

BULETINUL INSTITUTULUI POLITEHNIC DIN IAȘI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iași
Tomul LXI (LXV), Fasc. 3, 2015
Secția
CONSTRUCȚII. ARHITECTURĂ

FIVE PARAMETER MODEL OF PHOTOVOLTAIC PANEL IMPLEMENTED IN MATLAB/SIMULINK

BY

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Received: August 27, 2015

Accepted for publication: September 14, 2015

Abstract. The implementation of mathematical model of photovoltaic cell into specialized software Matlab-Simulink is presented. The equivalent model used for photovoltaic cell was the simple diode, with five parameters, taking into account both shunt and series resistances. The computing model is realized by using the equations for the following parameters: thermal voltage, photovoltaic current, diode saturation current and ideality factor. The study is realized on a polycrystalline photovoltaic panel, with 30 Wp maximum power. Therefore, the main characteristics are obtained, such as the variation of the output power, depending on the voltage and current of the PV panel, or the variation of the current with the voltage.

Key words: photovoltaic panel; equivalent circuit; IV curve; simple diode model.

1. Introduction

The analysis of the photovoltaic (PV) cells is realized using models based on simplified equivalent electric circuits (Cubas *et al.*, 2014). According

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to these, there are obtained some important information concerning the electric outputs like current, voltage and power of the PV cell. The mathematical model is based on the assumption that the photovoltaic cell, which is a semiconductor device, is operating like a diode, when it is not exposed to the light (<http://pveducation.org>). These simplified models are defined as: ideal model, simple diode model and double diode model (Elbasit *et al.*, 2013; Petreus *et al.*, 2008). Regarding the present work, the simple diode model is analysed.

The purpose of mathematical modelling of photovoltaic cells consist in obtaining high accuracy characteristic curves (Fig. 1), but also the values of the electrical parameters of the PV panel in different external conditions.

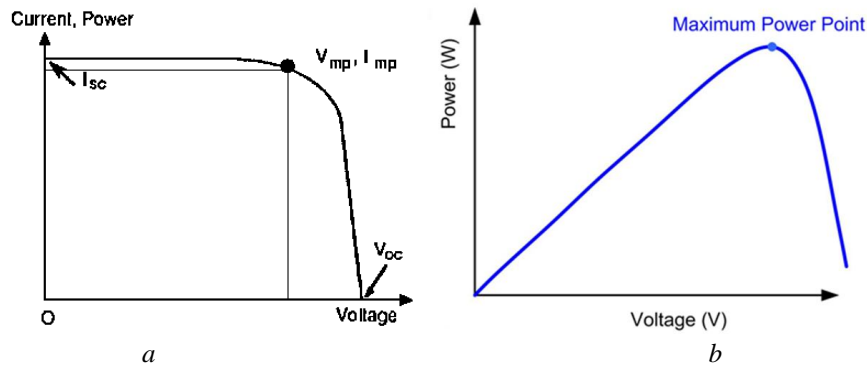


Fig. 1 – a – IV Curve of a PV cell (Petreus *et al.*, 2008);
 b – PV Curve of a PV cell (<http://www.re-innovation...>).

Ideal model (simple diode)

The equivalent circuit, Fig. 2, is represented by a source of electricity in parallel with a diode. This model is not very accurate, but is a simple one, which could yield a general overview of the phenomena inside PV cell.

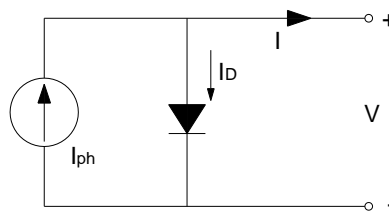


Fig. 2 – Equivalent circuit for ideal model of PV cell.

The following assumptions are considered for this model: $R_s = 0$ and $R_{sh} = \infty$, $I_{ph} = I_{sc}$.

Simple diode model with R_s

In real operating conditions, there are electric circuits in series with the PV cell that have a certain electric resistance, R_s . This model was developed to

model this resistance and it is more accurate than the ideal one, but it is not a comprehensive one.

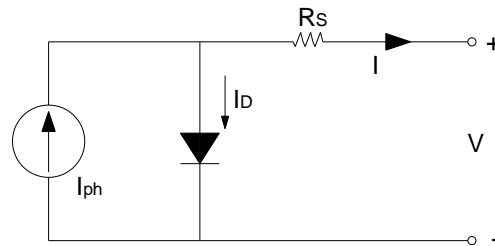


Fig. 3 – Equivalent circuit of PV cell model with R_s .

This circuit is also known as the four parameter model for PV cell (Aparicio *et al.*, 2013).

Simple diode model with R_s and R_{sh}

The model with R_s and R_{sh} it is the most spread model for simulating the operation of photovoltaic panels (Bellia *et al.*, 2014). This model takes into account both series resistance R_s and the other resistance of the PV cell, the shunt one, R_{sh} . Using this model, the more realistic results are obtained (Aparicio *et al.*, 2013).

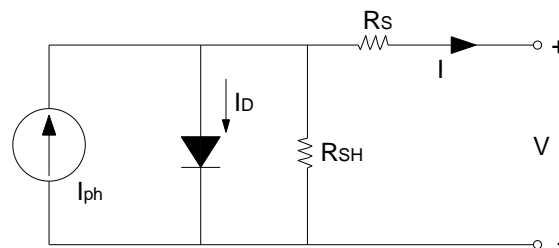


Fig. 4 – Equivalent circuit of PV cell model with R_s and R_{sh} .

The value for the output current of the PV cell is determined with the following expression:

$$I = I_{ph} - I_d - I_{sh}, \text{ [A]}, \quad (1)$$

Taking into account the expressions for the I_d - Eq. 2 and I_{sh} - Eq. 3, the Eq. 1 can be solved. Therefore, the intensity of electric current produced by photovoltaic cell to the load has the characteristic equation - Eq. 4.

$$I_d = I_0 \left[\exp \frac{q(V + R_s I)}{nKT_{op}} - 1 \right], \text{ [A]}, \quad (2)$$

$$I_{sh} = \frac{(V + R_s I)}{R_{sh}}, \text{ [A]}, \quad (3)$$

$$I = I_{ph} - I_0 \left[\exp \frac{q(V + R_s I)}{nKT_{op}} - 1 \right] - \frac{(V + R_s I)}{R_{sh}}, \text{ [A]}. \quad (4)$$

Eq. 4 can be simplified in case of high R_{sh} values, over 100 k Ω . Moreover, the photovoltaic current I_{ph} could be considered equal to short-circuit current I_{sc} . By applying these assumptions for the standard test conditions, Eq. 4 becomes:

$$I = I_{ph} - I_0 \left[\exp \frac{q(V + R_s I)}{nKT_{op}} - 1 \right], \text{ [A]}. \quad (5)$$

For the same hypothesis, the open circuit voltage of the cell can be determined:

$$V_{oc} \cong \frac{nKT_{op}}{q} \ln \left(\frac{I_{ph}}{I_0} + 1 \right), \text{ [V]}. \quad (6)$$

Effect of solar radiation

The intensity of solar radiation has the most important effect on the electric power generated by photovoltaic cells (Meral & Dincer, 2011). The variation of solar radiations determines a change of photovoltaic current produced I_{ph} (www.lstdiode.com).

$$I = \left[I_{sc} + K_i (T_{op} - 298.15) \right] \frac{G}{1,000}, \text{ [A]}. \quad (7)$$

Effect of the cell temperature

The operating temperature of the PV cell, T , is another important parameter that affects the output power (Meral & Dincer, 2011). Thus, its effect is noticed on the reversed saturation current, I_0 , and open circuit voltage, V_{oc} .

The reverse saturation current of diode is dependant with a cubed function of the temperature (Jafari *et al.*, 2011):

$$I_0(T) = I_0 \left(\frac{T}{T_{nom}} \right)^3 \exp \left[\left(\frac{T}{T_{nom}} - 1 \right) \frac{E_g q}{NV_t} \right], \text{ [A]}. \quad (8)$$

The open circuit voltage varies with temperature according to the following law:

$$V_{oc}(T) = V_{oc}(T_{nom}) - B(T - T_{nom}), \text{ [V]}. \quad (9)$$

Effect of series resistance - R_s

Once the series resistance is growing, the voltage drop between the junction and the terminals is raising for the constant intensity of the current. The result consist of an important drop of terminal voltage, while the influence over short-circuit is insignificant (Ghani *et al.*, 2013). In the case of very high R_s , the PV cell tends to behave like a resistor.

Loss of power determined by R_s can be determined with Eq. 10:

$$P_{loss} = V_{R_s} I = I^2 R_s. \quad (10)$$

This loss of power is dependent on the photocurrent, being greater for high levels of solar radiation (www.wikipedia.org).

The reducing of the fill factor (FF) depending on the total series resistance can be also calculated:

$$\Delta FF = \frac{-I_{sc}}{V_{oc}} R_s \times FF_{ideal}, \quad (11)$$

where, $FF_{ideal} = 0,824$ (Meier *et al.*, 2006).

Effect of shunt resistance - R_{sh}

While the shunt resistance is decreasing, the electric current deflected through it is raising for certain levels of voltage (Ghani *et al.*, 2013). The result consists in a significantly reduce of the terminal current as well as a small reduction of the V_{oc} . Similar to the case with high series resistance, a PV cell with low shunt resistance operates like an resistor.

Reverse saturation current

The reverse saturation current, I_0 , represents a measure of the circulation of charge carriers along $p-n$ junction in reversed way. The leakage is determined by the charge carrier recombination phenomenon into the neutral zone, on both sides of junction (<http://pveducation.org>).

When the current, I_0 , is high, the open circuit voltage, V_{oc} , reduces proportionally with the reverse of the raising logarithm (www.wikipedia.org). On the other hand, the functioning of a real diode is subjected to recombination effects of the charge carriers. This phenomenon is not described very precisely by the simple diode model, another term being used, ideality factor, n .

The equation for ideal model of diode, assumes that all recombination occur in the mass of the cell and not in the junction zone. Actually, this recombination is also developing in other zones of the cell, which generates ideality factors above 1. Practically, the raise of ideality factor determines a decrease of the produced voltage (<http://pveducation.org>).

However, it has been demonstrated (www.wikipedia.org) that the vast majority of photovoltaic cells made of silicon, being bigger than a conventional diode, behave like an ideal one ($n \approx 1$), with the approximation that the p-n junction is an infinite plane (www.wikipedia.org).

Moreover, the entire behaviour of the photovoltaic panel can be modelled when I_{ph} , I_0 , R_s and R_{sh} are known, together with two external parameters, solar radiation and operating temperature of the cell.

2. Problem Description

The study presents a method for modelling the operation of photovoltaic panels using Simulink application of MATLAB software. The simulation is realized by implementing the mathematical model of “simple diode with R_s and R_{sh} ”. For the present study a photovoltaic panel model NPA 30-12 SLIM ([www.ebay.com/...](http://www.ebay.com/)), made of polycrystalline silicon was considered, composed of 36 cells connected in series. The following characteristics of the PV panel, measured in standard test conditions (STC), were used ([www.ebay.com/...](http://www.ebay.com/)):

$$P_{MPP} = 30 \text{ W};$$

$$V_{MPP} = 17.4 \text{ V};$$

$$I_{MPP} = 1.74 \text{ A};$$

$$V_{oc} = 21.6 \text{ V};$$

$$I_{sc} = 1.94 \text{ A};$$

$$T_{NOCT} = 47 \text{ }^\circ\text{C};$$

$$\text{Temperature coefficient of } P_{MPP}: 0.48\%/^\circ\text{C};$$

$$\text{Temperature coefficient of } V_{oc}: 0.34\%/^\circ\text{C, approximate } -80.5 \text{ mV}/^\circ\text{C},$$

for the studied panel;

$$\text{Temperature coefficient of } I_{sc}: +0.037\%/^\circ\text{C};$$

$$\text{Efficiency: } \eta = 14.1 \text{ } \%$$

Therefore, the fill factor (FF) of PV panel is:

$$FF = \frac{P_{MPP}}{V_{oc} I_{sc}} = 0.72. \quad (12)$$

3. Numerical Modelling

The mathematical model, eqs. 1,...,12, was solved in Simulink computing environment, as interconnected blocks and subsystems. The blocks used for creating the model are: constant, step, ramp, blocks for graphical plotting and mathematical operators.

In order to obtain a stable simulation, the model was split on the following sections: input data: G , T_{op} , T_{nom} , n , V_{oc} , I_{sc} , R_s , R_{sh} and V_{PV} ; subsystem for mathematical model of PV cell; output data: I_{PV} , P_{PV} .

The block diagram is presented in Fig. 5.

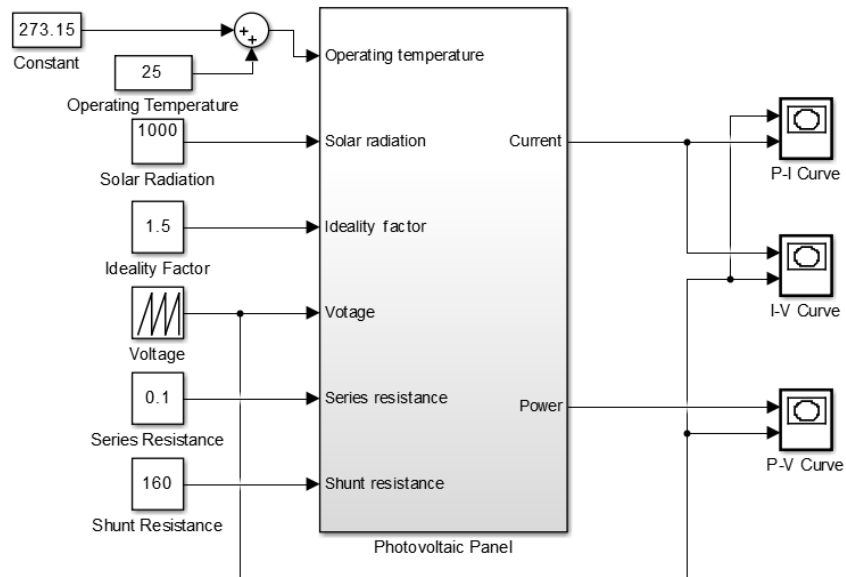


Fig. 5 – Block diagram of PV panel – MATLAB/Simulink.

4. Results

Results of simulation consist of the characteristic curves of operation for studied photovoltaic panel. Also, as a result of simulation, all the calculated parameters can be monitored: I_0 , I_{ph} , V_T or I_{sh} . The IV, PV and PI characteristics are presented in Fig. 6.

Table 1
Comparative analysis between producer data sheet and results of simulation

Parameter	Specification sheet	Results from model	Match, [%]
P_{max} , [W]	30	30.02	99.9
V_{mpp} , [V]	17.4	17.62	98.7
I_{mpp} , [A]	1.74	1.72	98.8
P_{NOCT} (W)	21	20.85	99.2

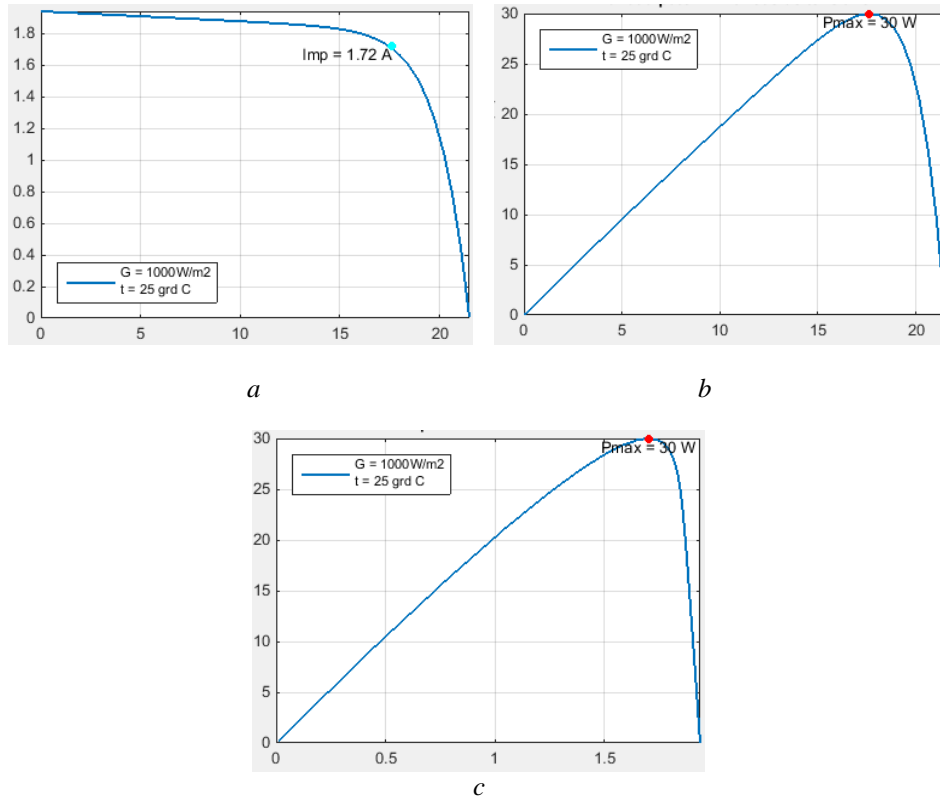


Fig. 6 – *a* – IV Curve of studied PV panel; *b* – Variation of the output power depending on the voltage; *c* – Variation of the output power depending on the current.

5. Conclusions

The high level of precision of the created model can be noticed. The maximum power produced by PV panel is about 30 W, at parameters near the values presented by the producer: $I = 1.72 \text{ A}$ and $U = 17.62 \text{ V}$ (Table 1). Simulation of PV panels by using Simulink software represents a viable solution for evaluating the operation in different external conditions. The present model can be also used as an accurate tool for determining the conversion efficiency of PV panels and cells.

Nomenclature

I_{ph} – photocurrent produced by PV cell, [A];
 I_0 – reverse saturation current of diode, [A];

q – Electric charge of electron, [C];
 V – Voltage on diode terminal, [V];
 k – Boltzmann constant, $k = 1.38 \times 10^{-23} \text{ J.K}^{-1}$;
 T_{op} – operating temperature of the junction, [K];
 n – ideality factor;
 R_s, R_{sh} – series and shunt resistances, [Ω];
 K_i – temperature coefficient of I_{sc} , $K_i = 0.0017 \text{ A}/^\circ\text{C}$;
 G – Intensity of solar radiation, [W/m^2];
 T_{nom} – nominal operating temperature of the PV cell, [K];
 E_g – band gap of semiconductor. [eV];
 $V_t = \text{KT}/q$ – thermal voltage, [V];
 B – Temperature coefficient of V_{oc} , [$\%/^\circ\text{C}$];
 FF – fill factor;
 FF_{ideal} – ideal fill factor;
 STC – standard test conditions: $G = 1000 \text{ W}/\text{m}^2$, $T_{cell} = 25 \text{ }^\circ\text{C}$, $AM = 1.5$ (IEC Standard);
 P_{max} – maximum power output, [W];
 I_{MPP} – intensity of the output current at P_{max} , [A];
 V_{MPP} – voltage output at P_{max} , [V];
 P_{NOCT} – output power of PV panel for NOCT, [W];
 NOCT – nominal operating cell conditions: $G = 800 \text{ W}/\text{m}^2$, $v = 1 \text{ m/s}$, $T_{air} = 20^\circ\text{C}$ (IEC Standard).

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MODEL CU CINCI PARAMETRI AL PANOURILOR FOTOVOLTAICE IMPLEMENTAT ÎN MATLAB/SIMULINK

(Rezumat)

Se prezintă implementarea modelului matematic al funcționării celulelor fotovoltaice în softul specializat Matlab-Simulink. Modelul electric echivalent al celulei fotovoltaice utilizat în studiu este cel al simplei diode cu cinci parametri, cu rezistență de șuntare și rezistență serie. În calcul sunt incluse ecuațiile ce descriu tensiunea termică, curentul generat prin efect fotovoltaic, curentul de saturație al diodei, precum și factorul de idealitate. Studiile sunt realizate pentru un panou fotovoltaic policristalin, de putere maximă 30 W. Rezultatele constau în obținerea graficului de variație al puterii panoului în funcție de curent și tensiune, precum și a curbei caracteristice U-I.