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Adaptation of the energy consumption of the solar electric stratospheric platform to the external lighting conditions of the onboard energy installation

The conversion of solar energy into electricity using photovoltaic cells is limited by the efficiency of the photovoltaic cells. This is all the more evident in photovoltaic installations for airplanes, which must provide relatively stable electricity to on-board consumers in conditions of non-stationarity of its consumption in typical flight modes. On the basis of the simulation of the current-voltage characteristic compiled for modern photovoltaic converters, the necessity of using maximum power point controllers in power plants of unmanned solar electric stratospheric platforms is substantiated. An optimal controller operation algorithm is also proposed.

Introduction. Unmanned solar electric stratospheric platforms (SESP) are aerial vehicles with an electric power plant based on solar cells and batteries [1-3]. Due to the absence of clouds at stratospheric heights (15...30 km), SESP flights are possible for an unlimited time. The use of SESP for communication and video surveillance is considered as an alternative to satellite systems. Compared to orbital spacecraft, solar stratospheric platforms are advantageously distinguished by the low cost of operational infrastructure, maneuverability, and potentially tight binding to national borders.

The technical implementation of SESP includes the question of the efficiency of converting solar energy into electrical energy using photovoltaic converters [4]. It is known that the current-current characteristic of photoelectric converters is significantly non-linear in nature, which imposes special restrictions in case of non-stationary nature of the electrical load. In this connection, there is a need to use maximum power point regulators at SESP power plants.

The theoretical basis of the operation of themaximum power regulators of solar photovoltaic cells (MPPT – Maximum Power Point Tracker) was first described in detail in the paper [7]. A simplified classification of regulation methods (finding the point of maximum power) includes the method of random disturbances, the method of successive load changes, methods of successive approximations with current or voltage measurement, the method of fuzzy logic, and methods of searching based on the principle of a neural network.

The listed methods are invariant to the parameters of the «solar battery – energy consumer» system. In many practical cases, systems with deterministic parameters are developed: with previously measured characteristics of solar cells, for charging the on-board battery with previously known parameters. An element with a random parameter value is the power plant of a maneuvering aircraft. The time constant when changing the illumination of the power plant corresponds to the maneuverability of the aircraft and is 0,2...1s. The time constant of the transition process of changes in illumination due to the movement of clouds has approximately the same value.

Statement of the problem. A typical equivalent circuit of a solar photovoltaic cell [5] includes (Fig. 1) a source of photocurrent I_p, proportional to the spectrally distributed illumination of the photocell $E(\lambda)$ and a p-n junction of the photocell with current I_d, which reflects the dynamic distribution of charge carriers in the transition volume.

In addition, the equivalent circuit includes the shunt resistance of the photocell R_p and the series resistance R_s [4].

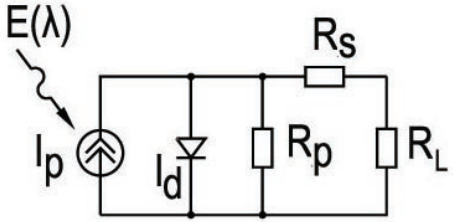

Fig. 1. Equivalent diagram of a photocell

The volt-ampere characteristic of the photocell relates the current and voltage across the external load resistance R_L:

$$I = I_p - I_h\{EXP(\frac{U}{A \times k \times T}) - 1\} - \frac{U}{R_p} \quad (1),$$

$$I_p = \int_{(\lambda)} E(\lambda) \times \vartheta(\lambda) d\lambda \quad (2),$$

where λ – the wavelength irradiating the photocell; $E(\lambda)$ – spectral density of irradiation; $\theta(\lambda)$ – spectral sensitivity of the photoeffect; I_h – is the thermal current of the reverse-biased p-n junction of the photocell; k – is the Boltzmann constant; T – is the absolute temperature; A – is the dimensionless coefficient that depends on the concentration gradient of impurity atoms in the p-n junction.

For the experimental measurement of the values of R_p, R_s and the parameters I_h , of the equivalent scheme of replacing the photocell, it is convenient to use the method based on the study of the dark and light current-voltage characteristics of the p-n junction of the photocell [6].

Table 1 shows the parameters of the equivalent circuit for replacing the C60 solar cell of the SunPower company, size 125 × 125 mm, measured according to the method [2]. Measurements of the current-voltage characteristics were carried out with photocells in the experimental fragment of the wing console (Fig. 2), manufactured for the Krokus SESP [3].

Fig. 2. An experimental fragment of a wing with applied photocells

Table 1

Parameters of the equivalent circuit for replacing the photocell C60

Parameter	R_p	R_s	I_h	A
Value	8,5 Ω	0,012 Ω	0,075 A	6

The classical formula (1) does not take into account the interaction of the volume charge of the p-n junction and the electric field of the current-collecting buses. The volt-ampere characteristic obtained during modeling in the area of maximum power is significantly different in shape from the real one [5, Fig. 4]. With a high degree of coincidence within the short-circuit and idle modes, near the point of maximum power, the model gives a significant error – up to 30 %.

Solving the problem. The effect of the potential of the current-collecting buses on the behavior of the p-n junction in the maximum power mode is manifested in the form of additional nonlinearity of the current-voltage characteristic. This can be taken into account by the dependence of parameters *A* on the distribution of the drift and diffusion components of the transition current. The resulting current-voltage characteristic can be described by the dependence:

$$I = I_p - I_h\{[EXP(\frac{U}{A \times k \times T}) - 1]^{\alpha}\} - \frac{U}{R_p} \qquad (3)$$

where, α – parameter in the range of 2,0...2,3 for a silicon substrate.

To separate the variables I, U in relation (3), it is convenient to use the numerical method of successive approximations. The equivalent scheme of photocell replacement can be presented in the form of a divider of the photogeneration current into linear and non-linear components, where the operating point of the system is located at the intersection of the lines of the current-voltage characteristics (Fig. 3). For different cases of photo generation current distribution between linear and non-linear branches ($U_2 > U_{dp}$) and ($U_2 < U_{dp}$), the direction and sequence of iterations of successive approximations are opposite. At the point of maximum power, the voltages are equal for the hypothetical flow of photocurrent separately along for linear and nonlinear branches of the circuit ($U_2=U_{dp}$).

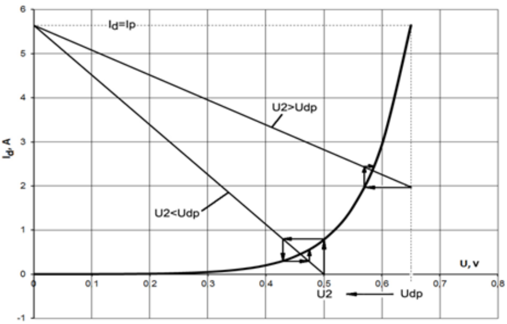

Fig. 3. Iterative solution of the nonlinear equation (3)

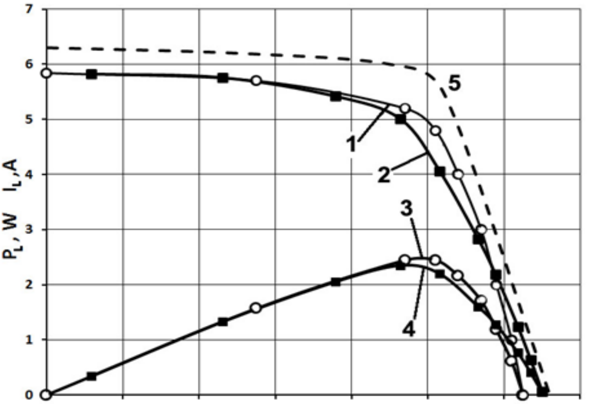

Fig. 4. Experimentally measured and calculated from (3) characteristics for Sun Power Maxeon C60 solar cells: *1* – experimentally measured current of the photocell; *2* – result of theoretical modeling according to (3); *3* – experimentally measured output power of the photocell; *4* – result of theoretical simulation of the output power; *5* – declared by the manufacturer current-current characteristic of the photocell for complex lighting 1000 W/m^2

Refined according to (3), the model of the current-current characteristic of Sun Power's Maxeon C60 photovoltaic cells is in good agreement with the experimental data; the power error near the maximum power point does not exceed 8 %. The application in model (3) of expression (2) for the photocurrent, taking into account the spectral density of radiation at different altitudes and at different angular altitudes of the Sun, makes it possible to study and optimize the flight modes of the SESP with such accuracy as sufficient for practical purposes.

As a result of limiting the output current of photovoltaic cells depending on the illumination, in the conditions of non-stationary nature of illumination and load (power regulation of SESP engines), the problem of continuous adaptation of the «solar battery – power plane» system according to the criterion of the maximum power supplied to the load arises. Figure 5 shows the typical volt-ampere characteristics of a solar battery under the conditions of maximum illumination S_1 and reduced illumination S_2.

In practice, these changes in illumination occur due to changes in the orientation of the aircraft relative to the Sun in mid-latitudes.

Illumination S_1 corresponds to the short-circuit current of $I_{sc.1}$, to reduced illumination corresponds to the short-circuit current of $I_{sc.2}$.

Under the condition of maximum illumination, the point of maximum power $P_{\max 1}$ is located on line 1; the maximum power can be calculated as follows:

$$P_{\max 1} = U_1 \times I_1 \cdot$$

When the illumination decreases, the operating point on the characteristic S_2 moves to the position with the voltage U_2. Due to the substantially non-linear form of the current-current characteristic, the power in the load decreases much more than the illumination, namely:

$$P \cong U_2 \times I_{sc2} \cdot$$

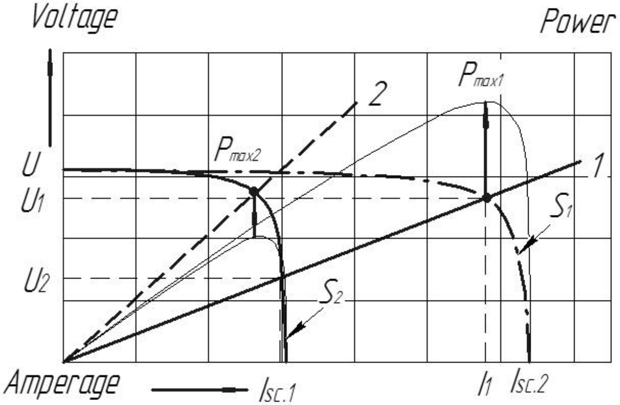

Fig. 5. Volt-ampere characteristics of the solar cell under conditions of different illumination of S_1 and S_2

In order to reach the point of maximum power $P_{\max 1}$, it is necessary to change the load characteristic to another one, which is shown by mark 2 in Fig. 5.

The new operating point will correspond to the mode of maximum power P_{max2}, under the condition of lighting S_2. Since the output voltage will return to the value of U_1, the power will decrease in proportion to the decrease in illumination.

Conclusions

It is known that the proper adjustment of the load characteristic in accordance with the illumination of the solar battery ensures the constant operation of the power system in the mode of maximum power. The presence of such a system in the SESP is due to the need to minimize the time from take-off to exiting the stratosphere. The theoretical basis of the operation of the maximum power regulators of solar photovoltaic cells (MPPT – Maximum Power Point Tracker) was first described in detail in the paper [7]. A simplified classification of regulation methods (finding the point of maximum power) includes the method of random disturbances, the method of successive load changes, methods of successive approximations with current or voltage measurement, the method of fuzzy logic, and methods of searching based on the principle of a neural network.

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It has been established that it is advisable to use battery charging current regulators or engine power regulators based on the algorithm of linear control of the current load based on the data of the solar radiation power meter in the maximum power regulators on board solar electric stratospheric platforms.

Having obtained a family of curves of current-voltage characteristics at different illumination, it is possible to unambiguously calculate the value of the current corresponding to the point of maximum power at a given illumination.

This method ensures the highest speed of the regulator, regardless of the position of the maneuvering aircraft relative to the Sun.

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