M. [Structures for constructing high-voltage power supply systems for space crafts based on inverter-transformer converters]. *Electrical engineering*. 2016, No. 12, P. 26–33 (in Russ.).

10. Shinyakov Yu. A., Gurtov A. S., Gordeev K. G., Ivkov S. V. [Choice of the structure of power systems for low Earth orbit spacecraft]. *Bulletin of the Samara State Aerospace University. academician S. P. Koroleva*. 2010, No. 1(21), P. 103–113 (In Russ.).

11. Chernaya M. M. *Issledovanie i razrabotka energopreobrazuyushchei apparatury vysokovol'tnykh sistem elektropitaniya kosmicheskikh apparatov. Dis. kand. nauk* [Research and development energy conversion equipment high-voltage power supply systems spacecraft]. Tomsk, TUSUR, 2017, 142 p.

12. Chernaya M. M., Shinyakov Yu. A. [Research and development of energy-converting equipment for high-voltage power supply systems for low-Earth orbit space remote sensing devices]. *Sbornik materialov VII Mezhdunarodnoi nauchnotekhnicheskoi konferentsii K. E. Tsiolkovskii – 160 let so dnya rozhdeniya. Kosmonavtika. Radioelektronika. Geoinformatika* [K. E Tsiolkovsky – 160 years from the birthday. cosmonautics. radio electronics. Geoinformatics. Proc. of the VII International Scientific and Technical Conference named K. E. Tsiolkovsky]. Ryazan', 2017, P. 134–136 (In Russ.).

13. Chen W., Rong P., Lu Z. Y. Snubberless bidirectional DC-DC converter with new CLLC resonant tank featuring minimized switching loss. *IEEE Trans. Ind. Electron*. 2010, vol. 57, No. 9, P. 3075–3086.

14. Wu. J., Li Y., Sun X., Liu F. A new dual-bridge series resonant DC-DC converter with dual tank. *IEEE*

Transactions on Power Electronics. 2017, Vol. 33(5), P. 3884–3897.

15. Nguyen D. D., Nguyen D. T., Fujtta G. Dual-active-bridge series resonant converter: A new control strategy using phase-shifting combined frequency modulation. *IEEE Conference Publications*. 2015, No. 10, P. 1215–1222.

Библиографические ссылки

1. Системы электропитания космических аппаратов / Б. П. Соустин [и др.]. Новосибирск : Наука. Сиб. издат. фирма, 1994. 318 с.

2. Электронные и электромеханические системы и устройства : сб. науч. тр. Томск : Изд-во политехн. ун-та, 2016. 512 с.

3. Автономная система электропитания с экстремальным регулированием мощности первичных источников энергии / О. А. Донцов [и др.] // Известия Томского политехнического университета. Инжиниринг георесурсов. 2016. Т. 327, № 12. С. 35–44.

4. Чеботаев В. Е., Косенко В. Е. Основы проектирования космических аппаратов информационного обеспечения : учеб. пособие / Сиб. гос. аэрокосмич. ун-т. Красноярск, 2011. 515 с.

5. Chernaya M. M., Shinyakov Y. A., Osipov A. V. Spacecraft power system // 17th Intern. conf. of young specialists on micro/nanotechnologies and electron devices (EDM). Erlagol, 2016. P. 589–593.

6. Лесных А. Н., Сарычев В. А. Исследование высоковольтных систем электропитания космических аппаратов со стабилизаторами напряжения вольтодобавочного типа // Вестник СибГАУ. 2006. № 6 (13). С. 63–66.

7. Акишин А. И. Воздействие электрических разрядов на солнечные батареи ИСЗ // Научно-исследовательский институт ядерной физики имени Д. В. Скобельцына МГУ. 2008. № 4. С. 68–71.

8. Привалов В. Д., Никифоров В. Е. Оценка эффективности применения экстремального регулятора в автономных СЭП. Куйбышев : КПИ, 1981. 16 с.

9. Структуры построения высоковольтных систем электропитания космических аппаратов на основе инверторно-трансформаторных преобразователей / А. В. Осипов [и др.] // Электротехника. 2016. № 12. С. 26–33.

10. Выбор структуры систем электроснабжения низкоорбитальных космических аппаратов / Ю. А. Шиняков [и др.] // Вестник Самарского государственного аэрокосмического университета имени академика С. П. Королева. 2010. № 1(21). С. 103–113.

11. Черная М. М. Исследование и разработка энергопреобразующей аппаратуры высоковольтных систем электропитания космических аппаратов : дис. … канд. техн. наук. Томск : ТУСУР, 2017. 142 с.

12. Черная М. М., Шиняков Ю. А. Исследование и разработка энергопреобразующей аппаратуры высоковольтных систем электропитания низкоорбитальных космических аппаратов дистанционного зондирования Земли // К. Э. Циолковский – 160 лет со дня рождения. Космонавтика. Радиоэлектроника. Геоинформатика : сб. материалов VII Междунар. науч.-техн. конф. Рязань, 2017. С. 134–136.

13. Chen W., Rong P., Lu Z. Y. Snubberless bidirectional DC-DC converter with new CLLC resonant tank featuring minimized switching loss // IEEE Trans. Ind. Electron. 2010. Vol. 57, No. 9. P. 3075–3086.

14. A new dual-bridge series resonant DC-DC converter with dual tank / J. Wu [et al.] // IEEE Transactions on Power Electronics. 2017. Vol. 33(5). P. 3884–3897.

15. Nguyen D. D., Nguyen D. T., Fujtta G. Dual-active-bridge series resonant converter: A new control strategy using phase-shifting combined frequency modulation // IEEE Conference Publications. 2015. No. 10. P. 1215–1222.