

The implementation of an ideal photovoltaic module in Matlab/Simulink using Simpowersystems Toolbox

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Abstract — This paper deals with creating a mathematical model of ideal photovoltaic module. The performance of the model is demonstrated with output characteristics which also show the effect of changes in temperature and solar radiation on the output parameters of cell, module, and field. The model is realized in Matlab/Simulink environment due to frequently using and complexity of this software.

Keywords— photovoltaic modules; model; Matlab; Simulink

I. INTRODUCTION

Photovoltaic cell is a device based on a semiconductor material that converts energy of sunlight into electrical energy. Due to its low power, it is necessary to combine multiple cells into series or into parallel, forming a photovoltaic module with the required values of current and voltage. In the same way are also combined individual modules. This creates the so-called fields. Output parameters of cells are most affected by climate conditions, especially by solar radiation and also by temperature at the input modules and the configuration diagram. Therefore, modeling this device necessarily requires ambient temperature and solar radiation as input variables. The output of the model can be voltage, current or power of the module. Any changes in the input variables are reflected by changes on the output.

II. EQUIVALENT CIRCUIT AND MATHEMATICAL MODEL OF A PHOTOVOLTAIC CELL

Photovoltaic cell, as the most basic component of photovoltaic system, is modeled in this paper by one diode equivalent circuit. It consists of a photocurrent source, diode, parallel resistor, which represents leakage current and a series resistor, which represents the internal resistance of the cell (Fig. 1).

The mathematical description of the model is further described by authors [1], [2], [3], [4].

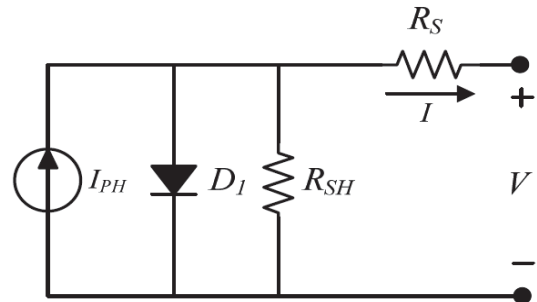


Fig. 1 General equivalent circuit of photovoltaic cell [2]

The basic equation describing the relationship between voltage and current is defined as follows [1][2][3]:

$$I = I_{PH} - I_S \left(e^{\frac{q(V+IR_S)}{kTA}} - 1 \right) - \frac{V + IR_S}{R_{SH}} \quad (1)$$

I_{PH} represents the current generated by photovoltaic cells called the photo current and I_S is the saturation current. Constant q (1.6×10^{-19}) is electric charge, k (1.38×10^{-23}) is Boltzmann constant. T is the operating temperature and factor A is a constant which depends on the technology used in photovoltaic cells. In the case of monocrystalline silicon factor A has a value of 1.2, in technology based on polycrystalline silicon factor A has a value of 1.3 [3][2].

Current generated by the photovoltaic cells is dependent on the ambient temperature and solar radiation, and can be calculated using the following equation [2]:

$$I_{PH} = \lambda(I_{SC} - k_i[T - T_r]) \quad (2)$$

Coefficient λ is the radiation temperature coefficient and k_i is short circuit current temperature coefficient. I_{SC} represents short circuit current measured under the standard test conditions, where in the case of PV modules the temperature is 25 °C and the solar radiation is 1000 W/m² [4].

Saturation current depends on the operating temperature, and it is defined as [2]:

$$I_S = I_{RS} \left(\frac{T}{T_r} \right)^3 e^{\left(qE_G \frac{\left[\frac{1}{T_r} - \frac{1}{T} \right]}{kA} \right)}, \quad (3)$$

where I_{RS} is the reverse saturation current under standard test conditions and E_G stands for the energy band gap, which depends on the semiconductor used in photovoltaic cells[5][6]. Reverse saturation current at the reference temperature can be approximate calculated by the following equation [2]:

$$I_{RS} = \frac{I_{SC}}{e^{\left(\frac{qV_{OC}}{N_S k T A}\right)} - 1}, \quad (4)$$

V_{OC} is the open circuit voltage of photovoltaic module at reference temperature and N_S is number of cells connected into series. In the case, when only single cell is modeled, the N_S equates to 1 [7].

Apart from general model, it is possible to derivate the equations for approximate and simplified model with doing some simplifications. The approximate model with appropriate complexity [8] can be derived from equation (1) without considering of leakage current represented by R_{SH} resistance. After editing, it is possible to rewrite the equation as follows [2]:

$$I = I_{PH} - I_S \left(e^{\left[\frac{q(V+I R_S)}{k T A}\right]} - 1 \right) \quad (5)$$

In the case of simplified model, it is a model of ideal photovoltaic cell [9]. It is created by further simplification of equation (1), namely with omission of R_S , which represents longitudinal loss on internal resistance of PV cell. Using some modifications, it is possible to rewrite the equation to the corresponding shape again [2]:

$$I = I_{PH} - I_S \left(e^{\left[\frac{qV}{k T A}\right]} - 1 \right) \quad (6)$$

III. EQUIVALENT CIRCUIT AND MATHEMATICAL MODEL OF PHOTOVOLTAIC MODUL AND ARRAY

As mentioned above, due to the low power it is necessary for practical applications in electrical power systems to achieve required performance of the module by wiring configuration. Voltage is increased by series connection and current is increased by parallel connection. In most cases, within the module only the series connection is used. [10] The simplified equivalent circuit of photovoltaic array consisting of the number of series connected cell N_S , and number of parallel connected cells N_P is described in figure 1. Resulting current of the circuit is described by next equation [3]:

$$I = N_P I_{PH} - N_P I_S \left(e^{\left[\frac{qV}{N_S k T A}\right]} - 1 \right) \quad (7)$$

When it is needed to model a cell, $N_S = N_P = 1$. In the case of module, $N_P = 1$ and N_S is number of series connected cells within the module. The last case is connection to an array, where N_S is number of cells within the module and N_P is number of parallel modules within an array.

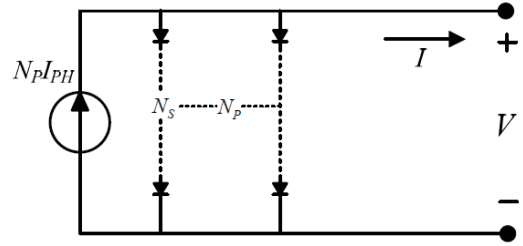


Fig. 2 Simplified equivalent circuit of photovoltaic array [2]

IV. MODELING IN MATLAB/SIMULINK ENVIROMENT

The object of this paper is the modeling of ideal photovoltaic module, which is also most suitable for implementation in Matlab/Simulink in terms of simplicity. In case of approximate and general model there is a problem with algebraic loops [2] that arise from necessity of loading output voltage into the input at the same time.

Equation for resulting current and any other necessary equations was implemented using blocks from mathematical library. Interface of mathematically modeled photovoltaic module with physical elements of SimPowerSystem is realized using controlled current source. It is controlled by results from equation (7). Each equation creates subsystem of the model.

The first step was creating of equation (2). This equation needs both input variables - solar irradiation λ and ambient temperature T . After solving the equation, the photocurrent is calculated in the output of this subsystem.

Next steps go with the implementation of equations for calculation of saturation current I_S and reverse saturation current I_{RS} . Input variables of these subsystems is ambient temperature, in the output of the subsystem is values of saturation respectively reverse saturation current.

After modeling each equation it is possible to join them, and to implement relation for resulting current. Solar irradiance and ambient temperature is an input to this equation and also to the whole model.

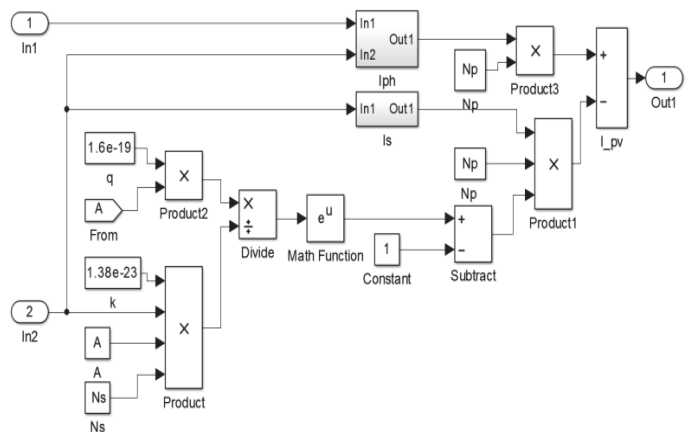


Fig. 3 Detailed view on the implementation of the equation for resulting module current

Solar irradiation is required to enter in kW/m^2 and temperature in kelvin, and these values may be constant throughout the entire simulation, the changing by pre-configured parameters, or even be loaded from an external file.

From a set of modeled equations was created functional subsystem, which was subsequently masked as a Simulink block. It makes it easy to use the model of photovoltaic modules for various applications. A user interface was also created.

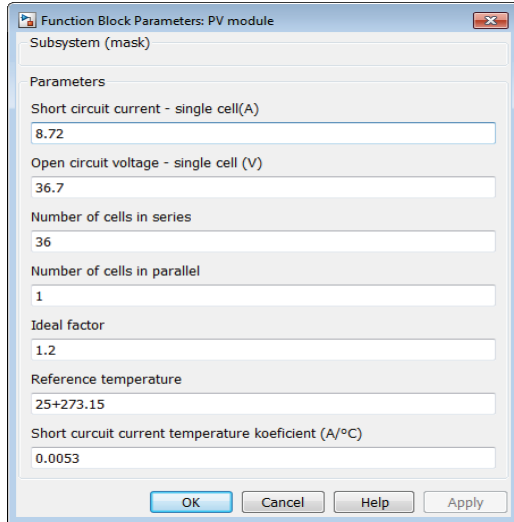


Fig. 4 User interface of PV module block

As can be seen in fig. 8, model outputs the current of the photovoltaic module according to (7) and fed a control input of controlled current source, which forms the interface between the mathematical and physical models.

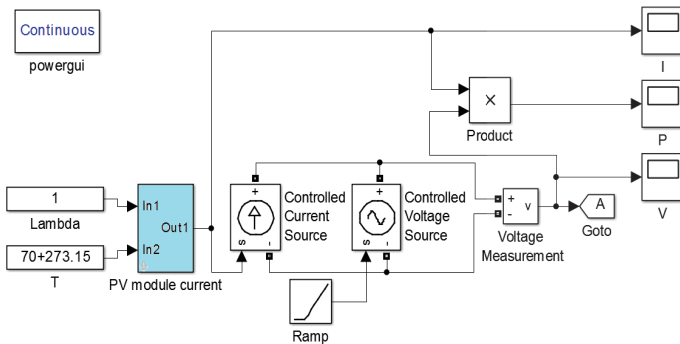


Fig. 5 Model of photovoltaic module prepared for measuring output characteristics

V. SIMULATION AND RESULTS

After modeling of photovoltaic module it is needed to verify its functionality by simulation. Model was modified by addition of certain blocks in order to measure its output characteristics, namely $I = f(V)$, $P = f(V)$, $P = f(I)$. Controlled voltage source with ramp function on input was added due to continuous increasing of the module output voltage. In addition, measuring and displaying blocks was added.

Parameters of the IBC Polysol 230 LS were used for testing. Ode 45 (Dormand Prince) was used as a simulation solver with variable time step. Maximum step size was set to 1×10^{-6} s and all other solver options to auto mode.

TABLE I. PARAMETERS OF THE IBC POLYSOL 230 LS PV MODULE

Parameter	Value
STC Open circuit voltage (V)	36.7
STC Short circuit current (A)	8.72
Short circuit current temperature coefficient (mA/°C)	0.005
Bang gap energy (eV)	1.11
Factor A (-)	1.2
Number of series connected cells N_S (-)	36

In addition to verifying the functionality of the model by monitoring of compliance its output characteristics with the parameters stated by the manufacturer, there has been investigated changes in output parameters according to changes in input variables (solar radiation, temperature). Because of this, several simulations were performed. Effect of temperature at constant solar irradiation and at the other side effect of solar irradiation at constant temperature was studied separately. In monitoring the effect of the temperature, the temperature was set from -5°C to 70°C with constant step of 15°C and constant irradiation $\lambda = 1000 \text{ W/m}^2$. In monitoring the effect of solar irradiation, the irradiation was set from 200 W/m^2 to 1000 W/m^2 with constant step of 200 W/m^2 and constant temperature $T = 25^\circ\text{C}$. Figures 9-14 show the graphical evaluation of measurement results.

Graphic dependence (Fig. 9) is a non-linear VA characteristic of photovoltaic modules. It can be seen that under standard test conditions, the model exhibits full compliance with the parameters specified by the manufacturer. It is possible to observe the impact of solar radiation on the parameters of the module. With increasing solar radiation significantly increases the value of short circuit current, on the other hand, the open circuit voltage increases only slightly.

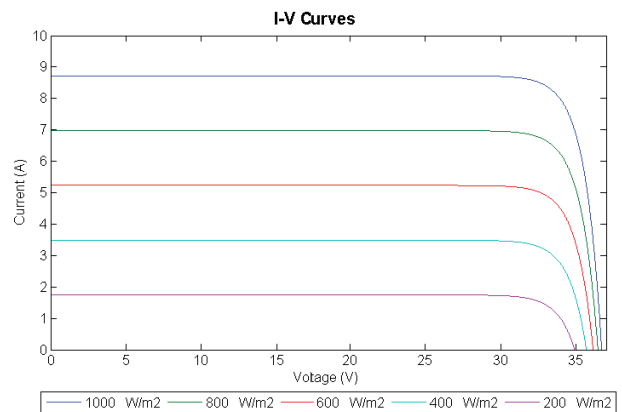


Fig. 6 The dependence of the output current from the voltage $I = f(V)$ at constant temperature $T = 25^\circ\text{C}$.

V-A characteristic $I = f(V)$ at constant sunlight shows, that with increasing temperature significantly increases the open circuit voltage and short current slightly decreases.

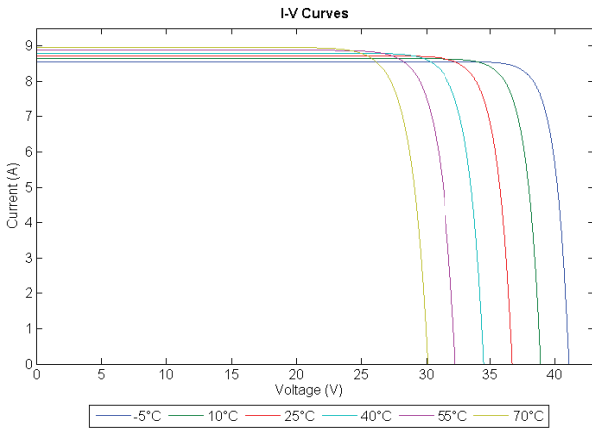


Fig. 7 The dependence of the output current from voltage $I = f(V)$ at constant irradiance $\lambda = 1000 \text{ W/m}^2$

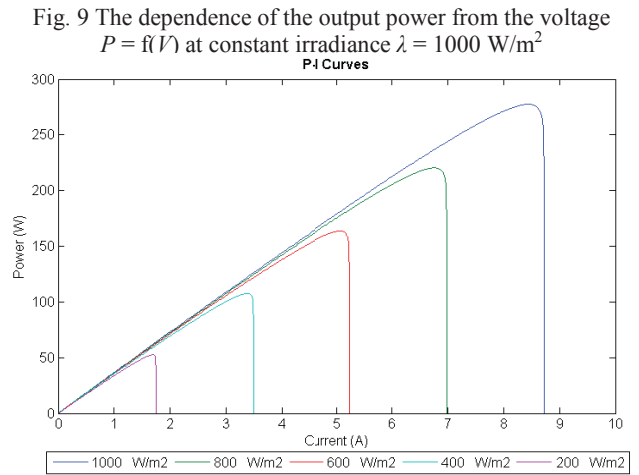


Fig. 9 The dependence of the output power from the voltage $P = f(I)$ at constant irradiance $\lambda = 1000 \text{ W/m}^2$

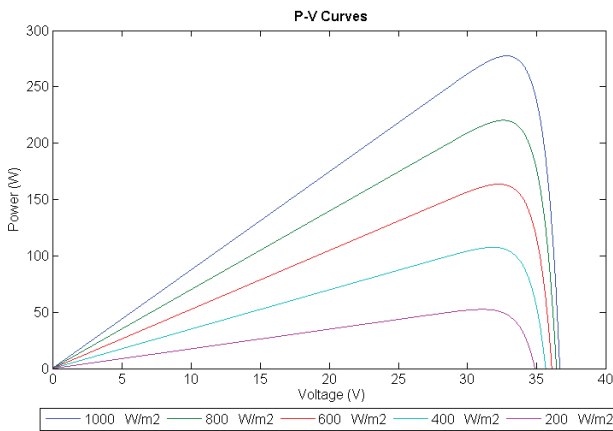


Fig. 8 The dependence of the output power from voltage $P = f(V)$ at constant temperature $T = 25^\circ\text{C}$

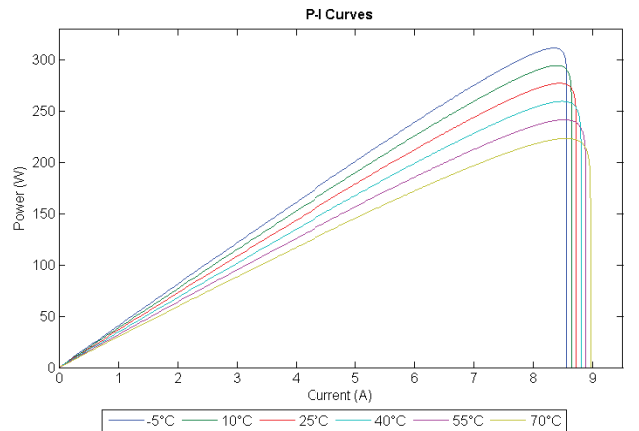


Fig. 10 The dependence of the output power from current $P = f(I)$ at constant temperature $T = 25^\circ\text{C}$

Figure 11 and following figures represent the power of photovoltaic modules depending on the output voltage or current respectively. Also show the effect of temperature and solar radiation on the performance of photovoltaic modules. These characteristics are important in determining the maximum power point, which can module achieve at any given time and the current temperature and sunlight.

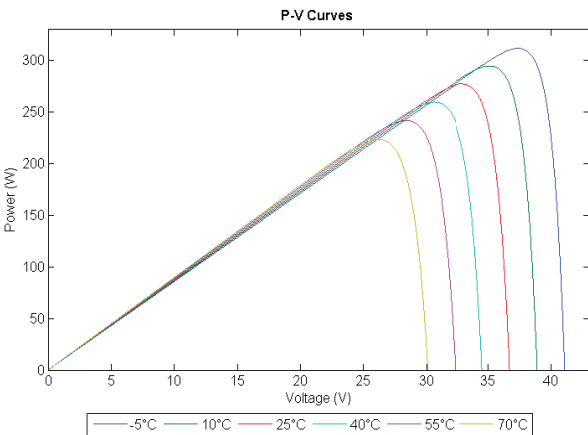


Fig. 11 The dependence of the output power from current $P = f(I)$ at constant irradiance $\lambda = 1000 \text{ W/m}^2$

VI. CONCLUSION

This paper describes the mathematical model of photovoltaic module and its subsequent implementation in Matlab/Simulink using SimPowerSystems toolbox. Furthermore, the functionality of the model was verified by simulating real photovoltaic module and at the same time was studied influence of temperature and solar radiation on the output characteristics.

Under standard test conditions results have been matched with the parameters specified by the manufacturer. When the value of solar radiation is 1000 W/m^2 and a temperature of 25°C , short circuit current is 8.72 A and the open circuit voltage is 36.7 V , what confirms a valid model.

During monitoring the effect of temperature it was found that the short-circuit current I_{SC} at changing temperatures from -5°C to 70°C was varied from 8.95 to 8.56 and the open circuit voltage V_{OC} varied from 30.10 to 41.05 V . When the impact of solar radiation was monitored it was found that the short current I_{SC} in range of 200 W/m^2 to 1000 W/m^2 varied

from 1.74 to 8.71 A and the open circuit voltage V_{OC} from 34.91 to 36.7 V.

From the dependence $P = f(V)$ and $P = f(I)$ arise, that the operating point, which is the maximum power point of the photovoltaic device is changing depending on the weather. The power in DC circuit is defined as the product of voltage and current, current is given and it is therefore possible to optimally operate photovoltaic module by modifying only the output voltage with respect to changing weather conditions.

This model can be used to test various types of photovoltaic modules and their behavior in the other than standard test conditions. Also it can be used to study different search techniques related to the searching for the maximum power point and then adjusting the working voltage. In order to extremely rapid computational time due to mathematical modeling, it can be used for complex simulations of various applications in the electric power systems.

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