

Modeling of photovoltaic modules in Simulink and Simscape packages of Matlab software

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Summary. The paper presents the possibilities of modeling the functioning of photovoltaic modules in MATLAB engineering software packages. In SIMULINK package one implemented a single-mode mathematical model of the photovoltaic module for determining current-voltage characteristics. The model was verified for manufacturer-supplied data and actual measurement results made with the I-V 400 meter. The new capabilities for physical modeling of photovoltaic modules are also available in the SIMSCAPE package. Simulation results obtained from the SIMSCAPE model were also compared with the results of selected measurements under the specified radiation and temperature conditions.

Key words: photovoltaic, mathematical model, MATLAB, SIMULINK, SIMSCAPE

INTRODUCTION

Literature has generally accepted the use of PV abbreviation (*Photovoltaic*), replacing the various grammatical forms of the word photovoltaics [3,4,5,6,9,13,15]. The currently manufactured PV modules are most often built with 60 PV modules connected in series and their rated power is up to 300 Wp (Watt-Peak). The peak power is provided by PV module manufacturers under standard conditions, the so called STC (Standard Test Conditions). Determining the I-V characteristics of the PV modules requires the system to be shut down and, as a result, it causes losses of energy generated by the PV system. Mathematical modeling and computer simulation make it possible to predict the performance of an installation under various environmental conditions without having to shut it down. The mathematical modeling performance of PV modules is verified by comparing the results with the data collected in the process of monitoring the basic parameters of the PV system [12].

MATHEMATICAL MODELING OF PV MODULES FUNCTIONING

The similarity of the silicon PV cell to the semiconductor diode determines the form of its mathematical model, which, with sufficient precision

for practical purposes, describes the initial responses to the induced inductions. In the literature one can find such modeling attempts [1,2,8] whose results were similar to the characteristics reported in the catalog cards by PV module manufacturers. The most common model is the PV module, which is shown in Figure 1. The PV module model is analogous to the PV cell model, the difference is only due to the serial connection of a suitable number of PV cells forming the module. PV modules in which PV cells are also connected in parallel are rarely produced, but in mathematical models such a connection model was provided. Dual-diode models are only an extended version of the single-diode models (fig. 2).

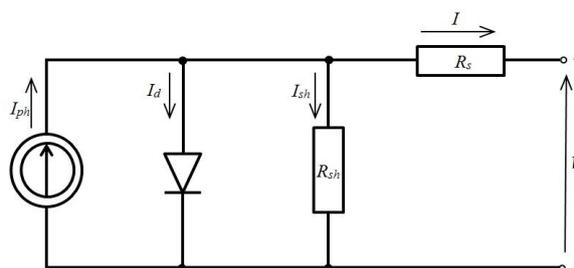


Fig. 1. Diagram of the single-diode replacement model of PV cell

For single-diode replacement diagram of PV cell, based on Kirchhoff's first law, the following formula can be written:

$$I = I_{ph} - I_d - I_{sh} \quad (1)$$

where:

I – PV amperage (load) [A],

I_{ph} – amperage (photocurrent) of the current generated in the cell [A],

I_d – diode amperage [A],

I_{sh} – Amperage of the current flowing through the shunt [A].

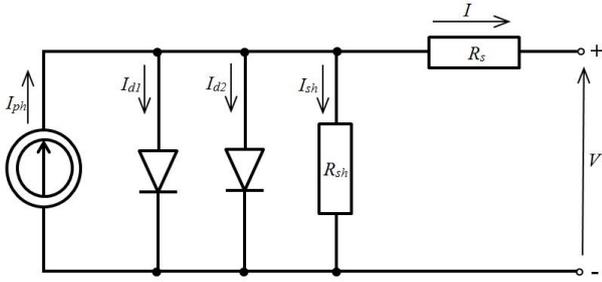


Fig. 2. Diagram of the dual-diode replacement model of PV cell

On the dual-diode replacement diagram of PV cell two various diodes were used instead of one. The output equation of this model is analogously determined based on the Kirchhoff's first law:

$$I = I_{ph} - I_{d1} - I_{d2} - I_{sh} \quad (2)$$

In the paper the single-diode model is discussed and it is implemented in SIMULINK and SIMSCAPE packages of MATLAB program. Developing the last two elements of the formula (1) we obtain an equation that takes into account the phenomena that occur in the diode and resistors of the PV replacement cell diagram:

$$I = I_{ph} - I_s \cdot \left[\exp\left(\frac{V + I \cdot R_s}{n \cdot V_t}\right) - 1 \right] - \frac{V + I \cdot R_s}{R_{sh}} \quad (3)$$

where:

I_s – Reverse current of the diode saturation [A],
 V – PV cell voltage (cell) [V],
 V_t – thermal voltage of PV cell,
 n – diode quality index,
 R_s – serial resistance [Ω] (one assumed 0.0038 Ω),
 R_{sh} – parallel resistance (shunt) [Ω] (one assumed 1000 Ω) acc. to [8].

Thermal voltage of PV cell (V_t), depending on its temperature (T_c) is calculated according to the following formula:

$$V_t = \frac{k_B \cdot T_c}{q} \quad (4)$$

where:

k_B – Boltzmann's constant equal to $1.38 \cdot 10^{-23}$ [J·K⁻¹],
 q – Electron charge equal to $1.602 \cdot 10^{-19}$ [C].

Reverse current of the diode saturation (I_s) can be calculated according to the following formula:

$$I_s = \frac{I_{sc}}{\exp\left(\frac{V_{oc}}{n \cdot V_t}\right) - 1} \quad (5)$$

where:

I_{sc} – cell short circuit current PV [A],
 V_{oc} – open cell voltage [V].

Additionally, one may make the formula dependent from (5) temperature (T_c) and the value of the semiconductor's power interval (E_g), from which PV cell was made:

$$I_s(T_c) = I_s \left(\frac{T_c}{T_{STC}} \right)^3 \cdot \exp \left[\frac{E_g}{n \cdot V_t} \left(\frac{T_c}{T_{STC}} - 1 \right) \right] \quad (6)$$

where:

T_{STC} – temperature of the cell in STC conditions [K],
 E_g – energy interruption of the semiconductor [eV],
 n – diode quality index ($n=1.3$ – for polycrystalline silicon according to [8]).

Amperage of the photocurrent generated in the cell (I_{ph}) is calculated according to the following formula:

$$I_{ph} = I_{sc} \frac{E}{E_{STC}} \quad (7)$$

Manufacturers of PV cells often also provide the so called temperature ratios for short circuit current (I_{sc}) and for open cell voltage (V_{oc}). If we have such data, then to the formulas (5) and (7) one should substitute proper dependencies, making these parameters dependent from PV cell temperature (T_c) to the following formulas:

$$I_{sc}(T_c) = I_{sc} \left[1 + (T_c - 298) \frac{\alpha_T}{100} \right] \quad (8)$$

$$V_{oc}(T_c) = V_{oc} \left[1 + (T_c - 298) \frac{\beta_T}{100} \right] \quad (9)$$

where:

α_T – temperature ratio for I_{sc} [%·K⁻¹],
 β_T – temperature ratio for V_{oc} [%·K⁻¹].

For the verification of the constructed models, in the paper the measurements of current-voltage characteristics of PV module are used, the basic catalogue data of which are provided in Tab. 1.

Table 1. Technical data of PV modules in STC conditions according to [10]

Selected parameters of PV module:	SunRise SR-660250
P_{MPP} [W _p]	250
tolerance P_{MPP} [+/- %]	-0 / +3
V_{MPP} [V]	30.11
I_{MPP} [A]	8.3
V_{OC} [V]	37.33
I_{SC} [A]	8.96
Temp. ratio for: I_{SC} α_T [%/°C]	+0,05
Temp. ratio for: V_{OC} β_T [%/°C]	-0,33
Temp. ratio for: P_{MPP} γ_T [%/°C]	-0.44
PV module efficiency η_{STC} [%]	17.2

NOCT [°C]	45±2
PV module dimensions [mm]	1637x992x40
Number of PV cells [pcs.]	60
PV cells dimensions [mm]	156x156
PV module mass [kg]	19.2

IMPLEMENTATION OF MODELS IN SIMULINK AND SIMSCAPE OF MATLAB PROGRAM

The mathematical model of the typical current-voltage characteristic of a PV cell, in the form of the function $I = f(V)$ is nonlinear and entangled, only possible to be solved in the iterative calculation process. A MATLAB-SIMULINK engineering calculation package can be used to solve this model, which also enables rapid visualization of simulation results. The diagram shown in Figure 3 describes the output equation (1), which will be further developed into the individual components of the model. All input / output blocks are implemented in the SIMULINK package using the "From-Goto" components. The "XY Graph" block was used for the current control of the simulation results, and the numerical results of the simulation were also sent to the Matlab workspace ("simout" block) for further processing.

The assumption in the proposed model in SIMULINK package for simulation of PV cell functioning is bringing in the input of the rising voltage signal in a suitably selected range and calculating the amperage in the PV cell.

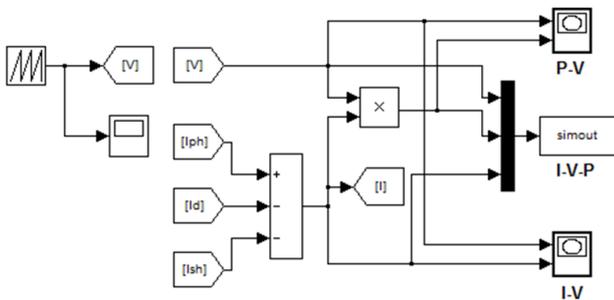


Fig. 3. Block diagram of simulation of PV cell functioning in SIMULINK package

The diagram presented in Fig. 4 considers a higher number of PV cells, connected serially N_s or in parallel N_p in formulas (3) and (7) and temperature ratio for I_{sc} current according to the formula (8).

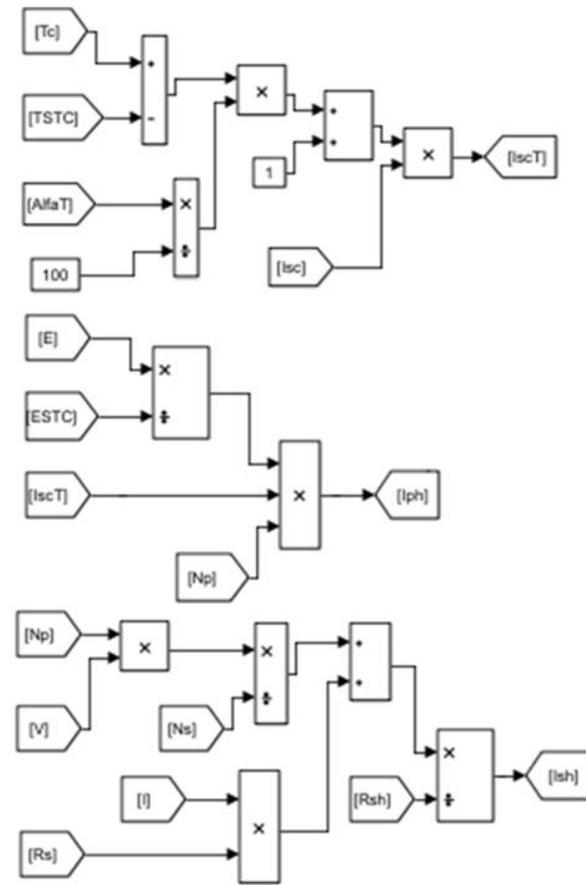


Fig. 4. Extended block diagram for calculating I_{ph} and I_{sh} in SIMULINK package

The block for calculating I_d current is more difficult to execute. Due to the complexity of the formulas, the algorithm was implemented in three separate blocks of the SIMULINK package (Fig. 5).

All the diagrams were placed on one SIMULINK package window and simulations were performed.

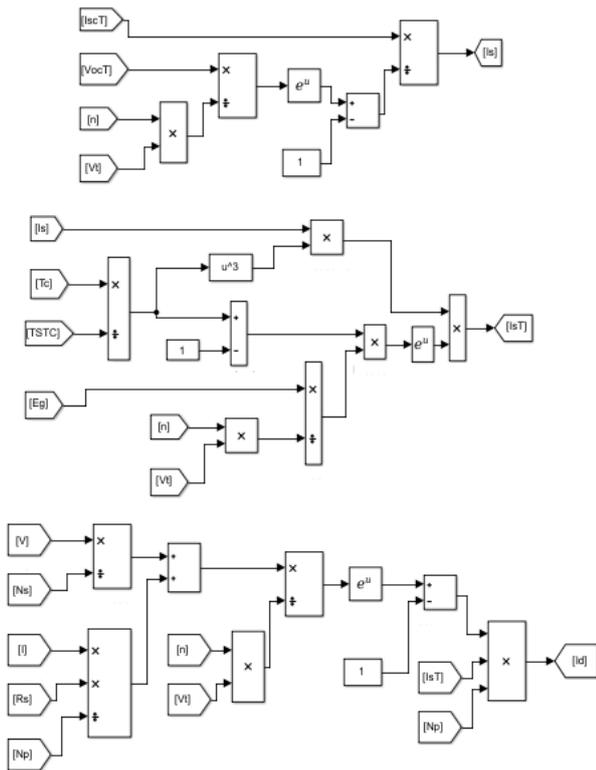


Fig. 5. Block diagram of I_d current calculation

The simulation diagram in SIMSCAPE package (Fig. 6) is visually less complicated. The majority of connections on the diagram executes only measurement-visualization functions. The most important element of the diagram (Fig. 6) is the „PV array” component which properties were presented in Fig.7. This component executes connections according to the mathematical model elaborated by NREL (National Renewable Energy Laboratory - USA) in 2014 [1]. The algorithm in this case is simplified as all parameters of the PV module supplied by the manufacturer are read from the SIMSCAPE module database (fig. 7).

In both SIMULINK and SIMSCAPE packages one performed simulation calculations for the exemplary results of current-voltage characteristics performed with I-V 400 meter [11], complying with the standard: PN-EN 60891 [14].

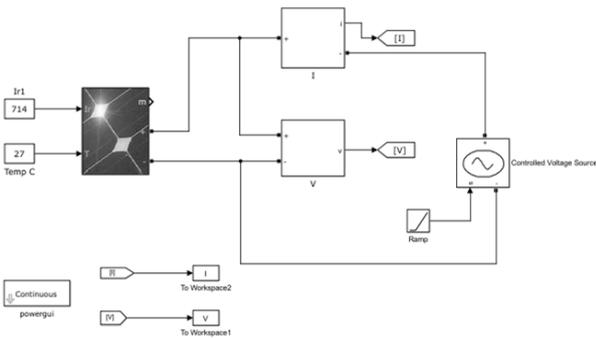


Fig. 6. Simulation diagram in SIMSCAPE package

Block Parameters: PV array (mask) (link)

Implements a PV array built of strings of PV modules connected in parallel. Each string consists of modules connected in series. Allows modeling of a variety of preset PV modules available from NREL System Advisor Model (Jan. 2014) as well as user-defined PV modules.

Input 1 = Sun irradiance, in W/m², and input 2 = Cell temperature, in deg.C.

Parameters: Advanced

Array data

Parallel strings: 1

Series-connected modules per string: 1

Module data

Module: Sunrise Solartech SR-M660250

Maximum Power (W)	250.2	Cells per module (Ncell)	60
Open circuit voltage Voc (V)	36.9	Short-circuit current Isc (A)	9
Voltage at maximum power point Vmp (V)	30	Current at maximum power point Imp (A)	8.34
Temperature coefficient of Voc (%/deg.C)	-0.36301	Temperature coefficient of Isc (%/deg.C)	0.0545

Fig. 7. Dialogue window of „PV array” component properties in SIMSCAPE package

RESULTS

The elaborated models of simulation diagrams in SIMULINK and SIMSCAPE package were subjected to initial verification consisting in comparison of results of calculations with measurement data imported from the memory of current-voltage characteristics meter. For comparison, one selected the results of tests conducted with intensity of solar radiation of 714 W·m⁻² and PV modules temperature of 27°C. The measurement was conducted on 30.06.2015 in Płock (Poland), with stable weather at 14:07.

Fig. 8 presents the comparison of current-voltage characteristics (I-V), determined on the basis of results of simulations in SIMULINK package with results of measurements with I-V 400 meter. Another fig. 9 represents analogical comparison, but the results of simulation are derived from SIMSCAPE package.

For the initial verification of results of simulation one selected three points of characteristics: short circuit point (I_{SC}), point of idle work (V_{OC}) and maximum power point (P_{MPP}). Table 2 presents the values for these points and the values of fill factor (FF) and efficiency (η) according to the formulas (10) and (11).

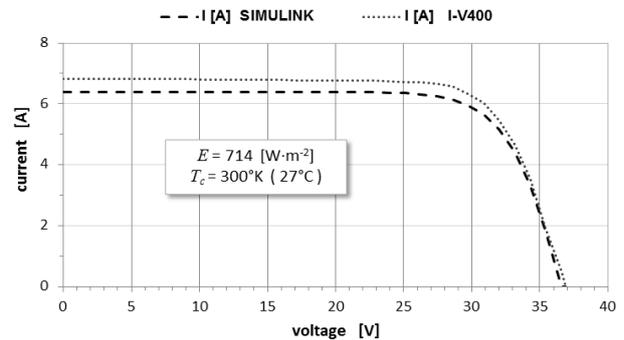


Fig. 8. Comparison of simulation results in the SIMULINK package with measurement results

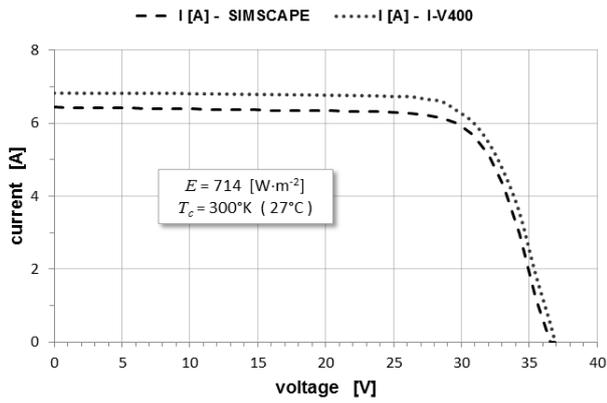


Fig. 9. Comparison of simulation results in the SIMSCAPE with measurements result

$$\eta = \frac{I_{MPP} \cdot V_{MPP}}{E \cdot S} \cdot 100 \quad [\%] \quad (10)$$

where:

S – PV module Surface (according to tab. 1) [m²].

For calculations of efficiency(η) of PV module one adopted the surface of $S=1.624 [m^2]$, which was indicated on the basis of measurements of PV module provided by the manufacturer (Tab. 1).

$$FF = \frac{I_{MPP} \cdot V_{MPP}}{I_{SC} \cdot V_{OC}} \cdot 100 \quad [\%] \quad (11)$$

Interpretation of the fill factor (FF) of the I-V characteristic is such that it is a measure of deviation from the ideal characteristic which is not obtainable (100%). In practice it is assumed that FF values above 75% are considered optimal and are often a measure of the quality of PV modules. Interpretation of the influence of the shape of the I-V curve on the value of the FF coefficient is presented in Fig. 10.

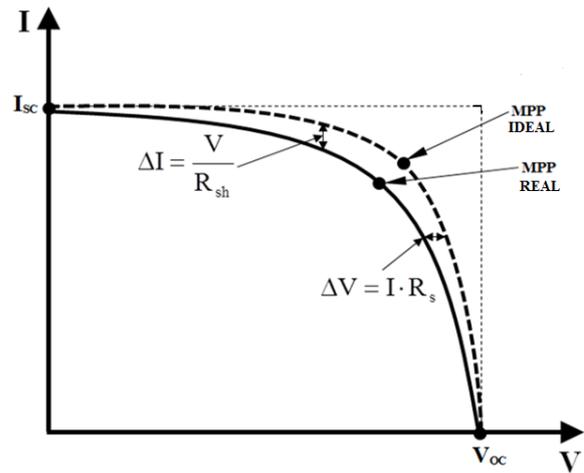


Fig. 10. Influence of resistances R_s and R_{sh} on the shape of I-V characteristics of the real cell PV [7]

The measurement of the results of the simulation with the measurement results are the calculated relative errors (δ), which are given in the last two columns of tab. 2. Simulation results in the Simulink and Simscape packages were compared with the results of the measurement with the I-V 400 meter.

CONCLUSIONS

1. The Simscape simulator model is less complicated than the Simulink diagram and requires no knowledge of detailed equations of the mathematical model, using the ready „PV array” component.
2. In both cases, the maximum power simulation results were lower than the I-V measurement results.
3. The smallest differences occurred when comparing the neutral voltage of the cell (V_{OC}) and in both compared cases the relative verification errors were less than 1%.

Table 2. Simulation results and their verification with the measurement results

Parameters:	Results of simulation in SIMULINK package	Results of simulation in SIMSCAPE package	Results of measurements with I-V 400 meter	Relative error $\delta_{SIMULINK}$ [%]	Relative error $\delta_{SIMSCAPE}$ [%]
I_{SC} [A]	6.39	6.44	6.83	6.44	5.71
V_{OC} [V]	36.57	36.56	36.91	0.92	0.95
I_{MPP} [A]	5.97	5.99	6.59	9.41	9.10
V_{MPP} [V]	29.72	29.71	28.57	4.03	3.99
P_{MPP} [W]	177.43	177.96	188.28	5.76	5.48
FF [%]	75.93	75.59	74.68	1.66	1.21
η [%]	15.30	15.35	16.24	5.76	5.48

4. The largest discrepancies were observed in the verification results for the current at the maximum power point (I_{MPP}). In both cases, relative verification errors exceeded 9%.
5. The coefficients of the current-voltage characteristics (FF) obtained from simulation calculations were higher in both cases (above 75%) than those measured with the meter. The interpretation shown in Fig. 10 suggests that higher resistance values should be used in simulation calculations R_{sh} .
6. The efficiencies calculated for the results of simulation and the meter measurements were lower than those reported by the manufacturer (17.2% according to Table 1).
7. Simulation models developed in the paper well reflect the current and voltage characteristics, and the differences revealed can be minimized with more real parameters of the PV module.
8. The next stage of the simulation study will be the construction and verification of the dual-diode PV model shown in Fig. 2.

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