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Solar cell parameters extraction optimization using Lambert function

Abstract. *Solar cells are characterized by internal electrical parameters not displayed by the manufacturer. Their identification is necessary because it allows the photovoltaic system simulation and optimization. Currently, the new and simple extraction methods development is a challenge for researchers. In this work, a new approach is presented for exact determination the single-diode model multi-crystalline silicon cell five parameters. Our method consists in calculating the parameters from the ideality factor estimation using the Lambert function and the parasitic resistances curve (series and shunt). Absolute and relative errors are also calculated to show the proposed method importance over another method.*

Streszczenie. *W artykule zaprezentowano mtodę opisu matematycznego obwodu fotowoltaicznego. Metoda polega na opisie parametrów z wykorzystaniem funkcji Lamberta. . Określono błąd przybliżenia tego modelu matematycznego.* ***Opis parametrów ogniwa fotowoltaicznego z wykorzystaniem funkcji Lamberta.***

Keywords: Parameter extraction, solar cell models, Lambert function, the ideality factor
Słowa kluczowe: ogniowo fotowoltaiczne, funkcja Lamberta

Introduction

Solar is an emerging sustainable technology with immense potential to contribute largest investment in Green technology applications. The photovoltaic solar energy is one of the most used and promising resources in the renewable energy domain. The photovoltaic energy conversion is performed by cells based on semiconductors such as silicon, which exploits the photovoltaic effect. The these cells operation cells is described generally by the I-V characteristic which provides the information on the intern electric transport mechanisms and the technological steps imperfections of their fabrications [1-3].

The photovoltaic (PV) systems modeling has been the subject studies many recent, especially with the extension of use PV systems in different applications. The single-diode model cell solar was first used by Shockley in 1949 [4, 5] and has since been used in many other research and applications. This equivalent circuit model is based on five main parameters to be determined.

The these parameters precise determination remains a challenge for the researchers, in fact, this determination is essential for the simulation, the quality control and the photovoltaic devices implementation answering to well-defined specifications [6]. These parameters also play an important role in the manufacturing processes optimization [7].The current in the Shockley equation is an implicit function; it includes dependent and independent variables at the same time. Implicit nature presents opposites to extract these parameters. An explicit analytic expression can be obtained using Lambert W [8-16].

In order to overcome these constraints that prevent the electrical parameters extraction, a new method is presented in this work. In its first part, the parameters are calculated using the Lambert function for different estimated values of the ideality factor in the interval [1-1.5], while the second part consists in determining graphically the best estimated the ideality factor value to extract these parameters taking into account only the resistances values . The method has been tested on a multi-crystalline MSX-83 commercial module.

Photovoltaic System Modeling

The photovoltaic cell acts in the most popular models as a current source connected in parallel with a diode (ideal case) and completed with a shunt and series resistors losses [17-20].

The this circuit behavior of Fig. 1 is given by the Shockley equation (1), the internal parameters I_{PV}, I_O, R_S, R_P and m characterizing this system are unknowns to be determined. I_{PV} is the photocurrent, I_O is the reverse saturation current corresponding to the diode, R_S is the series resistance, R_P is the shunt resistance and m is the ideality factor of the diode.

I: Current and V: Voltage

(1) $$\mathrm{I = I_{pv} - I_0 \left[\exp\left(\frac{V+IR_s}{mV_T}\right) - 1\right] - \frac{V+IR_s}{R_p}}$$

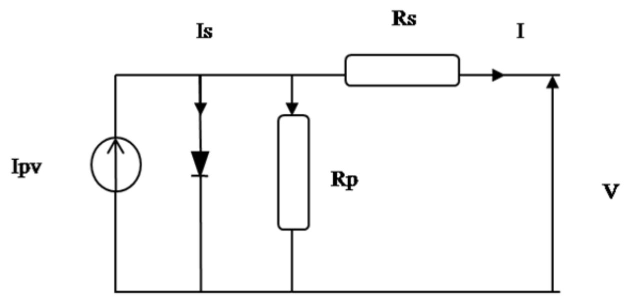

Fig.1. Single diode model of solar cell

The five internal parameters listed above that specify the solar cell must be calculated using only the data from the commercial product manufacturer.

Equation (2) represents the diode thermal voltage $\mathrm{V_T}$ which depends on the temperature T, the Boltzmann constant K, the electron charge q and the number of cells in series N.

(2) $$V_T = N\frac{KT}{q}$$

Photovoltaic System Parameters Extraction

Consider our five-parameter model, which will be evaluated at three operating points on the curve of Fig. 2.

The short-circuit operating point when $\mathrm{V} = 0$

(3) $$I_{sc} = I_{pv} - I_0\left[exp\left(\frac{I_{sc}R_s}{mV_T}\right) - 1\right] - \frac{I_{sc}R_s}{R_p}$$

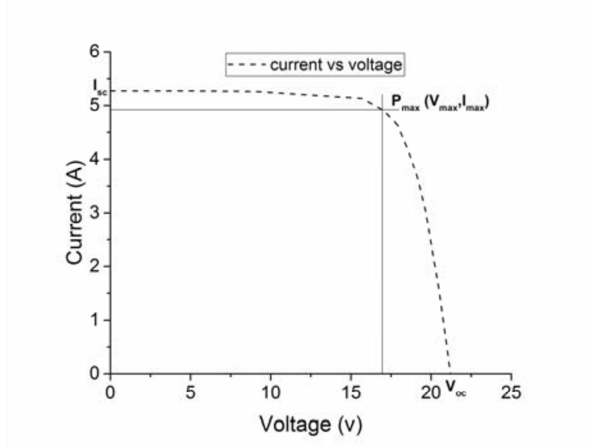

Fig.2. The I-V curve of a solar panel

The open-circuit operating point, $\mathrm{V}=\mathrm{V_{OC}}$ and $\mathrm{I}=0$

(4) $0 = I_{pv} - I_0\left[exp\left(\frac{V_{oc}}{mV_T}\right)-1\right] - \frac{V_{oc}}{R_p}$

The maximum power operating point, $\mathrm{V}=\mathrm{V_{mp}}$ and $\mathrm{I}=\mathrm{I_{mp}}$

(5) $I_{mp} = I_{pv} - I_0\left[exp\left(\frac{V_{mp}+I_{mp}R_s}{mV_T}\right)-1\right] - \frac{V_{mp}+I_{mp}R_s}{R_p}$

(6) $\frac{\partial P}{\partial V} = V\frac{\partial I}{\partial V} + I = 0$

The maximum power point, the power derivative with respect to voltage is zero.

Imposing the peak power condition (P = 0) to the equation above, the following expression is obtained [21, 22]:

(7) $\left.\frac{\partial I}{\partial V}\right|_{[I_{mp},V_{mp}]} = -\frac{I_{mp}}{V_{mp}}$

The first derivative of equation (1) with respect to voltage is:

(8) $\frac{dI}{dV} = -\frac{I_o}{mV_T}\left(1+\frac{dI}{dV}R_S\right)\left[exp\left(\frac{V+IR_S}{mV_T}\right)\right] - \frac{1}{R_P}\left(1+\frac{dI}{dV}R_S\right)$

The second term on the equation (3) right side can be neglected [21, 23]:

(9) $I_{pv} = \frac{R_p+R_s}{R_p}I_{sc}$

From equations (4) and (9), the saturation current can be reduced to [24]:

(10) $I_0 = ((R_p+R_s)I_{sc} - V_{oc})/R_p\, exp\left(\frac{V_{oc}}{mV_T}\right)$

The following expression can be derived from Equations (5), (9) and (10) [23]:

(11) $I_{SC} - \left(I_{SC} - \frac{V_{OC}-R_SI_{SC}}{R_P}\right)\left[exp\left(\frac{V_{mp}+I_{mp}R_{S-}\ V_{OC}}{mV_T}\right)\right] - \frac{V_{mp+}I_{mp}-I_{SC}R_S}{R_P} = I_{mp}$

From equations (9), (10) and (11) an implicit expression series resistance $\mathrm{R_S}$ is obtained:

(12) $\frac{mV_T\,V_{mp}\,(2I_{mp}-I_{SC})}{(V_{mp}I_{SC}+V_{OC}(I_{mp}-I_{SC}))(V_{mp}-I_{mp}R_S)-mV_T\,(V_{mp}I_{SC}-V_{oc}I_{mp})} = exp\left(\frac{V_{mp}+I_{mp}R_S-V_{oc}}{mV_T}\right)$

The $\mathrm{R_p}$expression results from the combination of equations (11) and (12):

(13) $R_p = \frac{(V_{mp}-I_{mp}R_s)(V_{mp}+R_s(I_{sc}-I_{mp})-aV_T)}{(V_{mp}-I_{mp}R_s)(I_{sc}-I_{mp})-aV_TI_{mp}}$

The implicit equation (12) resolution requires a transformation to an explicit equation using the Lambert (w) function to determine the $\mathrm{R_S}$ series resistance of the equivalent circuit [24]:

The Lambert W-function, W(z) , is defined as:

(14) $z = W(z)e^{W(z)}$

where z is any complex number

The Lambert W function consists of two branches, the main $W_0(x)$ and the secondary $W_{-1}(x)$ which is defined as follows:

(15) $W(x) = \begin{cases} Wo(x),\ x \geq -1 \\ W-1(x),\ x \leq -1 \end{cases}$

The function w Lambert is not injective because on the domain:

- [-1/e, 0], the real variable x of $W(x)$ has a single image.
- $x\ \geq$ -1 / e, the real variable x of $W(x)$has two images.

The usual technique that allows us to apply Lambert's W function in solving exponential equations is to use the equivalence below:

(16) $x = Ye^Y \leftrightarrow$Y= $W(x)$

Joining the the parameters expressions finalization to be extracted, equation (12) can be written

(17)

$$-\frac{V_{mp}\,(2I_{mp}-I_{SC})}{(V_{mp}I_{SC}+V_{OC}(I_{mp}-I_{SC}))}\exp\left(-\frac{2V_{mp}-V_{OC}}{mV_T}+\frac{V_{mp}I_{SC}-V_{oc}I_{mp}}{V_{mp}I_{SC}+V_{OC}(I_{mp}-I_{SC})}\right) = \left(\frac{I_{mp}R_S-V_{mp}}{mV_T} + \frac{V_{mp}I_{SC}-V_{oc}I_{mp}}{\left(V_{mp}I_{SC}+V_{OC}(I_{mp}-I_{SC})\right)}\right)exp\left(\frac{I_{mp}R_S-V_{mp}}{mV_T} + \frac{V_{mp}I_{SC}-V_{oc}I_{mp}}{\left(V_{mp}I_{SC}+V_{OC}(I_{mp}-I_{SC})\right)}\right)$$

Using the equation (16), the expression (17) becomes:

(18) $$\frac{I_{mp}R_S-V_{mp}}{mV_T} + \frac{V_{mp}I_{SC}-V_{oc}I_{mp}}{V_{mp}I_{SC}+V_{OC}(I_{mp}-I_{SC})} = W_{-1}\left(-\frac{V_{mp}\,(2I_{mp}-I_{SC})}{\left(V_{mp}I_{SC}+V_{OC}(I_{mp}-I_{SC})\right)}exp(-\frac{2V_{mp}-V_{OC}}{mV_T} + \frac{V_{mp}I_{SC}-V_{oc}I_{mp}}{V_{mp}I_{SC}+V_{OC}(I_{mp}-I_{SC})})\right)$$

From equation (18) we obtain the series resistance explicit expression of the equivalent circuit:

(19)

$$R_{S=}\frac{mV_T}{I_{mp}}\left(W_{-1}\left(-\frac{V_{mp}\,(2I_{mp}-I_{SC})}{(V_{mp}I_{SC}+V_{OC}(I_{mp}-I_{SC}))}\right) * exp\left(-\frac{V_{mp}I_{SC}-V_{oc}I_{mp}}{V_{mp}I_{SC}+V_{OC}(I_{mp}-I_{SC})} - \frac{V_{mp}-V_{OC}}{mV_T} + \frac{V_{mp}I_{SC}-V_{oc}I_{mp}}{V_{mp}I_{SC}+V_{OC}(I_{mp}-I_{SC})}\right)\right)$$

Estimation of the diode ideality factory

By estimating this parameter, it is possible to determine the four parameters values in the following order: series resistance, shunt resistance, saturation current and the current photo in the expressions (19), (13), (10) and (9).

Concerning the fifth parameter the diode ideality factor of the equivalent circuit, many authors have discussed the means the correct value choosing for this constant, but usually it is selected between [1-1.5] according to [24-26].

The our work purpose is to extract the circuit parameters accurately based on a better estimate the ideality factor value in the above-mentioned range.

Case study

An MSX-83 PV module is selected to test the proposed method since its I-V data measured at STC is available as a spreadsheet. The solar module is built from 36 multi-crystalline photovoltaic cells (with the assumption that all 36 cells are identical). This is a product of Solarex/BP Solar.

Table 1. The manufacturer's data sheet

Typical Electrical Characteristics	MSX-83
Maximum power (Pmax)	83W
Voltage at Pmax (Vmp)	17.1V
Current at Pmax (Imp)	4.85A
Short-circuit current (Isc)	5.27A
Open-circuit voltage (Voc)	21.2V

The four parameters are extracted Table 1 using the electrical specifications provided by the manufacturer's data sheet Table 2 for values of the ideality factor included in the domain already mentioned for standard environmental conditions (STC G=1KW/m2 and T=25°C)

From the results in Table 2, we note that for each value of m estimated:

- ❖ $I_{pv} \approx I_{SC}$.
- ❖ The series resistance is too low compared to the shunt resistance

On the other hand, we recorded a significant variation of the parameters R_S, R_P and Io for the extreme values m = 1.1 and m = 1.5 Table 3.

Table 2. The parameters extracted for the ideality factor estimated

m	$R_S(\Omega)$	$R_P(\Omega)$	$I_0(\mu A)$	$I_{pv}(A)$
1.10	0.252	146	4.50E-03	5.27
1.20	0.216	187	2.57E-02	5.27
1.30	0.180	260	1.13E-01	5.27
1.40	0.146	432	3.99E-01	5.27
1.50	0.113	1130	1.20	5.27

Table 3. The parameters variations R_S, R_P and Io

Parameter	m=1.1	m=1.5
$R_S(\Omega)$	0.252	0.113
$R_P(\Omega)$	146	1130
$I_0(\mu A)$	4.50E-03	1.20

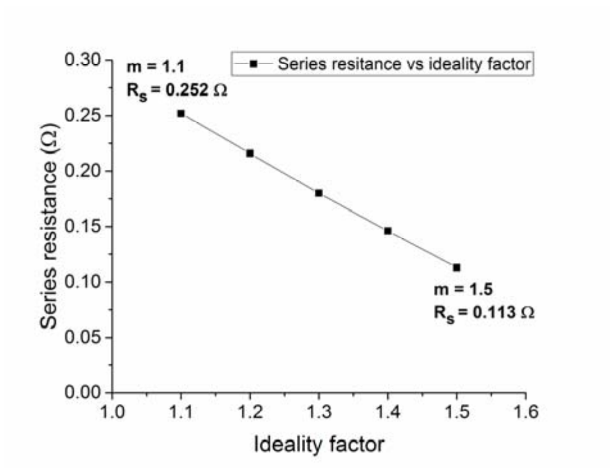

Fig.2. (a) Variation of resistance series R_S

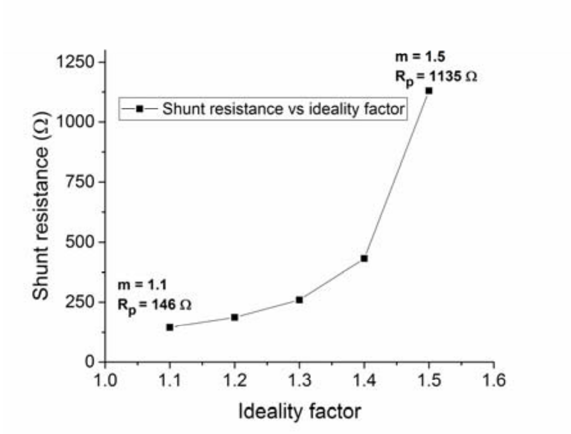

Fig.2. (b): Variation of resistance shunt R_P

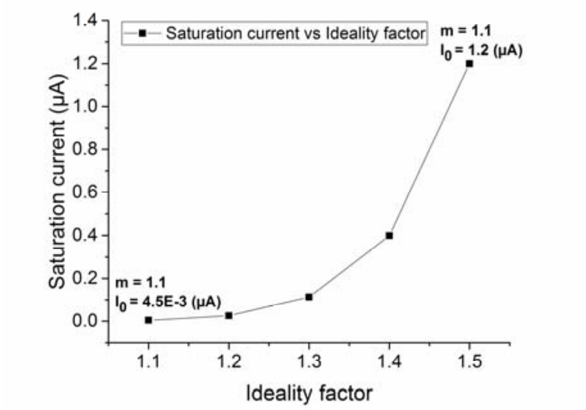

Fig.2. (c): Variation of the saturation current I_0

For our new approach, the determination of the best value of m among the five estimates is based on the graphical research of this point using the curves of parasitic resistance variations (series and shunt) Fig. 3. (a) and Fig. 3. (b) For this it is necessary to:

- ❖ Divide the values of the series and shunt resistors of the MSX-83 module found by N = 36 (number of cells connected in series) to have the cell-specific resistances.
- ❖ Multiply the values of the series resistors by 1000 to have the same order of magnitude with the values of the shunt resistors. Table 4
- ❖ Draw the two curves on the same graph.Fig.4

Table 4. (b). The new values of the series resistance (1000 *r_s)

m	1000*$r_s(\Omega)$	$r_p(\Omega)$
1.10	7.00	4.05
1.20	6.00	5.19
1.30	5.00	7.22
1.40	4.06	12.00
1.50	3.14	31.38

r_S: Series resistance of the cell r_P: Shunt resistance of the cell

The these two curves intersection zone in Fig. 3. which corresponds to an ideality factor m = 1.2 is considered as the optimal zone, since the intersection point which must be precisely located represents the optimal point Pop whose abscissa is the best solution of m

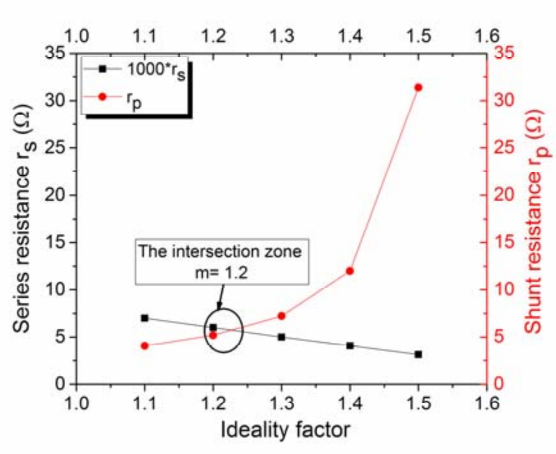

Fig.3. The curves 1000*r_s and r_p according to the ideality factor

Table 5. Extraction of parameters in the domain m [1.17-1.24]

m	r_s(mΩ)	r_p(Ω)	I_0(A)	I_{pv}(A)
1.17	6.32	4.56	1.53E-08	5.27
1.18	6.22	4.91	1.82E-08	5.27
1.19	6.12	5.06	2.41E-08	5.27
1.20	6.03	5.23	2.57E-08	5.27
1.21	5.93	5.38	3.10E-08	5.27
1.22	5.81	5.56	3.67E-08	5.27
1.23	5.71	5.74	4.43E-08	5.27
1.24	5.61	5.95	4.60E-08	5.27

To do this and to optimize the equivalent circuit parameters extraction, we have:

- ❖ Calculate parasitic resistances (series and shunt) for ideality factor values in the neighborhood of m = 1.2 in the range [1.17-1.24] Table5.
- ❖ Determine graphically with an accuracy of 1/10000 near this Pop point in this curve region using Origin Pro Version 9 software (see Fig. 4).

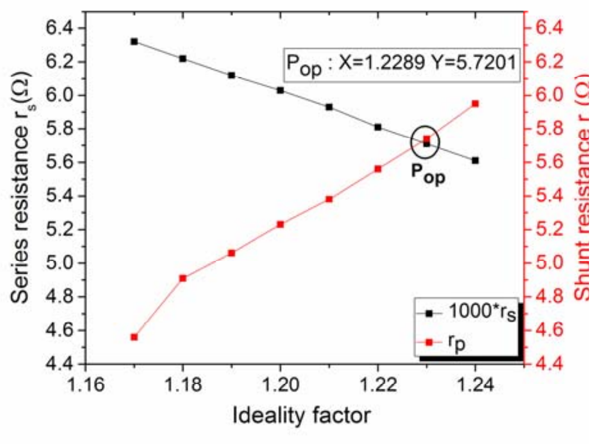

Fig.4. Exact graphical determination of the Pop point

It should be noted that the graphically extracted series resistance value is obtained by dividing by 1000, so that it regains its initial and actual value.

The data analysis and visualization in Fig. 4 allowed us to locate the Pop point and to determine its coordinates: X = m = 1.2289 Y = 1000 * r_s = r_p = 5.7201Ω

The graphically values parameters extracted m, r_s and r_p are replaced in equations (9) and (10) to calculate I_0 and I_{pv}: I_0 = 3.84E-08A I_{pv} = 5.2752A

Table 6. Comparison of results

Method	m	r_s(mΩ)	r_p(mΩ)	I_0(μA)	I_{pv}(A)
Present Method	1.2289	5.72	5720.1	3.84E-02	5.27
Method[27]	1.1886	5.30	4800.0	2.16E-02	5.27
Error	0.0403	0.42	920.1	1.68E-02	0.00
Relative error %	3.27	7.92	19.16	43.75	0.00

In Table 6, we compared the results achieved using our approach and those of the method [27].

Results and discussions

It can be seen in Table 2 that the shunt resistors values are of the order of 1000 relative to the series resistors.

In Table 3, the ideality factor variation on the domain [1.1-1.5] causes significant variations in the series resistance, the shunt resistor and the saturation current.

The parameters variations (r_S,r_p and I_0) become smaller in the intersection zone of the parasitic resistance curves or m varies between [1.17-1.24] in Table 5.

Table 6 provided us with information on the proposed method precision by comparing with the results recorded in [27].

Conclusion

This work was done to optimize the solar cell internal parameters extraction. In this article, it has been proved that it is sufficient to have the electrical specifications provided by the manufacturer's data sheet, to extract the five parameters of the equivalent circuit model chosen for the solar cell representation .The Lambert-W function allowed us to develop explicit expressions for parameter extraction (R_S,R_p ,I_0 andI_{pv}), thus bypassing the constraints and problems related to the Shockley's equation implicit nature. As for the graphical determination of the best estimated ideality factor value which is essentially based on the parasitic resistances intersection (after having placed them of the same order of magnitude), starting with a wider domain varying between [1.1-1.5] passing through the reduced optimum zone varying between [1.17-1.24] until reaching the optimum value m = 1.2289.

The performances developed by the new approach are very encouraging in accuracy terms by comparing with the method [27] knowing that we have recorded:

- ❖ A relative error of 3.27% for the ideality factor estimation.
- ❖ Relative errors of 7.92%; 19.16%; 43.75% and 0.00% respectively for extractionR_S,$R_{p,}I_0$ andI_{pv}.

The proposed method is direct, precise and non-iterative.

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