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Simulation of Electrical Characteristics of a Solar Panel

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Abstract. The fast-growing photovoltaic system market leads to the necessity of the informed choice of major energy components and optimization of operating conditions in order to improve energy efficiency. Development of mathematical models of the main components of photovoltaic systems to ensure their comprehensive study is an urgent problem of improving and practical using of the technology of electrical energy production. The paper presents a mathematical model of the solar module implemented in the popular software MATLAB/Simulink. Equivalent circuit of the solar cell with a diode parallel without derived resistance is used for modelling. The serie8s resistance of the solar module is calculated by Newton's iterative method using the data of its technical specifications. It ensures high precision of simulation. Model validity was evaluated by the well-known technical characteristics of the module Solarex MSX 60. The calculation results of the experiment showed that the obtained current-voltage and current-watt characteristics of the model are compatible with those of the manufacturer.

1. Introduction

Recent years have seen a rapid growth in the market of solar photovoltaic systems for various practical applications: from small autonomous power systems to large power stations [1].

Modern photovoltaic systems comprise solar panels and a large range of power equipment including various types of electronic power converters to ensure maximum power consumption from the generator, optimum modes of battery charging, electric energy conversion in accordance with the accepted standards, etc.

The right choice of basic energy components and optimization of operating modes are crucial for the efficient use of photovoltaic systems. The main tool to solve the stated problems is simulation, which predetermines the necessity to create universal mathematical models of the basic elements of photovoltaic stations enabling comprehensive study of their operating modes.

The research aims to develop the mathematical model of a solar panel implemented in the software package Matlab/Simulink.

2. Theoretical study

The solar panel is composed of a large number of identical solar cells which are semiconductor photovoltaic cells connected serial/parallel and functioning on the basis of photovoltaic effect. The diode equivalent circuit (figure 1) was used to create the mathematical model of a solar cell, physical processes were described by the following equation (1) [2–4]:

$$I = I_{PH} - I_D = I_{PH} - I_S \left[\exp\left(\frac{q\left(V + I R_s\right)}{A k T_C} \right) - 1 \right] - \frac{V + I R_S}{R_{SH}}, \tag{1}$$

generated under solar radiation referred to as photocurrent; I_S is reverse saturation current of the unlit diode (dark current); q is electron charge; R_S is series resistance of the photovoltaic cell; A is the coefficient obtained by comparing theoretical and experimental volt-ampere characteristics of solar cells to characterize the quality of a cell (coefficient takes the values from 1 to 5); k is the Boltzmann constant; T_C is current operating temperature of the device; R_{SH} is shunt resistance of the cell.

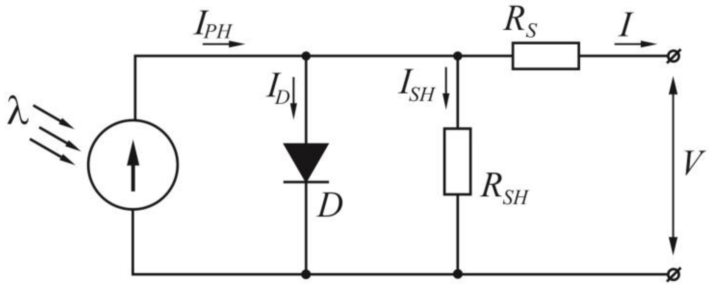

Figure 1. Equivalent circuit of the solar cell.

Equation (1) defines the volt-ampere characteristic of the solar cell to show the relation between output current I and voltage V. The equation is transcendental, contains five variables and has no analytic solution.

To simplify equation (1), make a set of assumptions and use the technical specifications for photovoltaic modules provided by the manufacturer.

The photocurrent value primarily depends on solar insolation λ and operating temperature of the cell T_C:

$$I_{PH} = \left[I_{SC} + K_I \left(T_C - T_R \right) \right] \lambda, \tag{2}$$

where I_{SC} is short circuit current of the photovoltaic cell under standard conditions: temperature of 25°C and solar insolation of 1 kW/m^2; K_I is temperature coefficient of the solar cell short circuit current (from technical specifications); T_R is cell temperature under standard conditions; λ is the value of solar insolation, kW/m^2.

Revers current also depends on the temperature, and it is calculated using the equation:

$$I_S = I_{RS} \left(T_C / T_R \right)^3 \exp\left[q E_G \left(1/T_R - 1/T_C \right) / k A \right], \tag{3}$$

where I_{RS} is reverse current under standard conditions; E_G is the width of semiconductor band gap (determined by the type of the solar cell).

The value of reverse current I_{RS} can be approximately determined by open-circuit voltage of the element V_{OC} measured at standard temperature of the cell T_R using the expression:

$$I_{RS} = I_{SC} / \left[\exp\left(q V_{OC} / k A T_R \right) - 1 \right]. \tag{4}$$

The values of open-circuit voltage and short-circuit current of the solar cell can be determined from technical specifications of the solar panel:

$$V_{OC} = \frac{V_{OC\_R}}{N_S}, \quad I_{SC} = \frac{I_{SC\_R}}{N_P}, \tag{5}$$

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where V_{OC_R}, I_{SC_R} are open-circuit voltage and short-circuit current of the solar panel measured under standard conditions; N_S, N_P are the number of series and parallel elements in the panel, respectively.

The analysis of actual energy characteristics of solar panels proves their sensitivity to minor changes in series resistance R_S, while the value of shunt resistance R_{SH} has no significant impact on their effectiveness [5, 6]. Furthermore, elementary cells of the solar panels are connected in serial chains to obtain the acceptable operating voltage. Therefore, shunt resistance of the panel is basically great and can be neglected without substantial reduction in the model accuracy assuming $R_{SH} = \infty$ [7, 8].

Take the derivative of equation (1) with respect to voltage to determine the value of series resistance R_S:

$$\frac{\mathrm{d}I}{\mathrm{d}V} = -I_S\left[\frac{q}{AkT_C}\left(1+\frac{\mathrm{d}I}{\mathrm{d}V}R_S\right)\exp\left(\frac{q(V+I\,R_S)}{AkT_C}\right)\right]. \quad (6)$$

Consider equation (6) with the solar cell in open circuit when V=V_{OC}, I=0. After simple transformations, we obtain:

$$R_S = -\frac{1}{\dfrac{\mathrm{d}I}{\mathrm{d}V}} - \frac{1}{\dfrac{I_S\,q}{AkT_C}\exp\left(\dfrac{qV_{OC}}{AkT_C}\right)} = -\frac{\mathrm{d}V}{\mathrm{d}I} - \frac{1}{\dfrac{I_S\,q}{AkT_C}\exp\left(\dfrac{qV_{OC}}{AkT_C}\right)}, \quad (7)$$

where dV/dI=ΔV/ΔI is cotangent of the slope angle of current voltage characteristic (CVC) of the solar panel at the point of open circuit (easily determined by the experimental CVC from technical specifications).

Equation (1) is solved using Newton's method in which the algorithm to find the numerical solution of equation $f(x) = 0$ is reduced to the following iterative calculation procedure:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}, \quad (8)$$

where $f'(x)$ is the function derivative.

Equation (1) takes the form:

$$f(I) = I_{PH} - I - I_S\left[\exp\left(\frac{q(V+I\,R_S)}{AkT_C}\right)-1\right] = 0\,. \quad (9)$$

With regard to equation (8), we obtain:

$$I_{n+1} = I_n - \frac{I_{PH} - I_n - I_S\left[\exp\left(q(V+I_nR_S)/(AkT_C)\right)-1\right]}{-1 - I_S\,q\,R_S\exp\left[q(V+I_nR_S)/(AkT_C)\right]/(AkT_C)}\,. \quad (10)$$

Equations (1)–(10) are the basis for solar panel mathematical modeling.

3. Computer implementation

The current values of solar radiation (G), semiconductor operating temperature (T), and the module parameters determined from the module technical specifications are the initial data to calculate the solar panel characteristics. The function subprogram implementing the solution of the system of equations (1)–(10) is developed in the MATLAB environment to calculate the photovoltaic module parameters. The mathematical model designed as a subsystem is presented in figure 2.

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The model is provided with the controllable current source to enable connection of the model with other components of photovoltaic systems. Certain parameters of the solar panel Solarex MSX 60 stated by the manufacturer [9] and presented in table 1 were used to verify the model.

The calculation results have shown that the developed model simulates the current voltage characteristics of a solar panel with satisfactory accuracy: maximum error in the calculated values of short-circuit current and open-circuit voltage within the entire range of possible changes in temperature and illuminance does not exceed 5.4%.

Table 1. Basic parameters of the solar panel Solarex MSX 60.

Parameter	Value
Max (peak) power, P_{max}, W	60
Voltage at max power, V_{max}, V	17.1
Current at max power, I_{max}, A	3.5
Open-circuit voltage, V_{OC}, V	21.1
Short-circuit current, I_{SC}, A	3.8
Open-circuit voltage temperature coefficient, K_U, mV/°C	80±10
Short-circuit current temperature coefficient, K_I, %/°C	0.065±0.015

4. Simulation results

Figure 3 shows the calculated current-voltage and current-watt characteristics of the photovoltaic module at different temperature and illuminance values. The results of calculations confirm the model adequacy in representation of physical processes in the photovoltaic module under various operating conditions.

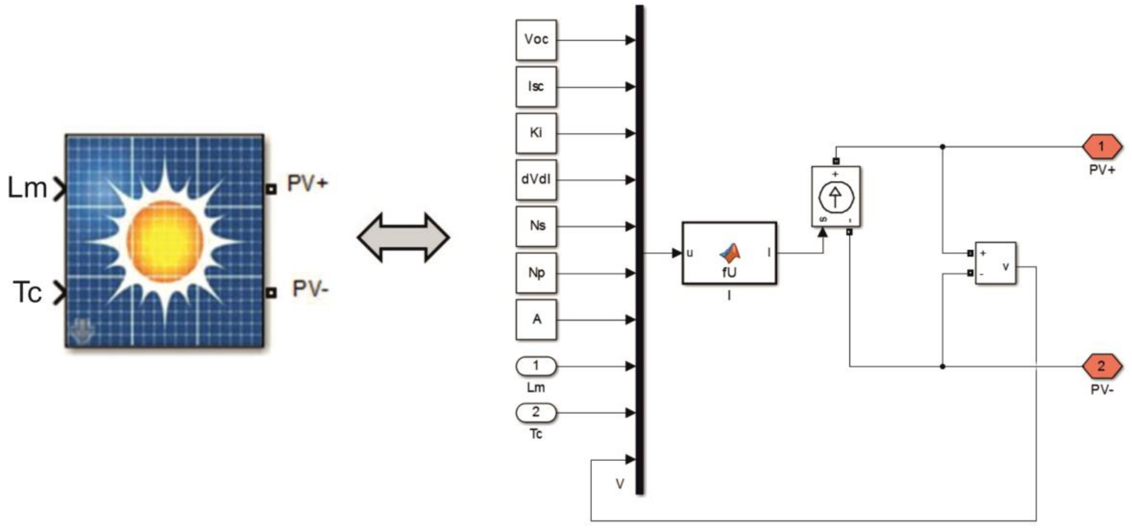

Figure 2. Model of the solar panel implemented in MATLAB/Simulink.

The proposed model can be used to research the operating modes of a single photovoltaic module and its various combinations (solar panels).

5. Conclusion

The model of the solar panel implemented in MATLAB/Simulink has been developed as a result of the research. Certain parameters of the panel Solarex MSX 60 were used to verify the model adequacy. The calculation results showed that the obtained current-voltage and current-watt characteristics of the model are compatible with those of the manufacturer.

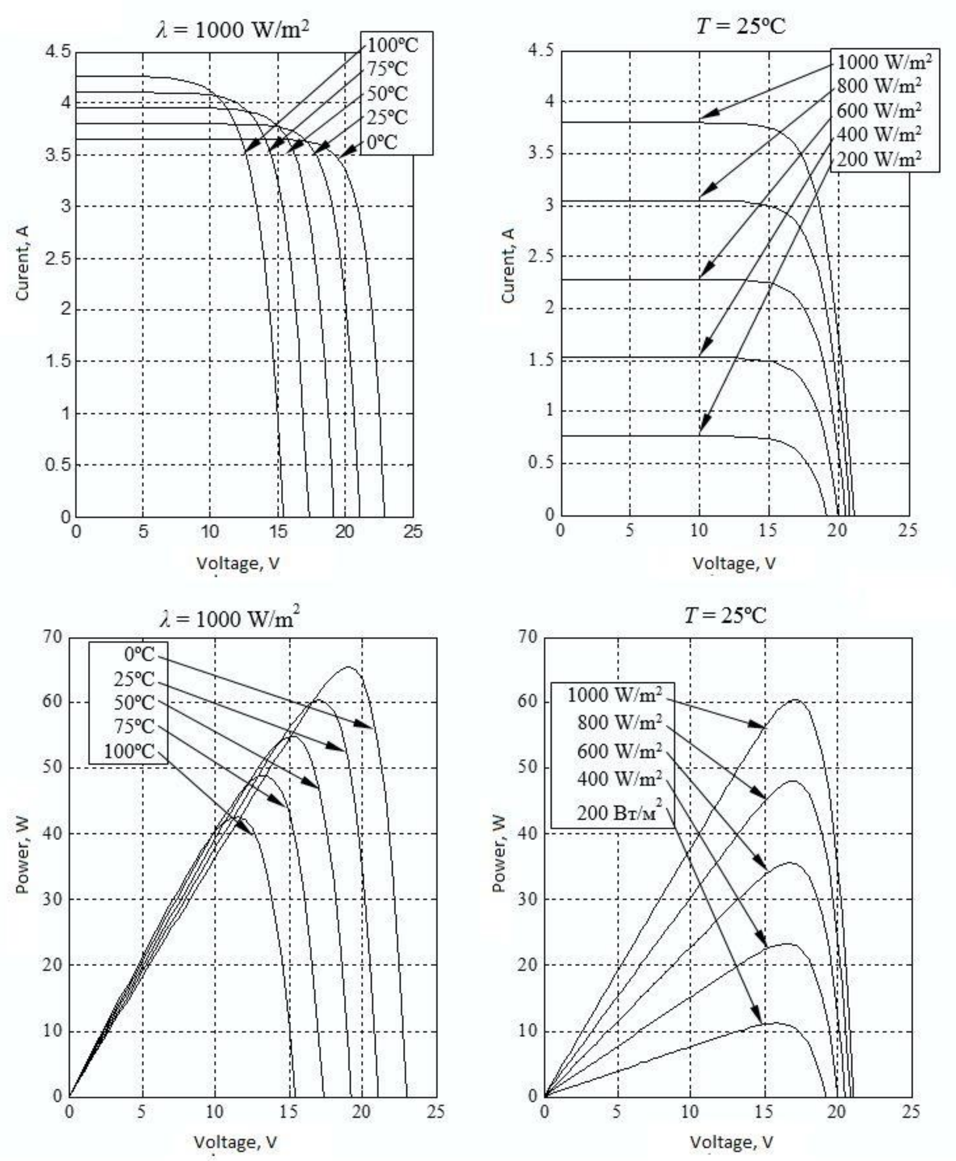

Figure 3. Calculated characteristics of the solar panel Solarex MSX 60.

The model is developed as a separate subsystem capable of the basic parameters input via a dialog box that ensures easy modification and application of the model to study the characteristics of solar cells of different types and to create models of solar panels and photovoltaic systems of any configuration based on these models.

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