Theoretical study of Hybrid solar cell parameters evaluation from I-V characteristics

N. NEHAOUA[1,2]*, I. AMI[1,3], F. MEBTOUCHE[1,2], H. MEZIANI[1,2], S.H. ABAIDIA[1,2]

[1] Faculty of Science, Physics Department, University M'Hamad Bougara Boumerdes, 35000, ALGERIA

[2] Laboratory of Coatings, Materials, and Environment (LRME), Mhamed Bougara Universty of Boumerdes (UMBB), ALGERIA

[3] Theoretical Physics Laboratory, Faculty of Physics, University of Sciences and Technology Houari Boumedien, ALGERIA.

Abstract. Photovoltaics, which convert directly solar energy into electricity, provide a practical and sustainable solution to the challenge of meeting the increasing global energy demand. Computer simulation is an important tool for investigating solar cell device's behavior and optimizing their performance. This work develops a new approach to retrieve the five parameters of the single diode equivalent solar cell/module model using the measured current-voltage data and its derivative (G=dI/dV). A nonlinear least-square technique based on the Newton-Raphson method under MATLAB Program is applied to determine the five parameters of the hybrid solar cell including under different temperature.

Keywords: solar energy, parameters extraction, organic-inorganic SCs, I-V characteristics.

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1. Introduction

Renewable solar energy is the clean alternative solution in general and, in particular, on the generation of electric power using photovoltaic cells which is the most important energy sources [1].

Solar cells provide more energy than other conventional sources with the additional advantage of being lightweight and cost-effective [2-3]. intensive studies are in progress to enhance the device's conversion efficiency and long-term stability, from crystalline silicon solar cells to thin-film, dye-sensitized (DSSCs), organic, and recently perovskite solar cells. enormous effort to obtain high efficiency and minimize all kinds of losses in the structure [4-6]. Solar cells are usually assessed by measuring the current-voltage characteristics of the device under different environmental conditions. Generally, most solar cells manufacturer provides panel datasheet that includes information like open-circuit voltage (V_{oc}), short circuit current (I_{sc}), and maximum power point (MPP) [7] which is not enough to build five parameters based on an accurate power prediction model. the equivalent model (fig.1) of the single diode (SDM) parameters is based on the employed circuit, such as photocurrent current (I_{ph}), saturation current (I_s), diode ideality factor (n), series (R_s) and shunt (R_{sh})

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resistances. Consequently, the choice of the solar cell model and the parameters extraction methods are based on different principles such as estimation speed, PV technology, complexity and accuracy [8].

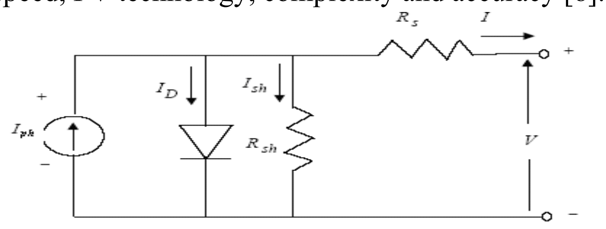


Fig. 1 – Equivalent circuit model of the illuminated solar cell.

The evaluation of these parameters has been the subject of an investigation by several authors. Some methods select a part of the current-voltage (I-V) characteristic [9-10] and others exploit the whole characteristic [11-12]. A special trans function theory (STFT) properties are presented for determining the ideality factor of a real solar cell as reported by Santakrus et al [13]. Priyank et al [14] method gives the value of series R_s and shunt resistance R_{sh} using illuminated I-V characteristics in the third and fourth quadrants and the V_{oc}-I_{sc} characteristics of the cell. Jain and Kapoor have presented an accurate method using the Lambert W-function [15-16] to study different parameters of organic solar cells, but it has been validated only on simulated I–V characteristics. The authors in [17] have used a slightly modified version of the Newton–Raphson method to solve a model reduced to three parameters instead of five, by using some algebraic manipulations.

The authors in [18] propose a two-step models, the simulated annealing algorithm and analytical formulations based on the manufacturer datasheet to estimate the series resistance and ideality factor and remaining parameters. Also depending on the PV module datasheet, the method presented in [19] uses analytical formulations to calculate the five SDM parameters using a numerical iterative method as a function of the environmental conditions, including the irradiance spectrum.

A novel parameter extraction method for the one-diode solar cell model is proposed by Wook et al [20] the method deduces the characteristic curve of an ideal solar cell without resistance using the I-V characteristic curve measured. Khalis et al [21] propose a new method to evaluate the five parameters of illuminated solar cells and the influence of temperature.

The presented research work considers the implicit non-linear equation for computing the SDM model parameters. A computational intelligence approach is proposed to solve this implicit equation. The root mean square algorithm is used for error minimization and fitting the model equation to the measured I–V characteristic curves and its derivative. This approach of fitting the model and extracting the five parameters is considered to be accurate because of using a full range I–V characteristics, a strong mathematical algorithm, and optimised steps for the parameter's initial guess values.

2. Theory and analysis

2.1. Solar cell single diode model

Under illumination and normal operating conditions, the single diode model is however the most popular model for solar cells [19], the SDM solar cell is described by the implicit form given [22] by :

$$I = I_{ph} - I_d - I_p = I_{ph} - I_s\left[\exp\left(\frac{\beta}{n}\left(V + IR_s\right)\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \quad (1)$$

The five parameters that appear in the SDM model equation to characterize the PV cell and module at a specific meteorological condition are photocurrent (I_{ph}), reverse saturation current (I_s), ideality factor (n), series resistance (R_s), and the shunt conductance (G_{sh} $(=1/R_{sh})$). I_p is the shunt current and $\beta=q/kT$ is the usual inverse thermal voltage.

The explicit form of the SDM can be formulated with the help of Lambert W-function as shown in eq. (2) [23]. we plot a new I-V characteristics cure using the extracted parameters to compare with the measured curves.

$$I = \frac{R_{sh}\left(Iph + I_S\right)}{R_{sh} + R_s} - \frac{nV_T}{R_s} W\left(\frac{R_s I_s}{nV_T}\frac{R_{sh}}{R_{sh}+R_s} e^{\frac{R_{sh}\left(V + R_{sh}\left(I_{ph}+I_s\right)\right)}{nV_T\left(R_{sh}+R_s\right)}}\right) - \frac{V}{R_{sh}+R_s} \quad (2)$$

Where W is the principal branch of Lambert W-function.

2.2. Development method

In this case, the current-voltage (I-V) relation of an illuminated solar cell is given by Eq. (1) which is implicit and cannot be solved analytically. The proper approach is to apply least squares techniques by considering the measured data over the entire experimental I-V curve and a suitable nonlinear algorithm to minimize the sum of the squared errors. In this section, we propose a new technique that uses the measured current-voltage curve and its derivative. A nonlinear least-squares optimization algorithm based on the Newton-Raphson model is hence used to evaluate the solar cell parameters. The problem, we have, is to minimize the objective function S with respect to the set of parameters θ:

$$S(\theta) = \sum_{i=1}^{N}\left[\frac{G - G_i(V_i, I_i, \theta)}{G_i(V_i, I_i, \theta)}\right]^2 \quad (3)$$

Where Θ is the set of unknown parameters Θ= (I_{ph}, I_s, n, R_s, G_{sh}) and I_i, V_i are the measured current, voltage and computed conductance $G_i = dI_i/dV_i$ respectively at the i^{th} point among N measured data points. Note that the differential conductance is determined numerically for the whole I-V curve using a method based on the least-squares principle and a convolution. The conductance G can be written as:

$$G = -\frac{\varphi}{1 + R_s\varphi} \quad (4)$$

Where:

$$\varphi = \frac{\beta}{n}\left\{I_{ph} + I_s - I - G_{sh}(V + R_s I)\right\} + G_{sh} \quad (5)$$

Consequently, by minimizing the sum of the squares of the conductance residuals instead of minimizing the sum of the squares of current residuals as reported by Easwarakhanthan et al [11]. The Newton-Raphson method can be used to obtain an approximation to the exact solution, and it is given by:

$$\theta^{i+1} = \theta^i - \left[J\left(\theta^i\right)\right]^{-1} F\left(\theta^i\right) \quad (6)$$

With $F_i = \frac{\partial S}{\partial \theta_i} = 0 \quad (7)$

Where $\boldsymbol{i}$ is the index for iteration number. Both of θ^{i+1} and θ^i are the five elements vectors that hold the next and the current values of the five parameters. J(Θ) is the Jacobian matrix that contains the partial derivatives for each equation corresponding to each of the five parameters, it will be a 5x5 matrix computed for the current value of the four parameters. $F\left(\theta^i\right)$ contains the five partial differential equations to be calculated for the current values of the parameters. The developed system of nonlinear equations can be represented in the following form:

$$\begin{pmatrix} I_{ph} \\ I_s \\ R_s \\ R_{sh} \\ n \end{pmatrix}^{i+1} = \begin{pmatrix} I_{ph} \\ I_s \\ R_s \\ R_{sh} \\ n \end{pmatrix}^{i} - \begin{bmatrix} \frac{\partial F_1}{\partial I_{ph}} & \frac{\partial F_1}{\partial I_s} & \frac{\partial F_1}{\partial R_s} & \frac{\partial F_1}{\partial R_{sh}} & \frac{\partial F_1}{\partial n} \\ \frac{\partial F_2}{\partial I_{ph}} & \frac{\partial F_2}{\partial I_s} & \frac{\partial F_2}{\partial R_s} & \frac{\partial F_2}{\partial R_{sh}} & \frac{\partial F_2}{\partial n} \\ \frac{\partial F_3}{\partial I_{ph}} & \frac{\partial F_3}{\partial I_s} & \frac{\partial F_3}{\partial R_s} & \frac{\partial F_3}{\partial R_{sh}} & \frac{\partial F_3}{\partial n} \\ \frac{\partial F_4}{\partial I_{ph}} & \frac{\partial F_4}{\partial I_s} & \frac{\partial F_4}{\partial R_s} & \frac{\partial F_4}{\partial R_{sh}} & \frac{\partial F_4}{\partial n} \\ \frac{\partial F_5}{\partial I_{ph}} & \frac{\partial F_5}{\partial I_s} & \frac{\partial F_5}{\partial R_s} & \frac{\partial F_5}{\partial R_{sh}} & \frac{\partial F_5}{\partial n} \end{bmatrix}^{-1} \begin{pmatrix} F_1\left(I_{ph}, I_s, R_s, R_{sh}, n\right) \\ F_2\left(I_{ph}, I_s, R_s, R_{sh}, n\right) \\ F_3\left(I_{ph}, I_s, R_s, R_{sh}, n\right) \\ F_4\left(I_{ph}, I_s, R_s, R_{sh}, n\right) \\ F_5\left(I_{ph}, I_s, R_s, R_{sh}, n\right) \end{pmatrix} \quad (8)$$

Although Newton's method converges only locally and may diverge under an improper choice of reasonably good starting values for the parameters, it remains attractive with the number of variables and their partial derivatives easily. To illustrate the approach, we have first applied the method to a computer-calculated curve reproducing the same solar cell characteristic used by Eswarakhantan et al [11]. To test the effects of different initial values on the method, the known exact solutions were multiplied by the factors [0.2-1.5] respectively and after carrying out the calculations; the extracted solar cell parameters were almost identical to the theoretical ones.

2.3. Experiments

The method was validated on different types of photovoltaic devices, organic and inorganic solar cells under illumination and using experimental I–V characteristics under different conditions including a temperature effect on parameters determination.
The first one, is an inorganic solar cell based on a silicon solar cell under a temperature of 33°C and a solar module in which 36 polycrystalline silicon solar cells are connected in series at 45°C.
Second, a polymer solar cells based on TiO_2 nanocrystals (anatase and rutile) as electron extraction layer under a temperature of 298.15 K and irradiation intensity of 100 mW/cm^2, where the currents are generally 1000 times smaller and have high series resistances compared to inorganic (silicon) solar cells.

3. Results and discussion

The experimental current-voltage (I–V) data were taken from Easwarakhantan et al [11] for the commercial silicon solar cell/module and from Lijie Zhu et al [8] for the polymer solar cell. The extracted parameters obtained using the method proposed here for the different devices are given in Table 1. Satisfactory agreement is obtained for most of the extracted parameters. A comparison with different methods is also given, and good agreement is reported. Statistical indicators of accuracy for the method of this work are shown in Table 2.
The best fits are obtained for the silicon solar cell and module with a root mean square error of less than 1% and 2% for the polymer solar cell. In figures 2, 3, and 4, the solid squares are the experimental data for the different solar cell and the solid line is the fitted curve derived from Eq. (1) with the parameters shown in Table 1 for the different solar cell organic and inorganic solar cell.
In order to test the quality of the fit to the experimental data, the percentage error is calculated as follows:

$$e_i = \left(I_i - I_{i,cal}\right)(100/I_i) \qquad (9)$$

Where $I_{i,cal}$ is the current calculated for each V_i, by solving the implicit Eq.(1) with the determined set of parameters (I_{ph}, n, R_s, G_{sh}, I_s). (I_i, V_i) are respectively the measured current and voltage at the ith point among N considered measured data points avoiding the measurements close to the open-circuit condition where the current is not well-defined [22]. Statistical analysis of the results has also been performed. The root means square error (RMSE), the mean bias error (MBE) and the mean absolute error (MAE) are the fundamental measures of accuracy. Thus, RMSE, MBE and MAE are given by:

$$RMSE = \left(\sum \frac{|e|_i^2}{N}\right)^{1/2} \qquad (10)$$

$$MBE = \sum \frac{e_i}{N}$$

$$MAE = \sum \frac{|e|_i}{N}$$

N is the number of measurements data taken into account.

For comparaison, The root means square error RMSE1 is calculated using the equation 11, where $I_{i,cal}$ is given by the equation (2) as following:

$$RMSE1 = \left[\sum \frac{1}{N}\left(\left|\frac{\left(I_i - I_{i,cal}\right)100}{I_i}\right|\right)^2\right]^{1/2} \qquad (11)$$

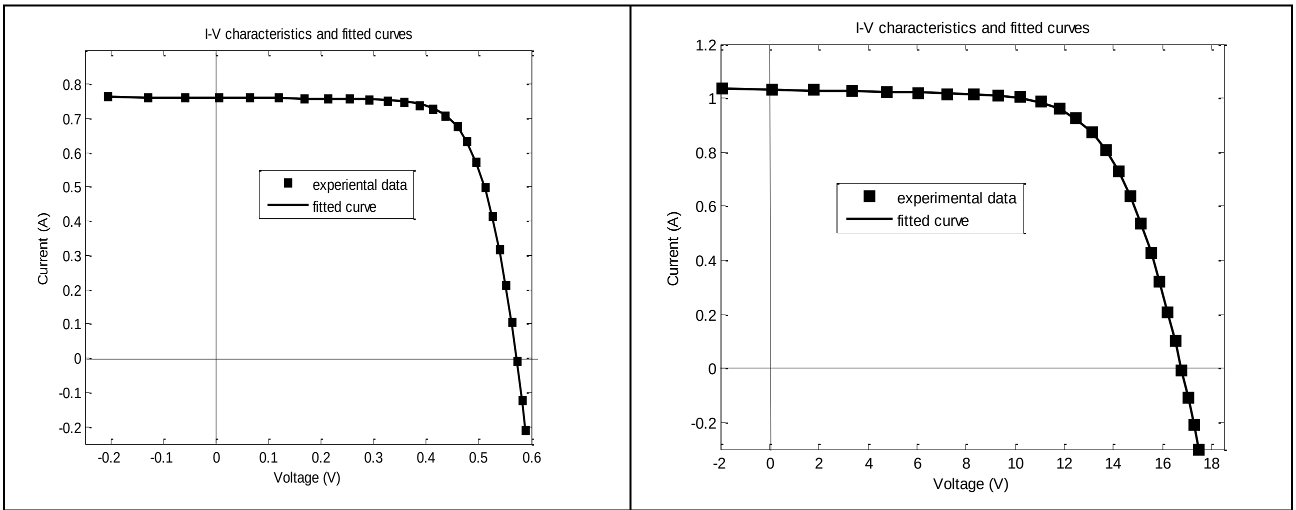
Table1: Extracted parameters for different solar cell and module

Model type	T(°C)	I_{ph} (A)	I_s (mA)	n	R_s (Ω)	G_{sh} (Ω^{-1})
	Crystalline silicon solar cell					
Mono-Si-solar cell	33	0.7606	0.2296	1.4425	0.0392	0.0114
	40	0.8235	0.2369	1.4835	0.0351	0.0208
	47	0.8987	0.2892	1.5058	0.0289	0.0198
Ref [11]	33	0.7608	0.3223	1.4837	0.0364	0.0186
Poly-Si- module	45	1.0333	2.4920	47.35	1.2373	0.00144
	50	1.0621	2.6682	47.85	1.086	0.0028
	55	1.0966	2.9831	48.26	1.058	0.0056
Ref [11]	45	1.0318	3.2876	48.450	1.2057	0.00182
	Polymer solar cell based on TiO_2					
TiO_2 anatase	25	15.35	1.01 e-6	1.65	1.40	0.20e-2
	30	15.60	1.03 e-6	1.78	1.35	0.19e-2
	35	15.96	1.04 e-6	1.88	1.31	0.13e-2
Ref [8]	25	15.66	1.08 e-5	1.69	1.45	0.18e-2
TiO_2 Rutile	25	13.95	3.77e-6	1.92	2.05	0.16e-2
	30	14.25	3.98e-6	1.96	2.00	0.13e-2
	35	14.58	3.88e-6	2.09	1.98	0.10e-2
Ref [8]	25	14.64	3.89e-6	1.88	2.18	0.12e-2

Table2: Statistical indicators prediction of accuracy for the method of this work

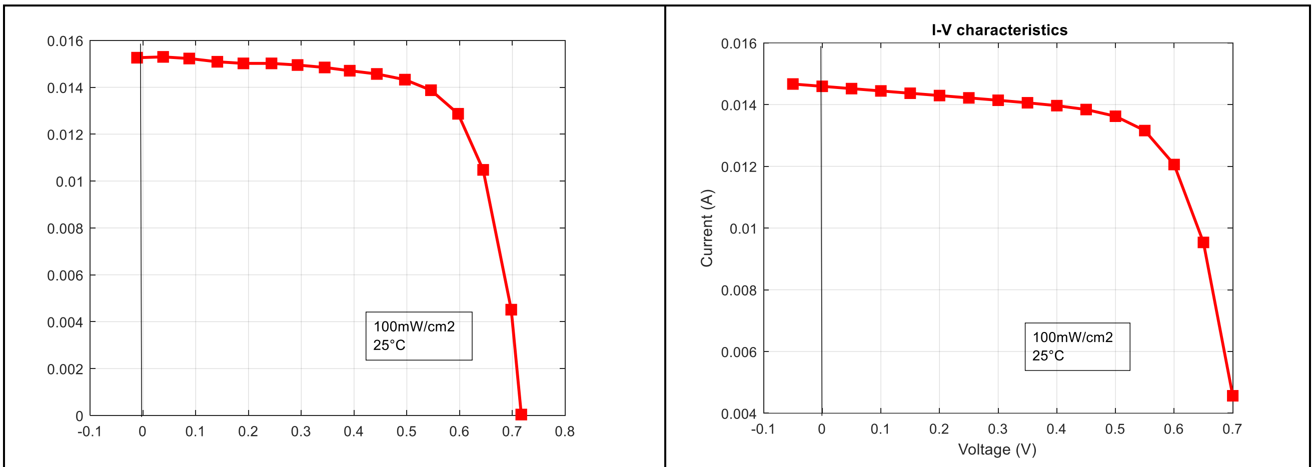
Model type	T (°C)	RMSE (%)	RMSE1 (%)	MBE (%)	MAE (%)
	Crystalline silicon solar cell				
Mn-Si	33	0.442	0.162	-0.016	0.310
	40	0.522	0.193	-0.023	0.365
	47	0.482	0.172	-0.018	0.273
Poly-Si	45	0.227	0.193	-0.007	0.183
	50	0.252	0.215	-0.008	0.204
	55	0.277	0.236	-0.009	0.222
	Polymer solar cell based on TiO_2 nanocrystal				
A-TiO_2	25	1.806	1.503	0.638	1.201
R-TiO_2	25	1.682	1.325	0.423	1.092

Good agreement is observed, especially for the inorganic solar cells. It is therefore necessary to emphasize that the proposed method is not based on the I-V characteristics alone but also on the derivative of this curve, i.e. the conductance G. Indeed, it has been demonstrated that it is not sufficient to obtain a numerical agreement between measured and fitted I-V data to verify the validity of a theory, but also the conductance data have to be predicted to show the physical applicability of the used theory. The interesting points with the procedure described herein is the fact that it has been successfully applied to experimental I–V characteristics of different types of solar cells from inorganic to organic solar cells with completely different physical characteristics and under different temperatures. In contrast to other methods that have already been developed for this purpose, the proposed method has no limitation condition on the voltage. Furthermore, the presented method, tested for the selected cases, is more reliable to obtain physically meaningful parameters and is straightforward to use.



Mono- silicon solar cell	Poly- silicon solar module.

Fig.2-Experimental data (■) and the fitted curve (-) for the commercial silicon solar and module.



TiO_2 anatase	TiO_2 rutile

Fig.3-Experimental data (■) and the fitted curve (-) for the polymer solar cells

5. Conclusion

This contribution presents and analyses a simple and powerful method of extracting solar cell parameters which affect directly the conversion efficiency, the power conversion, the fill factor, and the current-voltage shape of the solar cell. These parameters are the ideality factor, the series resistance, diode saturation current, and shunt conductance. This technique is not only based on the current-voltage characteristics but also the derivative of this curve, the conductance G. by using this method, the extracted parameters are I_s, n, R_s, G_{sh}, and I_{ph}. The method has been successfully applied to a silicon solar cell, a module, and an organic solar cell under different temperatures. The results obtained are in good agreement with those published previously. The method is very simple to use. It allows real-time characterization of different types of solar cells and modules in indoor or outdoor conditions.

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