МЕТРОЛОГІЯ, СТАНДАРТИЗАЦІЯ, СЕРТИФІКАЦІЯ ТА ВИМІРЮВАЛЬНА ТЕХНІКА В ТЕХНОЛОГІЧНИХ ПРОЦЕСАХ

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DEVELOPMENT OF A PHOTOVOLTAIC PANEL SIMULATION MODEL BASED ON ITS SINGLE-DIODE EQUIVALENT CIRCUIT

This paper describes a simple and accurate method of extracting unknown photovoltaic panel parameters from the information provided by manufacturers in datasheets. To represent a real photovoltaic panel, a single-diode equivalent circuit model is used. This model consists of current source which simulates photocurrent produced by sun light, single diode, series and parallel resistances. The main equation for a single-diode model was obtained from Shockley equation of ideal p-n-junction. This model represents a single solar cell, but can be easily expanded to a solar panel. A simple iterative algorithm for calculating series and shunt resistances was introduced. Short-circuit current, open-circuit voltage and current and voltage at maximum power point are referenced as input data, on the other hand, photocurrent, diode reverse saturation current, diode ideality factor, series and shunt resistance are output data. According to the mathematical model of a single-diode equivalent circuit, a simulation model was developed using Matlab/Simulink software environment. Real polycrystalline photovoltaic module was used as a prototype for simulation model. As a result, I-V and P-V characteristics for two different operation conditions were obtained by computer simulation using Simulink. Theoretical I-V curves were compared with the data extracted from datasheet. This paper could be used for analyzing and developing maximum power point tracking algorithms.
Keywords: photovoltaic, panel, array, module, PV, simulation, equivalent circuit, maximum power point.

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ПОБУДОВА ІМІТАЦІЙНОЇ МОДЕЛІ СОНЯЧНОЇ ПАНЕЛІ НА ОСНОВІ ЇЇ ОДНОДІОДНОЇ СХЕМИ ЗАМІЩЕННЯ

В роботі представлена математична модель та алгоритм розрахунку параметрів сонячної панелі на основі однодіодної схеми заміщення. Вихідними даними для розрахунку є значення струму короткого замикання, напруги холостого ходу, а також струму та напруги, що відповідають максимальній вихідній потужності при заданій інсоляції та температурі сонячної панелі. На основі отриманих результатів була побудована імітаційна модель сонячної панелі в середовищі MATLAB/Simulink. Результати моделювання були порівняні із паспортними даними конкретного фотоелектричного модуля. Матеріал даної роботи може бути корисним при вирішення задач, пов'язаних із моделюванням вольт-амперних характеристик сонячних панелей, а також при розробці та тестуванні алгоритмів відслідковування точки максимальної потужності сонячних панелей.
Ключові слова: сонячна панель, сонячна батарея, сонячна електростанція, імітаційна модель, точка максимальної потужності.

The problem of finding alternative energy sources has become particularly urgent over the last few decades. The reasons for this are the lack of extraction of fossil fuels, primarily oil and gas, as well as environmental pollution caused by their use. On the other hand, the energy of solar radiation is a free, almost everywhere available resource, which allows generating environmentally friendly electricity without the least damage to the environment. In this context, solar energy is one of the most promising sectors of rapidly developing alternative energy.

Today, semiconductor devices with p-n-junctions, which are called solar or photovoltaic (PV) cells, are widely used in the field of solar energy.

In such devices, due to the internal photoelectric effect under the influence of solar radiation, there is a redistribution of charges that results in the appearance of electromotive force (EMF), which makes it possible to directly convert the energy of sun light into electrical energy.

In the simulation of the systems based on PV panels a single-diode PV cell model received widespread application [1, 6, 8–13]. It provides an opportunity to perform calculations of the illuminated current-voltage characteristic of a separate panel as well as an array (string) of PV panels connected in series at different values of solar irradiance and the surface temperature of the panel.

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An equivalent circuit that corresponds to a single-diode PV cell model is shown in Fig. 1. The circuit consists of a current source, one diode, a series and a parallel resistance. The typical current-voltage and power-voltage characteristics of PV cell are shown in Fig. 2.
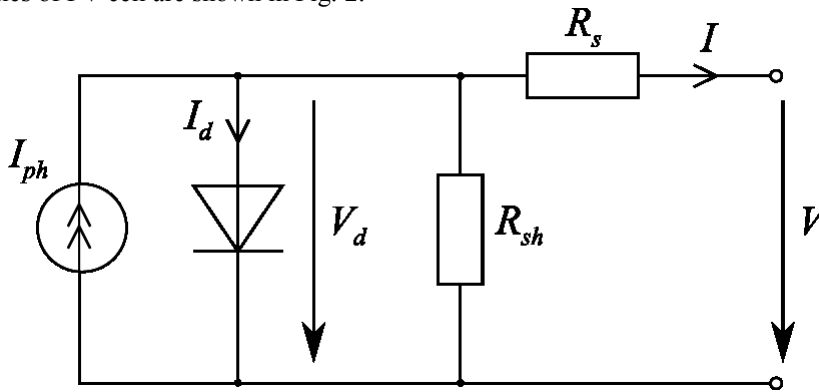

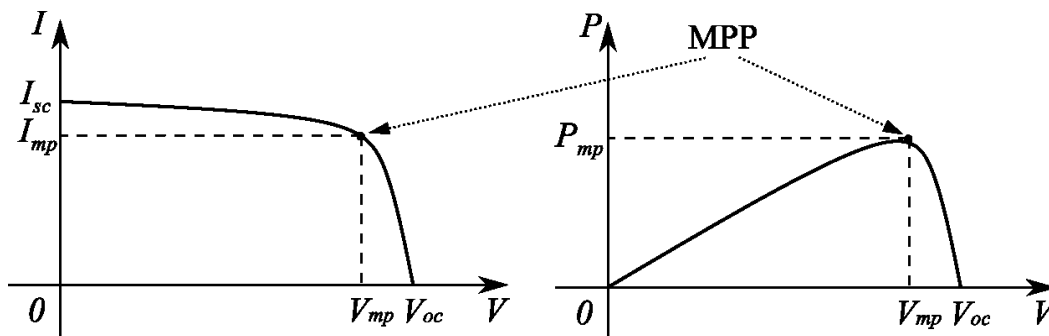**Fig. 1. A PV cell single-diode equivalent circuit**

Fig. 2. The typical I-V and P-V curves of PV cell

The single-diode model in Fig. 1 is characterized by a slight deviation of the theoretically calculated characteristics from the characteristics of the real PV cell, one of the reasons being the complexity of the accurate measurement of the series resistance in a PV cell model [2].

There are more complicated models that can provide more accurate description of the PV cell characteristics [2, 7]. For example, it is possible to use the model with two diodes [5, 7], one of which simulates the effect of recombination of charges [7, 11]. According to [5], the two-diode model quite accurately describes crystalline silicon PV cells, but for thin-film PV cells the accuracy of approximation may have some limitations. On the other hand, the use of the two-diode model leads to an increase in the number of unknown parameters, which complicates the calculation of the model. So, in this paper the single-diode model of the PV cell is preferred.

The question of choosing an adequate mathematical model for calculating the I-V curves of the PV cell is considered in the following papers [2, 7, 5, 11, 12]. In the paper [7] the problems of simulating I-V curves of PV panels are considered. The authors describe in detail different models of PV cell, analyze the conditions of their application and the accuracy of I-V curves simulation, depending on the solar irradiance and temperature. The single-diode and two-diode PV cell models are compared in works [12, 13].

The input data for calculating the PV cell parameters are the value of its I-V curve at three characteristic points corresponding to the short circuit, open circuit and maximum power point (MPP) at the solar irradiance G = 1 kW/m² and PV cell surface temperature T = 25 °C. These values of irradiance and temperature correspond to the so-called standard test conditions (STC) [8].

The values of short-circuit current I_{sc0}, open-circuit voltage V_{oc0}, as well as current and voltage at the maximum power point P_{mp0} under STC, are usually provided by solar panel manufacturers together with the corresponding temperature coefficients. Series resistance R_s, parallel resistance R_{sh}, photocurrent I_{ph}, as well as saturation current I_s and ideality factor for a diode m remain unknown [8, 9].

There are quite a lot of methods for calculating the unknown PV panel parameters [7], which differ in the approaches to the solution of the I-V equation given in an implicit form. For example, paper [6] describes a method based on the decomposition of the I-V equation for a PV cell into the Taylor series. In paper [8], the authors present a methodology for calculating PV module parameters based on the datasheet information. Paper [9] is devoted to the development of a PV panel model in the Matlab/Simulink software environment. Paper [10] presents a method for calculating series and parallel resistances of single-diode PV panel model on the basis of I-V curve analysis.

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In this paper, a detailed description of the procedure for calculating the parameters of a single-diode PV panel model is provided. The algorithm for calculating series and parallel resistances of the PV panel equivalent circuit is presented. On the basis of the obtained ratios, a simulation model of PV panel in Matlab/Simulink software environment was developed.

Mathematical model of a solar cell and a solar panel

Basing on Kirchhoff's laws, we can write the following expression for the circuit in Fig. 1:

$$I = I_{ph} - I_d - \frac{V + IR_s}{R_{sh}} \tag{1}$$

where I and V are PV cell output current and voltage; I_{ph} is photocurrent; I_d is current flowing through the diode; R_s is series resistance; R_{sh} is parallel (shunt) resistance.

The expression for the current I_d can be obtained on the basis of the ideal p-n-junction equation [2-5]. For the array consisting of N_s PV cells connected in series, current I_d is defined by the following ratio:

$$I_d = I_s \left[\exp\left(\frac{V_d}{mV_T} \right) - 1 \right] \tag{2}$$

where I_s is reverse saturation current, A; $V_d = V + IR_s$ is voltage at the diode, V; V_T is thermal voltage, V; m is diode ideality factor.

The value of the thermal voltage V_T is defined by the following expression:

$$V_T = \frac{N_s k T}{q} \tag{3}$$

where N_s is the number of PV cells connected in series; T is absolute p-n-junction temperature, K; k is Boltzmann constant, J/K; q – elementary charge equal to the module of electron charge, C.

Thus, taking to account (1) - (3), the analytical expression for the I-V curve of an array of N_s PV cells connected in series is the following:

$$I = I_{ph} - I_s \left[\exp\left(\frac{V + IR_s}{mV_T} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \tag{4}$$

The model, represented by expression (4), allows us to develop theoretical I-V curves of PV panels with an accuracy that is sufficient for engineering calculations and computer simulation [2].

It includes 5 unknown parameters that have to be found in different ways: I_{ph}, I_s, m, R_s and R_{sh}. There are many methods for defining these parameters, most of which are based on an assumption that R_s takes low values, but R_{sh}, on the contrary, is quite large.

Thus, assigning $R_s = 0$ and $R_{sh} = \infty$ in expression (4), we can get a simplified expression for I-V characteristic:

$$I = I_{ph} - I_s \left[\exp\left(\frac{V}{mV_T} \right) - 1 \right] \tag{5}$$

Expression (5) corresponds to the model of the ideal PV cell. It allows representing I-V characteristic in the form of explicit function $I = I(V)$, but with less precision than in expression (4) [4, 5].

The coefficient m is different for each material a PV panel is made of. For example, for the PV panels made of polycrystalline silicon m = 1,3 [9].

Let's consider I-V curve of PV panel at the point (0, I_{sc0}), which corresponds to short circuit (Fig. 2).

Substituting these values into equation (5), we obtain the approximate value of the photocurrent under the STC:

$$I_{ph0} \approx I_{sc0} \tag{6}$$

where I_{sc0} is short-circuit current under the test conditions.

Let's represent the exact photocurrent value I_{ph0} by the following expression:

$$I_{ph0} = \alpha I_{sc0} \tag{7}$$

where α is the coefficient of proportionality.

The actual photocurrent value I_{ph} depends on the temperature of the panel and solar irradiance, and, taking into account (6), is defined by the following ratio [8, 9, 11]:

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$$I_{ph} = \frac{G}{G_o}\left[1 - K_I\left(T - T_o\right)\right]I_{ph0} \tag{8}$$

where $G_o = 1$ kW/m² is the solar irradiance under the STC; $T_o = 25°C$ is the PV panel temperature under the STC; K_I is the temperature coefficient of short circuit, 1/K.

Let's consider I-V curve at the point (V_{oc0}, 0), which corresponds to PV panel open circuit (Fig. 2). Substituting these values into equation (5) and taking into account (6) we obtain the expression for the value of the diode saturation current under the STC:

$$I_{s0} = \frac{I_{sc0}}{\exp\left(\dfrac{V_{oc0}}{mV_{To}}\right) - 1} \tag{9}$$

where V_{oc0} and V_{T0} are open-circuit voltage and thermal voltage under the STC correspondingly.

The dependence of the current I_s on the temperature can be expressed with the help of temperature coefficients of short circuit and open circuit [8] according to the following ratio:

$$I_s = \frac{I_{sc0}\left(1 + K_I\Delta T\right)}{\exp\left(\dfrac{V_{oc0}\left(1 + K_V\Delta T\right)}{mV_T}\right) - 1} \tag{10}$$

where $\Delta T = T - T_0$; K_V is open-circuit temperature coefficient, 1/K.

For the mathematical model (4), resistances R_s and R_{sh} remain unknown. They can be defined on the basis of the equality of the experimental and theoretical maximum power values.

It is known that the PV panel output power is a product of output voltage V and current I:

$$P = V \cdot I \tag{11}$$

where I and V are PV panel output current and voltage correspondingly.

Let's substitute $I = I_{mp}$ and $V = V_{mp}$ into the equation (4) and, taking into account expression (11), write the expression which represents the ratio between R_{sh} and R_s:

$$R_{sh} = \frac{V_{mp} + I_{mp}R_s}{I_{ph} - I_s\left[\exp\left(\dfrac{V_{mp} + I_{mp}R_s}{mV_T}\right) - 1\right] - I_{mp}} \tag{12}$$

From equation (12), for some R_s we can find the corresponding value of R_{sh}, at which the theoretical I-V curve will pass through the experimental MPP. Gradually increasing the value of R_s, starting from $R_s = 0$, it's possible to find such a pair of [R_s, R_{sh}] at which the theoretical MPP will be equal (with the known error) to the experimental one. To achieve this, for each pair of [R_s, R_{sh}] from equations (4) and (12) we should find the maximum power value P which corresponds to the theoretical I-V curve. Thus, on each iteration of the algorithm the values of R_s and R_{sh} are approaching the optimal ones, that provide the best possible accuracy of the model.

The initial value of resistance R_{sh} can be defined according to the following expression [8]:

$$R_{sh0} = \frac{V_{mp}}{I_{sc0} - I_{mp}} - \frac{V_{oc0} - V_{mp}}{I_{mp}} \tag{13}$$

where I_{mp} and V_{mp} are current and voltage corresponding to the experimental MPP.

As shown in expression (6), $I_{ph0} \neq I_{sc0}$. The photocurrent value I_{ph0} under the STC can be expressed with higher accuracy if to put $\alpha = \left(1 + R_s/R_{sh}\right)$ into expression (7). So, the final expression for the photocurrent I_{ph0} looks like this:

$$I_{ph0} = \left(1 + \frac{R_s}{R_{sh}}\right)I_{sc0} \tag{14}$$

Since equation (4) sets the current and voltage ratio in the form of an implicit function $f = f(I,V)$, it cannot be solved directly; for its solution it is necessary to use numerical methods [14].

Let's present equation (4) as the function $f = f(I,V)$:

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$$f(I,V) = I_{ph} - I_s \left[\exp\left(\frac{V + IR_s}{mV_T} \right) - 1 \right] - \frac{V}{R_{sh}} - \left(1 + \frac{R_s}{R_{sh}} \right) I \qquad (15)$$

Then, calculation of the current I_n value which corresponds to the given V_n voltage is reduced to the solution of the following equation where I is unknown:

$$f(I,V_n) = 0 \qquad (16)$$

Equation (16) can be solved, for example, using the method of tangential (Newton's method) [14], which consists in step-by-step specification of the selected initial root approximation according to the formula:

$$I_{k+1} = I_k - \frac{f(I_k,V_0)}{f_I'(I_k,V_0)} \qquad (17)$$

The initial approximation I_0 has to be selected on the basis of the following condition:

$$f(I_0,V_0) \cdot f_I''(I_0,V_0) > 0 \qquad (18)$$

The algorithm of the tangential method is as follows:

1. Defining the initial approximation by formula (18).

2. Specifying the root value by formula (17).

3. If the absolute value of the function at the obtained point does not exceed a sufficiently low ε, then the root has been fined; otherwise it is necessary to return to p. 2.

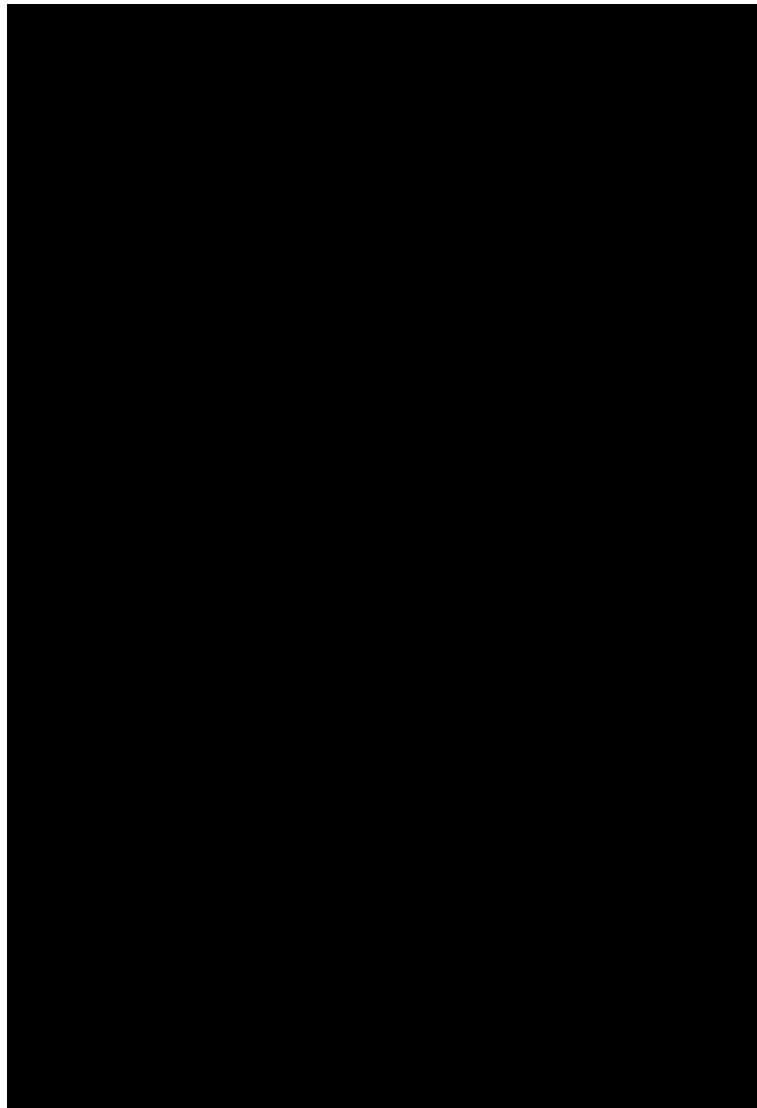A diagram of the algorithm for calculating resistances R_s and R_{sh} is shown in Fig. 3.

Fig. 3. A diagram of the algorithm for calculating series and parallel resistances in a PV panel equivalent circuit

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The main steps of the algorithm are as follows:

1. Defining I_{s0} by formula (9).

2. Assigning the initial values: $R_{s0} = 0$, R_{sh0} according to (13).

3. Defining I_{ph0} by formula (14).

4. Increasing R_{sh} on some ΔR.

5. Calculating R_{sh} by formula (12).

6. Dividing the interval $[0, V_{oc0}]$ into n parts, finding the solution of the equation (16) for each V_k at $V = V_k$.

7. For each $V_k \in [0, V_{oc0}]$ defining the corresponding P_k according to (11).

8. Defining the maximum value of P_k.

9. If $\delta = |P_{max} - P_{mp}|$ at the given values of R_s and R_{sh} does not exceed a sufficiently low ε, then the result has been found, otherwise it is necessary to return to p. 3.

The step value ΔR, the number of iterations n and the value of ε are selected depending on the necessary calculation accuracy.

A solar panel simulation model in the MATLAB/Simulink software environment

The PV panel model described by equations (1) – (10) was developed in the MATLAB/Simulink simulation software environment. The block diagram for simulating current-voltage and power-voltage characteristics of a PV panel is shown in Fig. 4. The developed PV panel model is presented as a PV Array subsystem, which takes the values of solar irradiance G and panel temperature T as the input data. It has two electric outputs ("Out+" and "Out-") compatible with the Simscape Power Systems components and the output vector of the measured values m.

For simulation of I-V and P-V curves, a controlled current source was used, which simulates linear increase in load current.
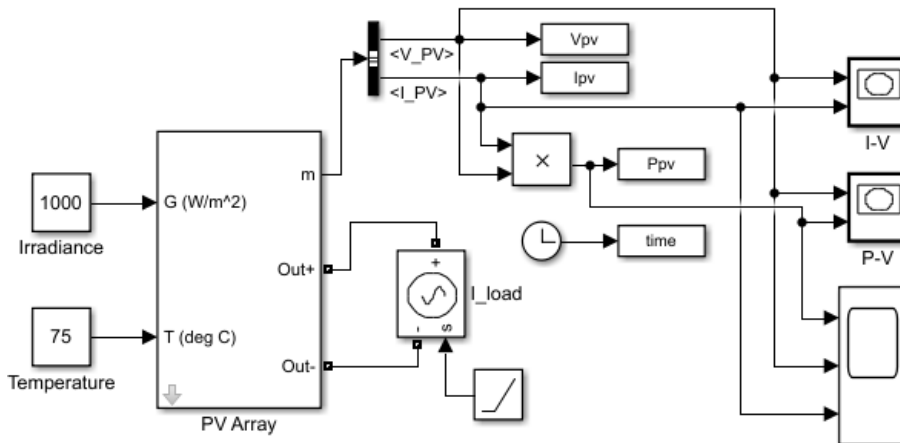

Fig. 4. A block diagram for simulation I-V and P-V characteristics of a PV panel

The structure of the PV Array subsystem, developed on the basis of equation (4), is presented in Fig. 5. It includes the subsystems for simulating currents I_{ph}, I_s, I_d. The output current for electric outputs is set by the controlled current source. The output vector m consists of the current and voltage values at the PV panel output, diode current value I_d and instantaneous values of T i G.

The internal structures of Is, Id and Iph subsystems are shown in Fig. 6, Fig. 7 and Fig. 8 correspondingly.

Let's consider as an example a KC200GT polycrystalline photovoltaic module with the power below 200 W [15]. For this module, the manufacturer provides the values of short-circuit current, open-circuit voltage, current and voltage which correspond to the maximum power of a PV panel. The data is given for two operation modes – under the standard test conditions (STC) and under the nominal operation conditions (NOC). For the KC200GT module the nominal conditions correspond to a power of solar radiation equal to 800 W/m² and a temperature of 47 °C [15]. In addition, the I-V curves of this module are given at different values of solar irradiation and panel temperature.
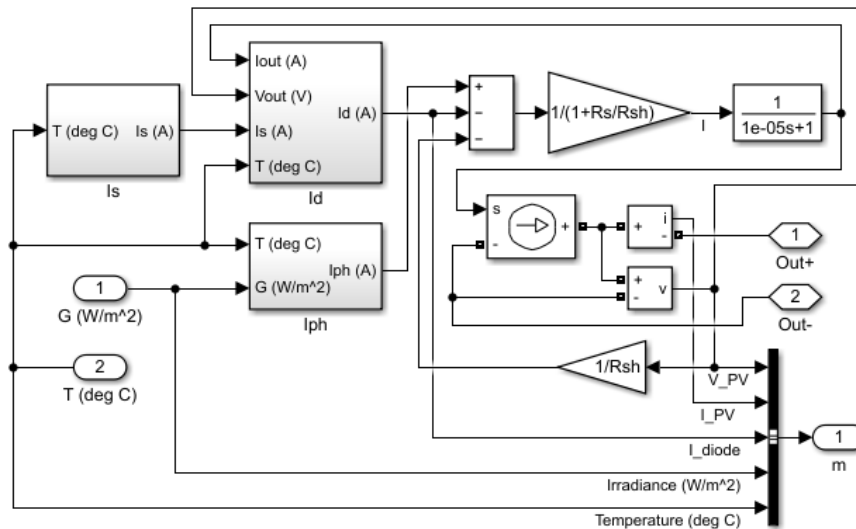
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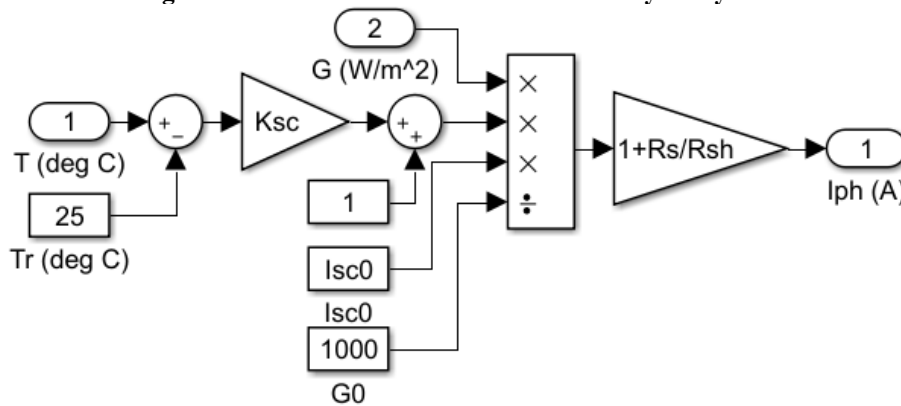**Fig. 5. The internal structure of the PV Array subsystem**

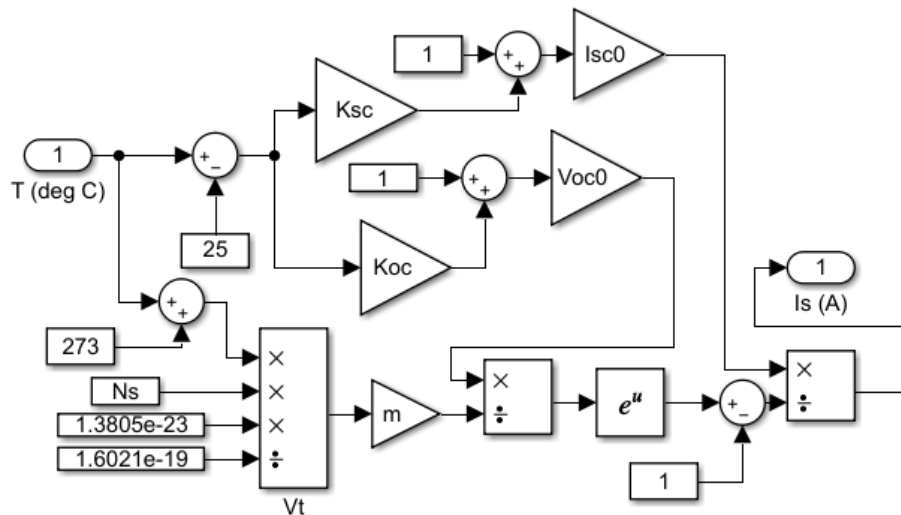**Fig. 6. The structure of the Iph subsystem**

Fig. 7. The structure of the Is subsystem

The technical characteristics of the KC200GT photovoltaic module are given in Table 1. The values of series resistance   and parallel resistance   were calculated according to the algorithm described above.
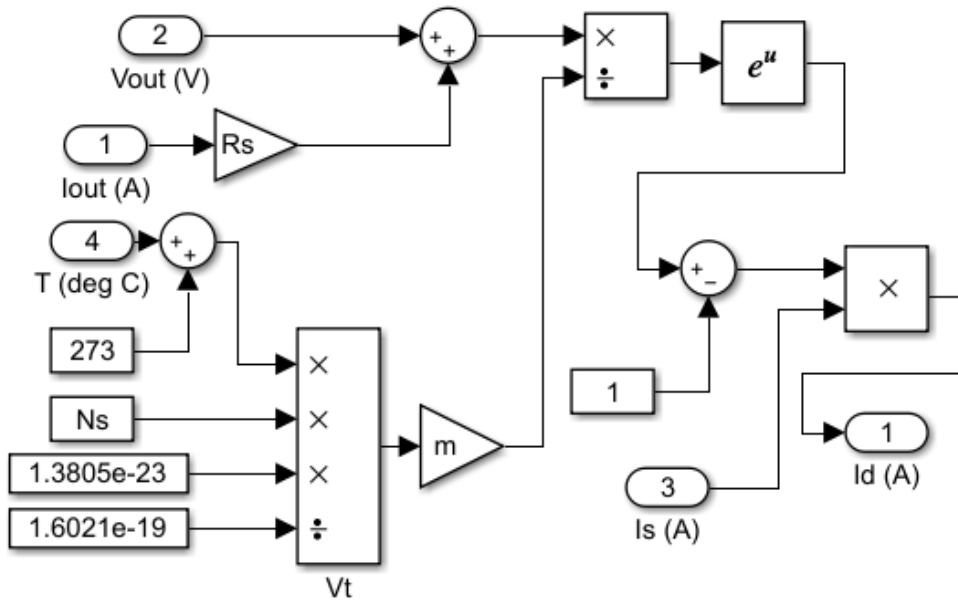
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Fig. 8. The structure of the Id subsystem

The simulation results for the KC200GT module under the STC and NOC are presented in Fig. 9. The calculated I-V curves of the PV panel at the points of short circuit, open circuit and maximum power practically coincide with the datasheet values.

Fig. 10 shows I-V curves obtained in the process of KC200GT photovoltaic module simulation at different irradiance and temperature values.

The slight deviations of theoretical I-V curves from experimental data can be explained by imperfection of a single-diode model. Accuracy of calculations can be increased by increasing the number of iterations when calculating the values of series and parallel resistances, as well as selecting the optimal ideality factor of the diode.

Table 1

Parameters of kc200gt pv module

Parameter	G = 1000 Вт/м², T = 25 °C		G = 800 Вт/м², T = 47 °C	
	Datasheet	Calculated	Datasheet	Calculated
I_{sc}, A	8,21	8,21	6,62	6,63
V_{oc}, V	32,9	32,88	29,9	29.75
P_{mp}, W	200,14	200,15	142,22	142,12
I_{mp}, A	7,61	7,60	6,13	6,05
V_{mp}, V	26,3	26,35	23,2	23,51
K_I, 1/A	$0{,}387 \cdot 10^{-3}$			
K_V, 1/V	$-3{,}739 \cdot 10^{-3}$			
N_s	54			
m	1,3			
R_s, Ω	0,222			
R_{sh}, Ω	425,742			

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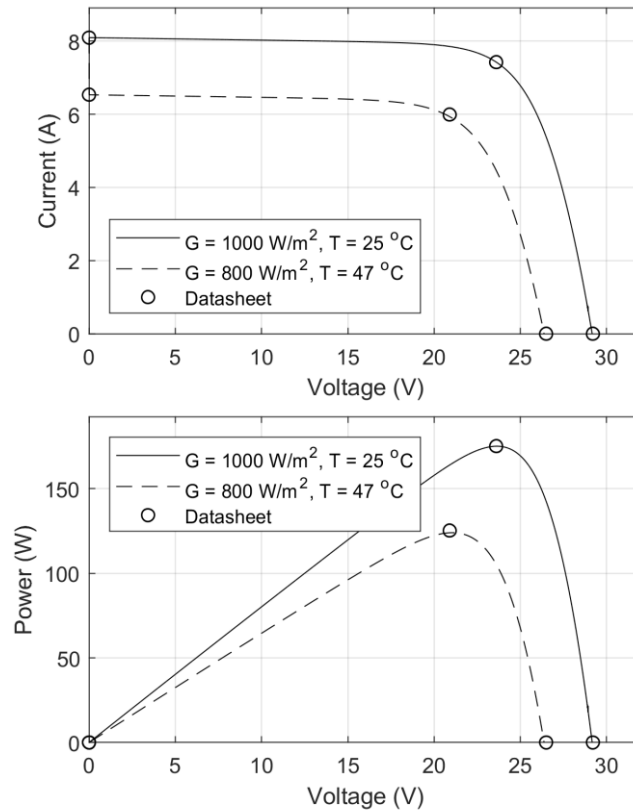
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Fig. 9. I-V and P-V curves for the KC200GT PV module at different conditions
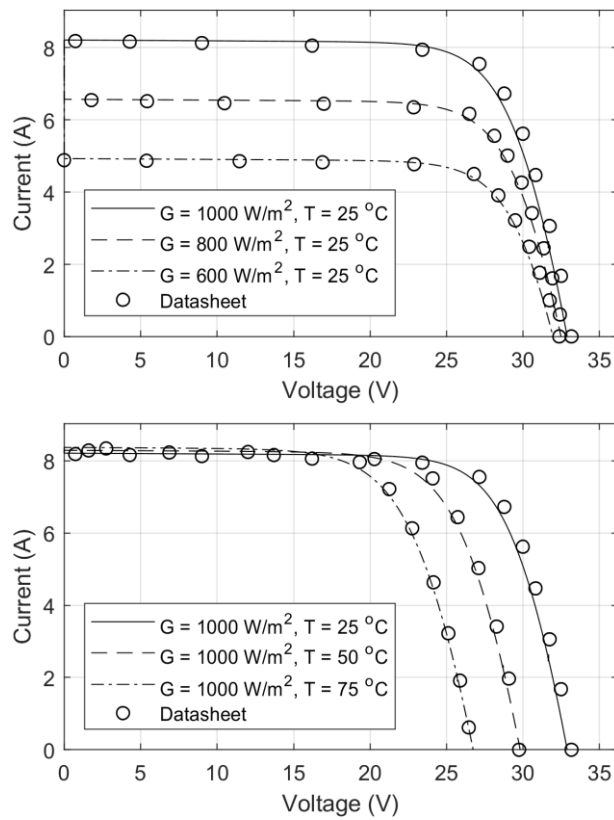
Fig. 10. I-V curves of the KC200GT PV module at different irradiation and temperature values

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CONCLUSIONS. 1. The methodology of calculating solar panel parameters based on its datasheet has been presented. The algorithm for calculating the series and parallel resistances of a single-diode equivalent circuit has been described. The input data for calculating the PV panel parameters are the value of I-V curve at three characteristic points corresponding to the short circuit, open circuit and maximum power point under the standard test conditions under STC.

2. The mathematical model of the PV panel, developed on the basis of a single-diode photovoltaic equivalent circuit, shows sufficient accuracy in the simulation of the current-voltage characteristics of industrial PV modules used in solar energy systems. The theoretical curves of current and power obtained in the process of KC200GT photovoltaic module simulation practically coincide with the corresponding curves provided in the documentation. Accuracy of calculations can be increased by selecting the optimal value of the diode ideality factor in equation (4) and increasing the number of iterations when calculating the values of R_s and R_{sh}.

3. The simulation model developed in the MATLAB/Simulink software environment is compatible with the elements of the Simscape Power Systems power electronics unit and can be further used in the simulation of surface photovoltaic systems of varying degrees of complexity.

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