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MODELING OF THE ELECTRICAL CHARACTERISTICS OF THE SILICON-BASED SOLAR CELL

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In this paper, we have proposed the simulation model of the solar cell electrical characteristics, which gives the possibility to determine the dependences of its electrical characteristics on the environmental conditions, temperature and solar insolation, as well as on the change in the parameters of diode model, series and shunt resistances. Calculations are performed using the Matlab environment.

Keywords: *MODEL, SOLAR CELL, DIODE, OPTIONS, MATLAB.*

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1. INTRODUCTION

In connection with the aggravation of the problem connected with the fossil fuel shortage, lack of proper regulation of the prices, imbalance of ecosystem, developments in the search of high-efficiency and ecologically clean alternative energy sources are actively carried out. Those energy sources, which are based on the photoelectric solar energy conversion, can be considered as the most promising among others [1]. For solar energy conversion into electrical one, photoelectric systems (PhES), which generate constant electrical current during sunbeam illumination and convert it into alternating current using the inverter, are used. Thus, electric energy can be used for local load supply or redistributed with general network. Photoelectric units (PhEU), which are assembled of separate photoelectric devices (PhED) [2], are one of the PhES components.

In the sequel, we will call PhED, which converts energy of sunlight photons into electrical one, solar cell (SC). Voltage 0,5-0,7 V [3] is generated under the action of light in the *p-n* junction. SC produced based on monocrystalline silicon have better price-efficiency-operating time ratio among similar elements of serial production.

In the work, we report about the simulation model and calculations of the electrical characteristics of SC produced using the single-diode model.

2. THE SOLAR CELL MODEL

Energy conversion in SC is based on the photoelectric effect which appears in non-uniform semiconductor structures under the action of light radiation. The specified non-uniformity of SC structure (*p-n* junction) can be obtained, for example, using doping of semiconductor by different impurities (donor or acceptor). Light quanta with the energy exceeding the band gap of semiconductor form pairs of charge carriers [1]. Carriers, which were formed on the distance less than the diffusion length, are separated by the internal field (see Fig. 1); and electrons move toward the *n* and holes – toward the *p* junction region. Thus, potential difference arises on metal electrodes and generates an electrical current through the *p-n* junction. Potential barrier in the structure is decreased that leads to the electrical current from *n* to *p* region.

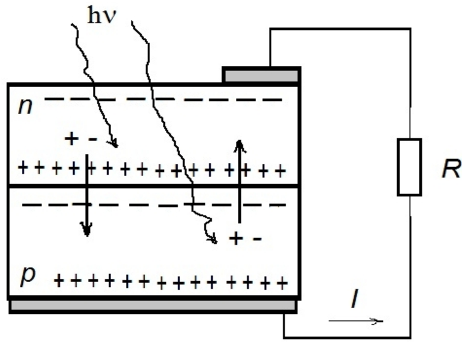

***Fig. 1** – Solar cell structure*

Calculations of the SC electrical characteristics are carried out using two main models of the electrical circuit, namely, single-diode model or two-diode model [4]. In this work, we report about modeling and calculations of PhEU using Shockley equation for diode. For modeling we have chosen the single-diode model (Fig. 2). Outward current (I_{PH}) from the source (G) is proportional to the incident light quantity. In the absence of illumination, SC operates as a usual diode, i.e. current does not pass through it. But after connection with the external source, it generates the diode current (I_D) or dark current. The main parameters, which describe the SC model, are the following: saturation current $I_0 = f(T)$, photocurrent $I_{PH} = f(T)$, open-circuit voltage, series resistance R_S, shunt resistance R_{SH}, ideality coefficient of the volt-ampere characteristic (VAC) n. For perfect SC $R_S = R_{SH} = 0$ [5].

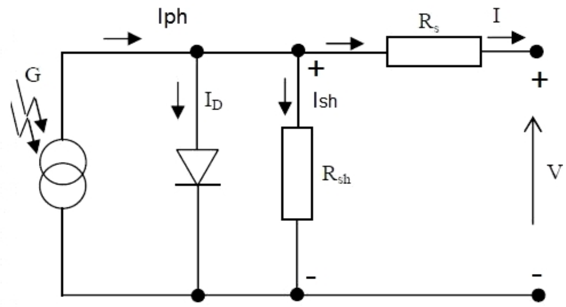

***Fig. 2** – SC equivalent circuit by the single-diode model*

For calculation of the SC electrical characteristics we will use two main parameters, namely, short-circuit current I_{SC}) and open-circuit voltage (U_{OC}). At contact closure in the external circuit ($R \to 0$), outward current is determined as the short-circuit current $I_{PH} = I_{SC}$. For the open external circuit ($R \to \infty$), current $I \to 0$, and voltage in the *p-n* junction is defined as the open-circuit voltage (U_{OC}) [6].

SC total current on the load is determined using the following equation: $I = I_{PH} - I_D - I_{SH}$. SC VAC by the single-diode model and taking into account shunt and series resistances, takes the form of [7]

$$I = I_{PH} - I_0\left[\exp\left(\frac{V + IR_S}{nkT}q\right) - 1\right] - \frac{V + IR_S}{R_{SH}}, \tag{1}$$

where V is the voltage; I is the current passing through the load; T is the temperature; n is the ideality coefficient of the rectifying p-n junction; I_0 is the saturation current.

Typical SC VAC is shown in Fig. 3. Three main parameters can be singled out there: short-circuit current I_{SC}, open-circuit voltage V_{OC}, and maximum power $P_{\max}$ [8].

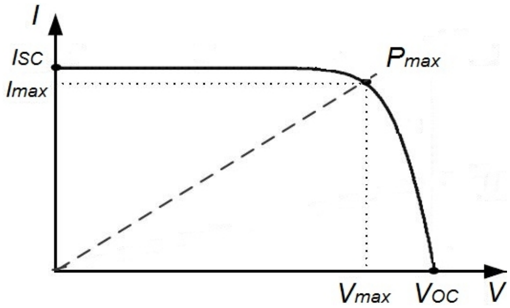

***Fig. 3** – Typical SC VAC*

In the point $V = V_{OC}$ of the VAC one can see that $I = I_{SC} = 0$. After substitution of these parameters into expression (1) we obtain

$$0 = I_{PH} - I_0\left[\exp\left(\frac{qV_{OC}}{n_0kT}\right) - 1\right] - \frac{V_{OC}}{R_{SH}} \tag{2}$$

or

$$I_{PH} = I_0\left[\exp\left(\frac{qV_{OC}}{n_0kT}\right) - 1\right] + \frac{V_{OC}}{R_{SH}}. \tag{3}$$

In the point $I = I_{SC}$ of the VAC, expression (1) takes the following form:

$$0 = I_0\left[\exp\left(\frac{qV_{OC}}{n_0kT}\right) - \exp\left(\frac{qI_{SC}R_S}{nkT}\right)\right] - I_{SC}\left(1 + \frac{R_S}{R_{SH}}\right) + \frac{V_{OC}}{R_{SH}}, \tag{4}$$

where $n_0 \geq 1$ if almost all photocurrent passes through the p-n junction (diffusion current); $n_0 \geq 2$ if minor current passes through the p-n junction (low injection level).

In the point $I = I_{\max}$, $V = V_{\max}$ on the VAC (Fig. 3) power $P_{\max} = I_{\max} \cdot V_{\max}$, which is sent to the load, takes the maximum value, and expression (1) is transformed into the following one:

$$I_{\max} = I_{PH} - I_0 \left[\exp\left(\frac{V_{\max} + I_{\max} R_S}{n_{\max} kT} q \right) - 1 \right] - \frac{V_{\max} + I_{\max} R_S}{R_{SH}} \quad (5)$$

or

$$0 = I_0 \left[\exp\left(\frac{qV_{OC}}{n_0 kT} \right) - \exp\left(\frac{V_{\max} + I_{\max} R_S}{n_{\max} kT} q \right) \right] - I_{\max} \left(1 + \frac{R_S}{R_{SH}} \right) + \frac{V_{OC} - V_{\max}}{R_{SH}}, \quad (6)$$

where $n_{\max}$ is the ideality coefficient in the maximum point.

Slope of the SC VAC in the point $V = V_{OC}$ can be described using the following equation:

$$\frac{qI_0}{n_0 kT} \exp\left(\frac{qV_{OC}}{n_0 kT} \right) = \frac{1}{R_{So} - R_S} - \frac{1}{R_{SH}}, \quad (7)$$

where n_0 and n_s are the diode ideality coefficients in the open-circuit and the short-circuit points, respectively; $R_{So} = -\frac{dV}{dI}\Big|_{V=V_{OC}}$ [9]; and slope of the VAC in the point $I - I_{SC}$

$$\frac{qI_0}{n_s kT} \exp\left(\frac{qI_{SC} R_S}{n_s kT} \right) = \frac{1}{R_{SHo} - R_S} - \frac{1}{R_{SH}}, \quad (8)$$

where $R_{SHo} = -\frac{dV}{dI}\Big|_{I=I_{SC}}$ [9]. In action, $\exp(qV_{OC}/n_0kT) >> \exp(qI_{SC}R_S/n_skT)$.

With the aid of the transformations of equations (2)-(8), we obtain

$$I_{PH} = I_{SC} + \frac{I_{SC} R_S}{R_{SH}} + I_0 \left[\exp\left(\frac{qI_{SC} R_S}{n_{\max} kT} \right) - 1 \right], \quad (9)$$

where $I_0 = (I_{SC} - V_{OC}/R_{SH})\cdot\exp(-\,qV_{OC}/n_{\max}kT)$ is the saturation current; $R_{SH} = R_{SH0} - R_S$ is the shunt resistance; $R_S = R_{S0} - \exp(-\,qV_{OC}/n_{\max}kT) \times n_skT/qI_0$ is the series resistance; and

$$n_{\max} = \frac{(V_{\max} + I_{\max} R_S - V_{OC})\, q}{kT \ln\left[\frac{(I_{SC} - I_{\max})(1 + R_S/R_{SH}) + (V_{OC} - V_{\max})/R_{SH}}{I_{SC}(1 + R_S/R_{SH}) - V_{OC}/R_{SH}} \right]}$$

is the quality factor.

Photons incident on the SC surface generate photocurrent

$$I_{PH} = [I_{PH} + K_I(T - 298)]G, \quad (10)$$

where current I_{SC} is directly proportional to the light intensity G (W/m^2) [10]: $I_{SC|G} = (G / G_0)\cdot I_{SC|G_0}$; $G_0 = 1000$ W/m^2 is the power of solar radiation at the atmospheric mass AM 1,5 and temperature 298 K; T is the SC current temperature; $K_I = [I_{SC}(T) - I_{SC}(25)]/(T - 25)$ (A/°C) is the temperature coefficient of the short-circuit current. Temperature dependence of the photocurrent is linear.

We have to note that the reverse saturation current depends on the SC temperature by the formula [11]

$$I_0(T) = I_0(298) \cdot \left(\frac{T}{298}\right)^{3/n} \cdot \exp\left[qE_g \Big/ \left(nk\left(\frac{1}{T} - \frac{1}{298}\right)\right)\right], \qquad (11)$$

where E_g is the band gap of semiconductor (eV).

Maximum power generated by the SC can be estimated using the following expression [8]:

$$P_{\max} = I_{\max} \cdot V_{\max} = FF \cdot I_{SC} \cdot V_{OC}, \qquad (12)$$

where FF is the duty factor of SC VAC.

Calculations of the SC characteristics were performed using the Matlab environment. Silicon photoconverters K5M165L-N of the class L263 with the parameters presented in Table 1 were used for the modeling. Output parameters of the SC were measured by the standard conditions: G_0 = 1000 W/m^2; AM 1,5; T = 298 K.

Table 1 *– SC output parameters*

Parameter	Designation	Value
Maximum power	$P_{\max}$	2,63 ± 0,03 W
Short-circuit current	I_{SC}	4,77 A
Open-circuit voltage	V_{OC}	0,62 V
Maximum current	$I_{\max}$	4,71 A
Maximum voltage	$V_{\max}$	0,53 V

3. INFLUENCE OF R_S AND R_{SH}

According to Fig. 2, main losses of the electrical power occur on the resistances R_S and R_{SH}. So, increase in the series resistance R_S leads to the abrupt degradation of the VAC shape and reduction in the SC output power (see Fig. 4, 5). This can be observed in the increase in the curve slope near point V_{OC}. At the same time, decrease in the shunt resistance R_{SH} from $1K\Omega$ to 10Ω influences slightly the VAC shape (Fig. 6, 7). Ideality coefficient of the VAC is equal to $n_{\max}$ = 1,22. Thus, to increase the SC output power it is necessary to provide the increase in R_{SH} and decrease in R_S.

Influence of the light intensity of the SC surface (G). As follows from the expression (10), dependence of the photocurrent I_{PH} on the insolation level at constant temperature is directly proportional. Results of the G influence on the SC characteristics are represented in Fig. 8, 9. One can see that with the increase in the insolation level, the short-circuit current increases and the output power grows. This can be explained by the logarithmic dependence of the open-circuit voltage on the solar intensity, as well as of the short-circuit current on the ray energy. Calculations show that with the increase in the light intensity I_{SC} and V_{OC} increase, but change in the open-circuit voltage is not so substantial as in the short-circuit current.

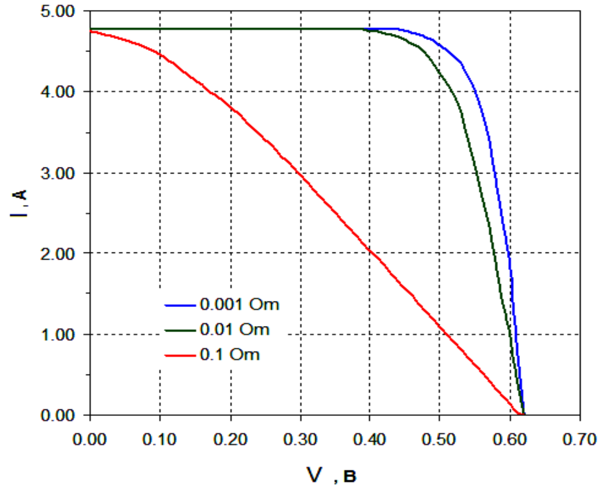

Fig. 4 *– I-V characteristic of the SC at different values of* R_{SH}

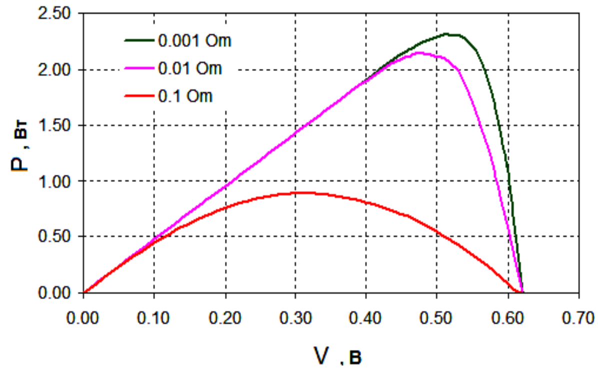

Fig. 5 *– P-V characteristic of the SC at different values of* R_{SH}

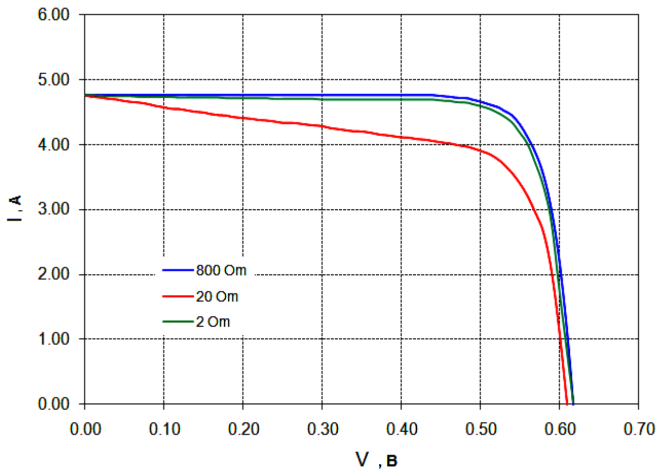

Fig. 6 *– I-V characteristic of the SC at different values of* R_S

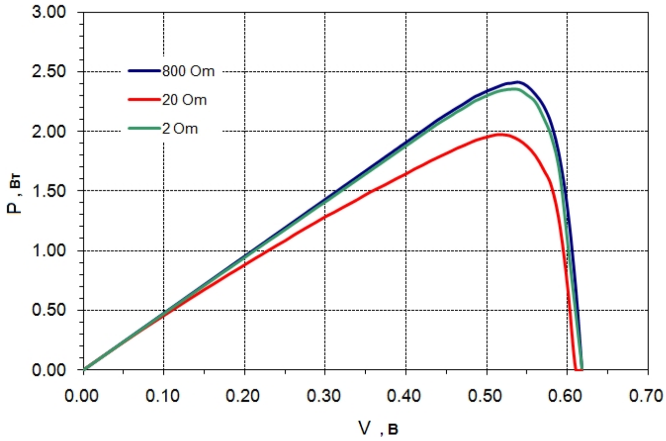

Fig. 7 – *P-V characteristic of the SC at different values of R_S*

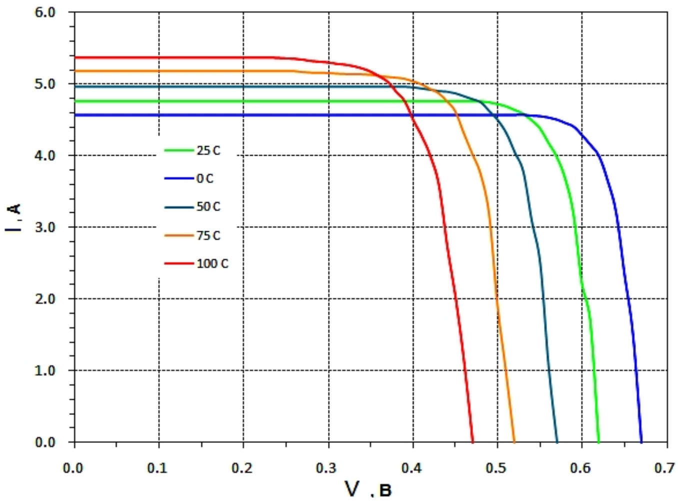

Fig. 8 – *I-V characteristic of the SC at different values of the temperature*

4. INFLUENCE OF THE TEMPERATURE

Increase in the SC temperature is manifested in the following: in a slight increase in the short-circuit current in accordance with the equation (10); in increase in the saturation current according to the equation (11); in linear drop of the open-circuit voltage in compliance with the dependence $V_{OC} \propto (E_g/q) - \ln(T^3 / I_{SC})$ [3].

Calculations resulted in the following values: temperature coefficient of the short-circuit current is equal to $K_I = 0{,}0027$ A/°C; temperature coefficient of the open-circuit voltage is equal to $K_V = 0{,}074$ V/°C. Results of the temperature effect on the SC characteristics are illustrated in Fig. 10, 11.

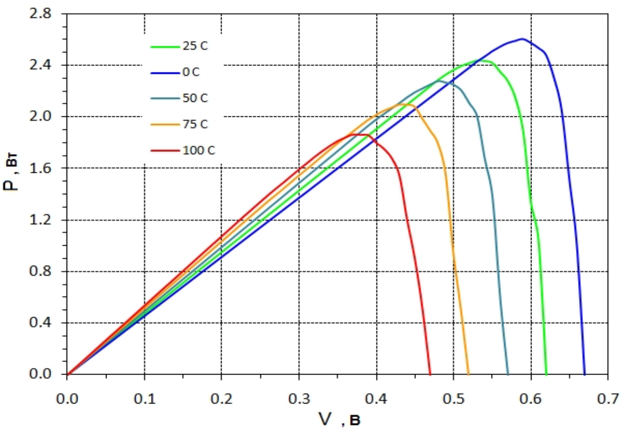

Fig. 9 *– P-V characteristic of the SC at different values of the temperature*

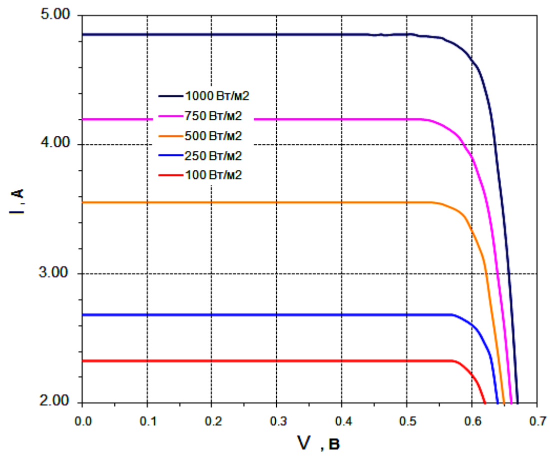

Fig. 10 *– I-V characteristic of the SC at different lighting*

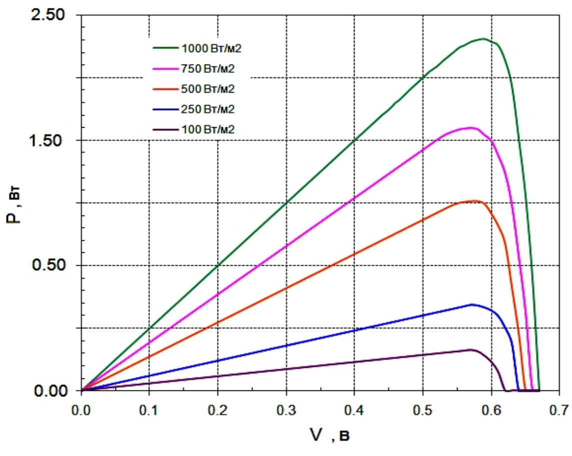

Fig. 11 *– P-V characteristic of the SC at different lighting*

5. CONCLUSIONS

Based on the developed model, sufficiently precise calculations of the SC parameters were carried out using the Matlab environment. Obtained *I-V* and *P-V* characteristics showed correct confirmed dependences of the SC on the series and shunt resistances, as well as on the influence of solar radiation and temperature. The model can be used for the calculation and analysis of the SC, solar units, and solar cell systems.

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