

PERFORMANCE ANALYSIS OF ORGANIC-INORGANIC SOLAR CELL PARAMETERS EVALUATION FROM I - V - G CURVE: NUMERICAL CALCULATION

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Abstract. An accurate estimation of solar cell and module parameters from current-voltage data is essential to study the behavior of the solar cell device and optimize their performance. In this work a simple, accurate and fast approach is presented to estimate the five parameters of the single diode equivalent solar cell/module using the measured current-voltage data and its derivative ($G = dI / dV$). These parameters are the photocurrent (I_{ph}), ideality factors (n), saturation current (I_s), series and shunt resistance (R_s , R_{sh}). A nonlinear least-square technique based on the Newton-Raphson and Lambert W-function method under MATLAB Program is applied to different solar cell technologies, including Mono-Si, Poly-Si, and organic solar cell based on TiO₂ anatase and rutile nanocrystal under different environmental conditions.

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

1. INTRODUCTION

Energy crisis and environmental pollution have been widely considered as two critical issues that humans have to deal with [1]. Solar energy has been shown to be a suitable solution for clean renewable resources, as they produce ecological and cheap energy. Solar energy provides more energy than other conventional sources with the additional advantage of being lightweight and cost-effective [2–3].

Photovoltaic (PV) cell technology has advanced significantly in recent years as a sustainable source of energy [2–3]. Intensive research is in progress to enhance the device's efficiency and long-term stability. Different technologies are being developed, ranging from crystalline silicon solar cells with high efficiency but high manufacturing costs to thin-film, dye-sensitized (DSSCs) solar cell and, more recently, perovskite solar cells with low prices, ease of fabrication and the potential

to increase efficiency [4–7]. Solar cells are usually assessed by measuring the current-voltage (I - V) characteristics under different conditions as temperature, solar irradiance, and the equivalent circuit model [6]. Most solar cells manufacturers provide panel datasheets that include information such as the open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), and maximum power point (MPP) [7], which is insufficient for analysing and improving the performance of PV cells and modules. The equivalent model (Fig. 1) of the single diode (SDM) parameters is based on the employed circuit, such as the photocurrent (I_{ph}), saturation current (I_s), the diode ideality factor (n), the series (R_s) and shunt (R_{sh}) resistances. As a result, the solar cell model and parameters extraction methods are chosen based on various principles such as estimation speed, PV technology, complexity and accuracy [8].

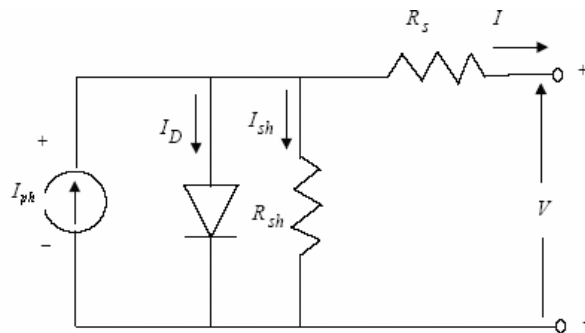


Fig. 1 – Equivalent circuit model of the single diode solar cell.

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 algebraic manipulations.

The authors in [18] propose 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] 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 means square algorithm is used for error minimization and fitting the model equation to the measured I - V characteristic curves and its derivative G expressed by the Lambert W -function. This approach of fitting the model and extracting the five parameters is 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:

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

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.

Where I and V are found in both sides of the equation, to solve (Eq. 1), one has to employ a numerical or iterative algorithm with all associated difficulties. The explicit form of the SDM (Eq. 1) can be formulated as $I=f(V)$ or $V=f(I)$ with the help of Lambert W -function is shown in Eqs. (2) and (3) [23].

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

$$V = R_{sh}(I_{ph} + I_s) - (R_s + R_{sh})I - \frac{n}{\beta} W \left(\frac{\beta R_{sh} I_s}{n} e^{\frac{\beta R_{sh}(I_{ph} + I_s - I)}{n}} \right). \quad (3)$$

where W denotes the principal branch W_0 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 :

$$S(\theta) = \sum_{i=1}^N \left(\frac{G_i - G_{th}}{G_{th}} \right)^2 \quad (4)$$

$$\frac{\partial S}{\partial \theta} = 0 \Rightarrow \left(\frac{G_i - G_{th}}{G_{th}} \right) \frac{G_i}{G_{th}^2} \frac{\partial G_{th}}{\partial \theta} = 0 \quad (5)$$

where θ is the set of unknown parameters $\theta = (I_{ph}, I_s, n, R_s, G_{sh})$ 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 current-voltage (I - V_i) data. 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:

$$G_{th} = -\frac{\varphi}{1 + R_s \varphi} \quad (6)$$

$$\varphi = \frac{\beta}{n} \{ I_{ph} + I_s - I - G_{sh}(V + R_s I) \} + G_{sh}. \quad (7)$$

Equation (5) represents a system of five non-linear equations with five unknowns, thus, it can be solved. The implicit nature of these equations implicates the use of a numerical method. The Newton-Raphson is considered as a fast

convergence and robust performance. The general expression of this method is given by:

$$\theta^{i+1} = \theta^i - [J(\theta^i)]^{-1} F(\theta^i) \tag{8}$$

with

$$F = \frac{\partial S}{\partial \theta} = 0 \Rightarrow \left(\frac{G_i - G_{th}}{G_{th}} \right) \frac{G_i}{G_{th}^2} \frac{\partial G_{th}}{\partial \theta} = 0. \tag{9}$$

where i is the index for the 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. $J(\theta)$ is the Jacobian matrix that contains the partial derivatives for each equation corresponding to each of the five parameters, it will be a 5×5 matrix computed for the current value of the four parameters. $F(\theta^i)$ 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:

$$\begin{pmatrix} I_{ph} \\ I_s \\ R_s \\ R_{sh} \\ n \end{pmatrix}^{i+1} = \begin{pmatrix} I_{ph} \\ I_s \\ R_s \\ R_{sh} \\ n \end{pmatrix}^i - \begin{bmatrix} \frac{\partial F_1}{\partial I_{ph}} & \frac{\partial F_1}{\partial I_s} & \frac{\partial F_1}{\partial R_s} & \frac{\partial F_1}{\partial R_{sh}} & \frac{\partial F_1}{\partial n} \\ \frac{\partial F_2}{\partial I_{ph}} & \frac{\partial F_2}{\partial I_s} & \frac{\partial F_2}{\partial R_s} & \frac{\partial F_2}{\partial R_{sh}} & \frac{\partial F_2}{\partial n} \\ \frac{\partial F_3}{\partial I_{ph}} & \frac{\partial F_3}{\partial I_s} & \frac{\partial F_3}{\partial R_s} & \frac{\partial F_3}{\partial R_{sh}} & \frac{\partial F_3}{\partial n} \\ \frac{\partial F_4}{\partial I_{ph}} & \frac{\partial F_4}{\partial I_s} & \frac{\partial F_4}{\partial R_s} & \frac{\partial F_4}{\partial R_{sh}} & \frac{\partial F_4}{\partial n} \\ \frac{\partial F_5}{\partial I_{ph}} & \frac{\partial F_5}{\partial I_s} & \frac{\partial F_5}{\partial R_s} & \frac{\partial F_5}{\partial R_{sh}} & \frac{\partial F_5}{\partial n} \end{bmatrix}^{-1} \begin{pmatrix} F_1(I_{ph}, I_s, R_s, R_{sh}, n) \\ F_2(I_{ph}, I_s, R_s, R_{sh}, n) \\ F_3(I_{ph}, I_s, R_s, R_{sh}, n) \\ F_4(I_{ph}, I_s, R_s, R_{sh}, n) \\ F_5(I_{ph}, I_s, R_s, R_{sh}, n) \end{pmatrix} \tag{10}$$

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 test the effects of different initial values on the method, the known exact solutions were multiplied by the factors [0.1–1.5] respectively and after carrying out the calculations; the extracted solar cell parameters were almost identical to the theoretical ones. To ensures convergence to solution and enlarged the region of convergence of the five parameters that have been to be initialized, the explicit form of I - V expression by Lambert W-function is used as shown in Eqs. (2) and (3),

which reduces the problem of undesired oscillation and eventual overflow in the objective function. The first derivative satisfies:

$$W'(x) = \frac{\partial W(x)}{\partial x} = \frac{W}{x(1+W)}. \quad (11)$$

To ensure a good solution and finding the global minimum, at each iteration, the obtained five parameters are substituted in equation (2). The calculated I - V curve is compared to the experimental value using the root means square error (RMSE), and the mean absolute error (MAE) are the fundamental measures of accuracy. Thus, RMSE and MAE are given by:

$$\text{RMSE} = \left[\sum \frac{1}{N} \left(\left| \frac{(I_i - I_{i,cal})100}{I_i} \right| \right)^2 \right]^{1/2} \quad (12)$$

$$\text{MAE} = \frac{1}{N} \sum \left| \frac{(I_i - I_{i,cal})}{I_i} \right|$$

The value of the RMSE and MAE of each iteration are stored together with the corresponding extracted five parameters. After reaching the maximum number of iterations, the stored errors will be compared, and the lowest value will be considered as the best solution. This procedure highly improves the solution and leads to a better fitting compared to the traditional way of comparing the sum of the squared errors to a specific limit. Since the equation with the highest value will have the highest impact on the summed error. Another important feature provided by our proposed method is the possibility of selecting an acceptable level of accuracy to reduce the computational cost. This concept has been implemented by comparing the calculated RMSE after each iteration with a preselected limit. If a value of the RMSE below the acceptable limit is detected, the iteration process will be terminated, and the five parameters will be considered. Otherwise, the iteration will continue until the specified maximum number of iterations is reached.

2.3. EXPERIMENTS

The proposed method is used to extract the five SDM parameters of PV cells/modules for a given I - V measured curve. 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 environmental conditions. Three different PV samples have been used for validating the proposed model. The first sample is a crystalline silicon cell under a temperature of 33°C. The second

sample is a solar module in which 36 polycrystalline silicon solar cells are connected in series at 45°C. The third organic solar cell based on TiO₂ nanocrystals (anatase and rutile) as electron extraction layer under a temperature of 298.15 K and irradiation intensity of 100 mW/cm², 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 Ref. [11] for the commercial silicon solar cell/module and from Lijie Zhu *et al.* [8] for the organic solar cell. The extracted parameters obtained using the method proposed here for the different devices are given in Tables 1 and 2. First, we use Eqs. (1, 4) (method1-COM), second, by introducing Lambert W-function, Eqs. (2, 3, 4) are used to estimate the five parameters (method 2-LWF). 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 Tables 1 and 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 Figs. 4–5, the solid squares are the experimental data for the different solar cell and the solid line is the fitted curve derived from Eq. (2) with the parameters shown in Tables 1 and 2 for the different solar cell organic and inorganic solar cell.

- Figure 2 shows how the RMSE changes by increasing the number of iterations. The accuracy of the results is clearly improved by increasing the number of iterations up to value between 1000 and 2000. This allows the optimum number of iterations to be selected for the various PV devices. However, even with a low number of iterations, we are still getting a good solution.

- Tables 1 and 2 show the extracted results for the five parameters and the calculated statistical errors for the different PV technologies. The parameters shown in Tables 1 and 2 are extracted using the I - V curve that has been measured under different conditions of temperature and irradiation.

- With Tables 1 and 2, it is easy to see that parameters extracted by using the proposed method, are very close to those reported in the other references. Figures 4 and 5 show that the new method can achieve high accuracy, which are in good agreement with the experimental results. The new method can represent the cell and module characteristics with small absolute errors of current.

- Figure 3 shows the relation between ideality factor (n) and parasitic resistance (R_s and R_{sh}). The value of the ideality factor represents the quality of a junction and the carries recombination mechanism in a heterojunction solar cell, as its value is highly dependent on the parasitic resistance. A small R_s is necessary for high-performance solar cells. The device base on anatase TiO₂ shows the best performance for organic solar cells.

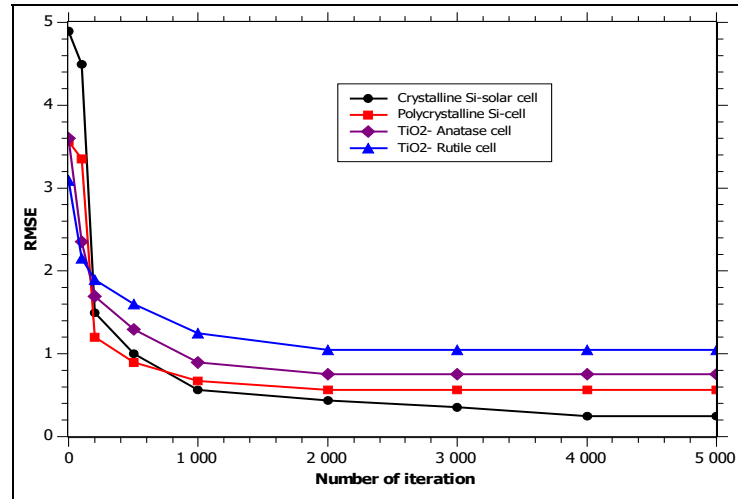


Fig. 2 – Method accuracy *versus* the maximum number of iterations.

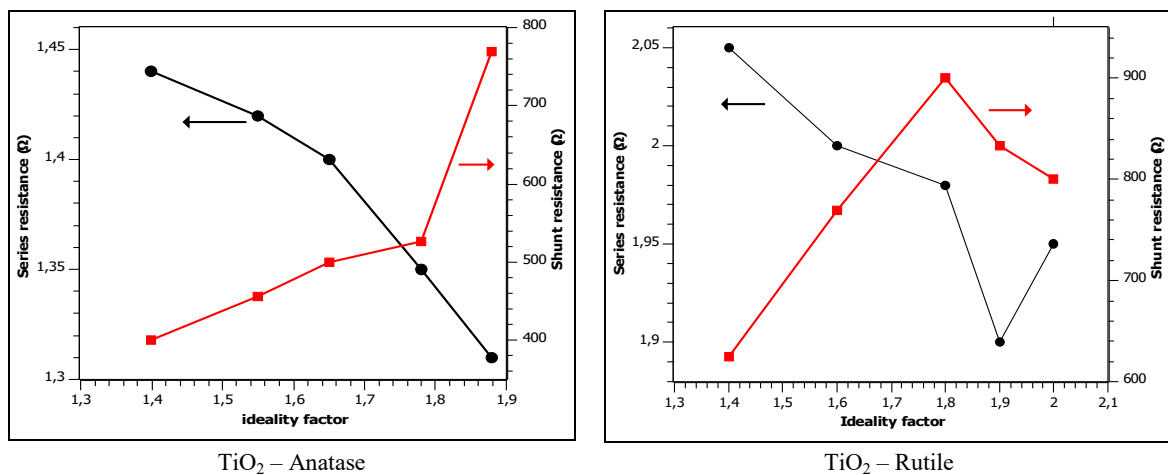


Fig. 3 – Variation of series and shunt resistance function of ideality factor for the organic solar cells.

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.

Table 1

Extracted parameters for crystalline silicon solar cell and module

Model type	T(°C)	I_{ph} (A)	I_s (mA)	n	R_s (Ω)	G_{sh} (Ω^{-1})	RMSE	MAE
Crystalline silicon solar cell								
Method1(COM)	33	0.7606	0.2296	1.4425	0.0392	0.0114	0.162	0.310
	40	0.8235	0.2369	1.4835	0.0351	0.0208	0.193	0.365
	47	0.8987	0.2892	1.5058	0.0289	0.0198	0.172	0.273
Method2 (LWF)	33	0.7605	0.3223	1.4836	0.0363	0.0186	0.004	0.023
	40	0.7606	0.3222	1.4837	0.0364	0.0185	0.002	0.019
	47	0.7607	0.3223	1.4838	0.0365	0.0187	0.002	0.015
Ref [11]	33	0.7608	0.3223	1.4837	0.0364	0.0186	–	–
Polycrystalline silicon solar cell								
Method 1(COM)	45	1.0333	2.4920	47.35	1.2373	0.00144	0.193	0.183
	50	1.0621	2.6682	47.85	1.086	0.0028	0.215	0.204
	55	1.0966	2.9831	48.26	1.058	0.0056	0.236	0.222
Method 2 (LWF)	45	1.0317	3.2875	48.449	1.2056	0.00181	0.007	0.083
	50	1.0318	3.2876	48.451	1.2058	0.00183	0.005	0.054
	55	1.0316	3.2877	48.450	1.2055	0.00179	0.009	0.022
Ref [8]	445	1.0318	3.2876	48.450	1.2057	0.00182	–	–

Table 2

Extracted parameters for organic solar cell based on nanocrystallineTiO₂ (anatase-rutile)

Model type	T(°C)	I_{ph} (mA)	I_s (mA)	n	R_s (Ω)	G_{sh} (Ω^{-1})	RMSE	MAE
TiO ₂ anatase								
Method1(COM)	25	15.35	1.01 e-6	1.65	1.40	0.20e-2	1.503	1.201
	30	15.60	1.03 e-6	1.78	1.35	0.19e-2	1.462	1.195
	35	15.96	1.04 e-6	1.88	1.31	0.13e-2	1.408	1.189
Method2 (LWF)	25	15.65	1.07e-5	1.68	1.44	0.18e-2	0.007	0.225
	30	15.64	1.06e-5	1.67	1.46	0.17e-2	0.005	0.198
	35	15.67	1.09e-5	1.70	1.43	0.19e-2	0.007	0.156
Ref [8]	25	15.66	1.08 e-5	1.69	1.45	0.18e-2	–	–
TiO ₂ Rutile								
Method1 (COM)	25	13.95	3.77e-6	1.92	2.05	0.16e-2	1.325	1.092
	30	14.25	3.98e-6	1.96	2.00	0.13e-2	1.156	1.080
	35	14.58	3.88e-6	2.09	1.98	0.10e-2	1.267	1.056
Method2 (LWF)	25	14.66	3.88e-6	1.87	2.17	0.12e-2	0.012	0.955
	30	14.62	3.87e-6	1.90	2.16	0.11e-2	0.014	0.875
	35	14.60	3.90e-6	1.86	2.19	0.13e-2	0.011	0.823
Ref [8]	25	14.64	3.89e-6	1.88	2.18	0.12e-2	–	–

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. 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 Figs. 4–5, the solid squares are the experimental data for the different solar cell and the solid line is the fitted curve derived from Eq. (2) with the parameters shown in Tables 1 and 2 for the different solar cell organic and inorganic solar cell.

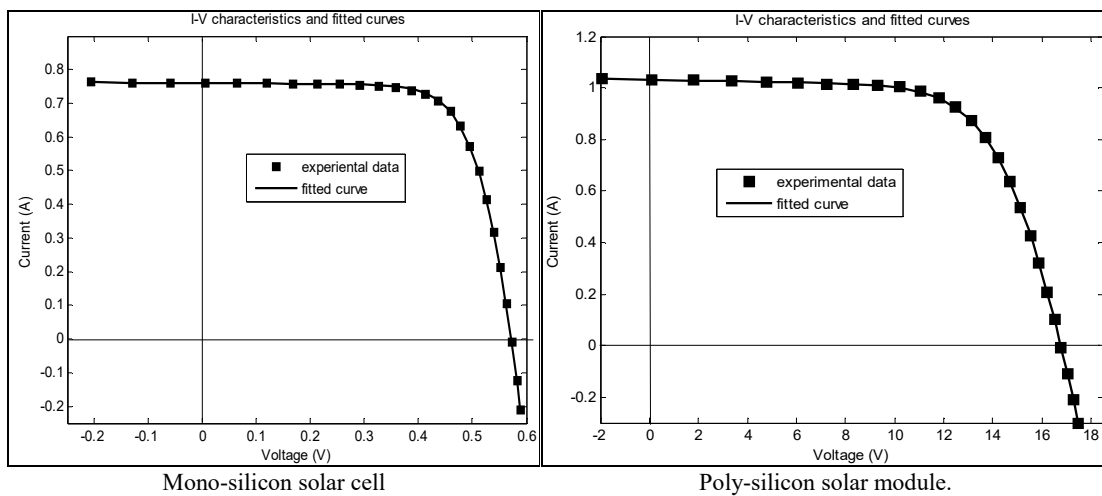


Fig. 4 – Experimental data (■) and the fitted curve (–) for the commercial silicon solar and module.

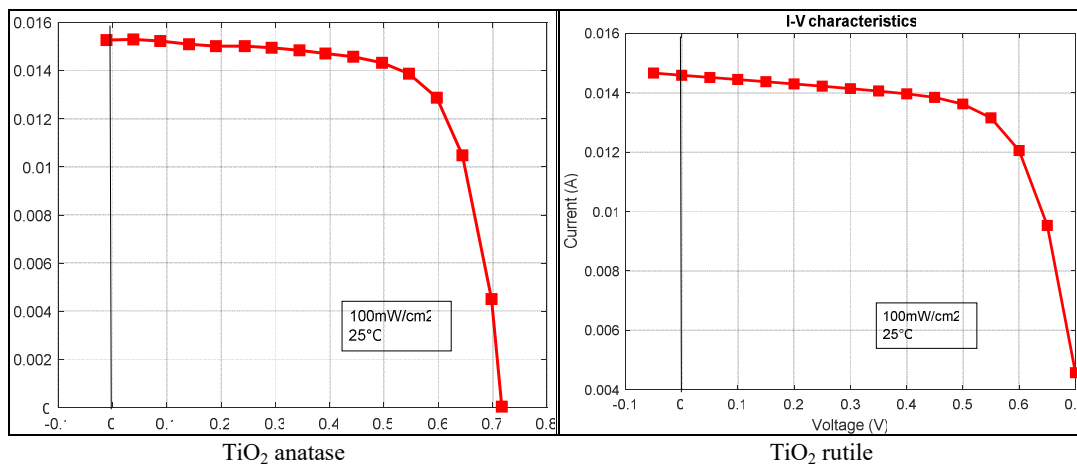


Fig. 5 – Experimental data (■) and the fitted curve (–) for the polymer solar cells.

4. CONCLUSION

In this paper, we have presented a new numerical method for retrieving the five single diode model parameters using the I - V characteristics of solar cells. These parameters are the photocurrent, ideality factor, the series resistance, diode saturation current, and shunt conductance. This method is not only based on the current-voltage characteristics but also the derivative of this curve, the conductance $G = dI/dV$. This approach is based on curve fitting using list square method to form a system of equations and solving them by modified version of the Newton-Raphson method by introducing Lambert W-function and compare between the two with or without Lambert W-function. The method has been successfully applied to organic-inorganic solar cell and module. The results obtained are in good agreement with those published previously. In addition, the quality standard of a good method has not only a small current error, but also with low number of iterations we are still getting a good solution.

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