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The application of Trust Region Method to estimate the parameters of photovoltaic modules through the use of single and double exponential models.

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Abstract. ***This paper presents a methodology for the extraction of parameters of photovoltaic (PV) modules through the use of electric models with single and double exponentials. The aim of the proposed method was extract the parameters directly from measured curves applying the Trust Region Method to solve a system of equations f(x_i). The variables x_i are the photocurrent (I_{ph}), the reverse saturation current (I_o), the ideality factor (A_i), series resistance (R_s) and the shunt resistance (R_{sh}). The validation method is made by approximating the IV curves using the calculated parameters. So, is provided a statistical analysis of errors from the curves obtained in a way to assess the feasibility of the method. A comparison between the results obtained through the two circuit models is also provided.***

Key words

Photovoltaic modules, Parameters extraction, Trust region method.

1. Introduction

The determination of an efficient method able to estimate the parameters of a photovoltaic panel is essential for the development and performance analysis of such equipments. In this context several methodologies have been proposed in order to obtain these parameters from measurements performed on these devices.

The search for methods to estimate these parameters based on experimental data is justified by the difficulty in determining the values of some variables that describe the analytical equations, when focusing on an analysis of the chemistry and physics of materials. This analysis based on physics of materials can be seen in [1].

Some methods have been proposed using measurements taken at different light levels [1] - [7], while others use light and dark conditions [8] - [13]. There are also methods that differ by the proposed analysis model, in other words, the equivalent electric circuit used for analysis. In short, there are two models used frequently in this area of study: the model with one exponential [14], [15] and the model with two exponentials [16] - [18].

Figs. 1 and 2 show the model of a cell with one and two exponentials, respectively.

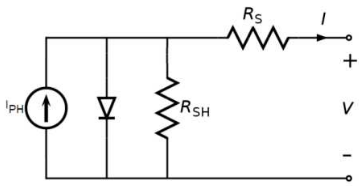


Fig.1. Electric model of photovoltaic cells with one (exponential) diode.

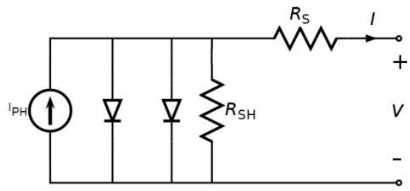


Fig.2. Electric model of photovoltaic cells with two (exponentials) diodes.

The main advantage of using the model with single diode is to simplify the electric circuit and consequently the equation that describes the device operation. The model with two diodes may represent more closely the observable effects on the device under consideration in various lighting conditions.

Equations (1) and (2) are governing statements of the electrical behavior of a solar cell represented by one and two diodes, respectively.

$$I = I_{ph} - I_o(e^{\frac{q}{kTA}(V+IR_s)} - 1) - \frac{V + IR_s}{R_{sh}} \quad (1)$$

$$I = I_{ph} - I_{o1}(e^{\frac{q}{kTA_1}(V+IR_s)} - 1) - I_{o2}(e^{\frac{q}{kTA_2}(V+IR_s)} - 1) - \frac{V+IR_s}{R_{sh}} \quad (2)$$

where I_{ph} defines the total current generated by the cell for a given lighting and temperature conditions in Amperes; I_{oi} is the reverse saturation current in Amperes; k is the Boltzmann constant (1.381×10^{-23} J/K); q is the electron charge (1.602177×10^{-19} C); T is the temperature in Kelvin; A_i is the ideality factor, R_s is the series resistance and R_{sh} is the *shunt* resistance.

The purpose of this work is to use the *Trust Region Optimization Method* to extract the parameters of silicon photovoltaic modules considering the uncertainty in the behavior of current when the panel approaches the point of short circuit. Furthermore, the method validation is done by calculating the errors in the curves obtained using the estimated parameters with respect to those curves obtained experimentally.

The use of numerical methods, such as optimization methods, is of paramount importance when working with equations whose complexity hinders or prevents the analytical solution; as the equations that describe the behavior of cells and solar panels.

2. Theoretical description

According to (1) and (2) it appears that both models have a different number of variables. In the first case there are five variables, ie, five parameters to be determined: photocurrent (I_{ph}), reverse saturation current (I_o), diode ideality factor (A), series resistance (R_s) and shunt resistance (R_{sh}).

In the second case, there are two reverse currents (I_{O1} and I_{O2}) and two ideality factors (A_1 and A_2), plus the other parameters that are the same presented in the first model. So that, the two models have five variables, the ideality factors take on their theoretical values, according to (3).

$$A_1 = n \text{ and } A_2 = 2n \quad (3)$$

where, n is the number of cells connected in series.

Thereby, the equation (2) can be simplified as (4)

$$I = I_{ph} - I_{o1}(e^{\frac{q}{kTn}(V+IR_s)} - 1) - I_{o2}(e^{\frac{q}{2kTn}(V+IR_s)} - 1) - \frac{V+IR_s}{R_{sh}} \quad (4)$$

So, the parameters to be determined in this model are I_{ph}, I_{o1}, I_{o2}, R_s e R_{sh}.

A. Trust Region Method

The Trust Region Method is an optimization method widely used in solving systems of nonlinear equations with a high rate of convergence.

The aim of the method is to minimize the system of equations $f_i(x) = 0$ in order to determine the values of x_i which suits the problem. The first iteration of the method is made so that $f_i = (x_0) = f_0$, where x_o is the initial value of x and f_o is the initial value of $f(x)$.

Thus, for iteration k [19], the subproblem indicated in (5) must be solved.

$$\min_{p \in \Re^n} m_k(p) = f_k + g_k^t p + \frac{1}{2} p^T B_k p, \quad for \|p\| \leq \Delta_k \quad (5)$$

where $f_k = f(x_k)$ is the function value at point x_k, $g_k = \nabla f(x_k)$ is the gradient of $f(x_k)$, $B_k = \nabla^2 f(x_k)$ is the Hessian matrix of $f(x_k)$ and $\Delta_k > 0$ is the trust region radius.

An essential condition for defining a trust region method is to choose the radius of this region at each iteration. This choice was based on the approximate relationship between the model function and the objective function at previous iteration, according to equation (6). The numerator of the equation is called *actual reduction* and the denominator is the *predicted reduction* [19].

$$p_k = \frac{f(x_k) - f(x_k + p_k)}{m_k(0) - m_k(p_k)} \quad (6)$$

This radius indicates that the points whose distance from the center x_k, is at most equal to p_k, are part of the trust region. Yet, if p_k is negative the value of the new function $f(x_k + p_k)$ is greater than the current value $f(x_k)$, then the calculated value should be rejected.

The approach is valid when p_k is close to 1, i.e., the approximation m_k is close to the function f_k. In the case where p_k is close to 0 the radius of trust region should be reduced and, if it is positive, but far from 1, the trust region is not changed.

Done this, the actual x_k point is updated, as shown by (7).

$$x_{k+1} = \begin{cases} x_k; & if \quad p_k \leq \tau_0 \\ x_k + p_k; & on\ the\ contrary \end{cases} \quad (7)$$

where τ_0 represents the established tolerance for the variation of x_k.

3. Problem definition

The definition of the problem to be optimized is initially made by determining the equations that will compose the non-linear system to be solved. To do so, in view of the proposal made in this work, were used five representative points of IV measured curves that will result in five equations required to extract the parameters in the two models under analysis.

Figure 3 shows the points used in each equation.

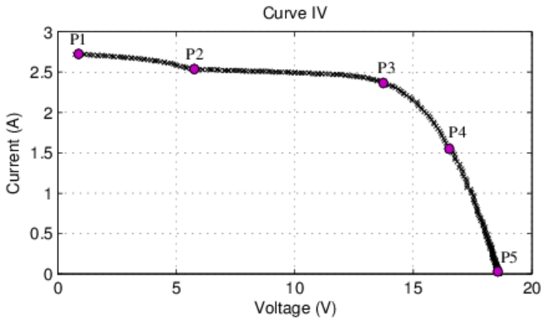


Fig. 3. Points used to define the system of equations

The choice of the points was made according to the following definitions:

- P1: $(V_1, I_1) = (0, Isc)$ – open circuit voltage. As the measure does not starts at 0, was used the lowest voltage measured.
- P2: $(V_2, I_2) = (0.3V_{oc}, I_{0.3Voc})$ – the voltage is about 30% of the open circuit voltage.
- P3: $(V_3, I_3) = (V_{max}, I_{max})$ – maximum power point.
- **P4:** $(V_4, I_4) = (0.9V_{oc}, I_{0.9Voc})$ – the voltage is about 90% of the open circuit voltage.
- P5: $(V_5, I_5) = (V_{oc}, 0)$ – the voltage is equal the open circuit voltage and the current is zero.

From the sampled points, it is possible to demonstrate the two systems of equations to be solved for each of the methods discussed, as in (8) and (9).

$$\begin{cases} f_1(x) = x_1 - x_2(e^{\lambda\left(\frac{V_1+I_1x_4}{x_3}\right)} - 1) - \dfrac{V_1 + I_1x_4}{x_5} - I_1 \\ f_2(x) = x_1 - x_2(e^{\lambda\left(\frac{V_2+I_2x_4}{x_3}\right)} - 1) - \dfrac{V_2 + I_2x_4}{x_5} - I_2 \\ f_3(x) = x_1 - x_2(e^{\lambda\left(\frac{V_3+I_3x_4}{x_3}\right)} - 1) - \dfrac{V_3 + I_3x_4}{x_5} - I_3 \\ f_4(x) = x_1 - x_2(e^{\lambda\left(\frac{V_4+I_4x_4}{x_3}\right)} - 1) - \dfrac{V_4 + I_4x_4}{x_5} - I_4 \\ f_5(x) = x_1 - x_2(e^{\lambda\left(\frac{V_5+I_5x_4}{x_3}\right)} - 1) - \dfrac{V_5 + I_5x_4}{x_5} - I_5 \end{cases} \tag{8}$$

where $\lambda = {}^{q}/_{kT}$, $x_1 = I_{ph}$, $x_2 = I_o$, $x_3 = A$, $x_4 = R_s$ e $x_5 = R_{sh}$..

$$\begin{cases} f_1(x) = x_1 - x_2(e^{\lambda\left(\frac{V_1+I_1x_4}{n}\right)} - 1) - x_3(e^{\lambda\left(\frac{V_1+I_1x_4}{2n}\right)} - 1) - \dfrac{V_1 + I_1x_4}{x_5} - I_1 \\ f_2(x) = x_1 - x_2(e^{\lambda\left(\frac{V_2+I_2x_4}{n}\right)} - 1) - x_3(e^{\lambda\left(\frac{V_2+I_2x_4}{2n}\right)} - 1) - \dfrac{V_2 + I_2x_4}{x_5} - I_2 \\ f_3(x) = x_1 - x_2(e^{\lambda\left(\frac{V_3+I_3x_4}{n}\right)} - 1) - x_3(e^{\lambda\left(\frac{V_3+I_3x_4}{2n}\right)} - 1) - \dfrac{V_3 + I_3x_4}{x_5} - I_3 \\ f_4(x) = x_1 - x_2(e^{\lambda\left(\frac{V_4+I_4x_4}{n}\right)} - 1) - x_3(e^{\lambda\left(\frac{V_4+I_4x_4}{2n}\right)} - 1) - \dfrac{V_4 + I_4x_4}{x_5} - I_4 \\ f_5(x) = x_1 - x_2(e^{\lambda\left(\frac{V_5+I_5x_4}{n}\right)} - 1) - x_3(e^{\lambda\left(\frac{V_5+I_5x_4}{2n}\right)} - 1) - \dfrac{V_5 + I_5x_4}{x_5} - I_5 \end{cases} \tag{9}$$

Thus the solution of the systems is done by applying these equations in (5). Moreover, were used the settings shown in (10) and (11)

$$g_k = \nabla f(x_k) = \begin{vmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \cdots & \frac{\partial f_1}{\partial x_5} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \cdots & \frac{\partial f_2}{\partial x_5} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_5}{\partial x_1} & \frac{\partial f_5}{\partial x_2} & \cdots & \frac{\partial f_5}{\partial x_5} \end{vmatrix} \tag{10}$$

where $x_1 = I_{ph}$, $x_2 = I_{o1}$, $x_3 = I_{o2}$, $x_4 = R_s$ and $x_5 = R_{sh}$. It can be noticed that in the iterative method this is the well known Jacobian matrix.

$$B_k = \nabla^2 f(x_k) = \begin{vmatrix} \frac{\partial^2 f_1}{\partial x_1^2} & \frac{\partial f_1 \partial f_2}{\partial x_1 \partial x_2} & \cdots & \frac{\partial f_1 \partial f_5}{\partial x_1 \partial x_5} \\ \frac{\partial f_2 \partial f_1}{\partial x_2 \partial x_1} & \frac{\partial^2 f_2}{\partial x_2^2} & \cdots & \frac{\partial f_2 \partial f_5}{\partial x_2 \partial x_5} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_5 \partial f_1}{\partial x_5 \partial x_1} & \frac{\partial f_5 \partial f_2}{\partial x_5 \partial x_2} & \cdots & \frac{\partial^2 f_5}{\partial x_5^2} \end{vmatrix} \tag{11}$$

It is easy to see, from Eq. (11), that B_k is a symmetrical matrix and follows the common architecture of matrices in physical systems; this matrix is embedded in the Trust Region Method as described by equation (5).

4. Simulations and results

All curves used in the simulations were experimentally obtained from a photovoltaic panel whose characteristics are listed in Table I.

Table I – Nominal characteristics of the panel

Features	**Value**
Power	40 W
Voltage at maximum power point	16.6 V
Current at maximum power point	2.45 A
Open circuit voltage	20.5 V
Short circuit current	2.80 A
Type of material	Monocrystalline silicon
Numbers of cells connected in series	36

Measurements were made using a gauge called Mini KLA [20]. For all measurements, as shown in Figure 3, the current shows a very non-uniform behavior when the voltage approaches zero. Thus, the objective was to develop a method that is able to extract the parameters of this panel from these curves measured. To this end, tests were carried out in different curves using the two models mentioned above. Table II shows data related to the curves used in the simulations.

Table II - Input data

Curve	Light Intensity (W/m^2)	Temperature (°C)
1	225.00	25
2	596.80	35
3	698.00	54
4	860.20	52

As the Trust Region Method is an iterative method, is necessary to set up the variables. Values should be established to enable the convergence mathematics, namely that the method should perform valid mathematical operations. However, it was observed that there is no need to use an initial value for each curve. Therefore, were used the same initial values for all curves.

Moreover, in order to test the accuracy of the curves obtained, was made a statistical analysis of calculated data. Were calculated the *root mean squared error* (RMSE), the *mean bias error* (MBE) and *mean absolute error* (MAE) which are key measures of accuracy for fitting curves [21].

$$\begin{cases} RMSE = \sqrt{\dfrac{1}{N}\displaystyle\sum_{i=1}^{N}\left(\dfrac{V_{i(meas)}}{V_{i(calc)}}-1\right)^2} \\ MBE = \dfrac{1}{N}\displaystyle\sum_{i=1}^{N}\left(\dfrac{V_{i(meas)}}{V_{i(calc)}}-1\right) \\ MAE = \dfrac{1}{N}\displaystyle\sum_{i=1}^{N}\left|\left(\dfrac{V_{i(meas)}}{V_{i(calc)}}-1\right)\right| \end{cases} \qquad (12)$$

where $V_{i(meas)}$ is the measured voltage; $V_{i(calc)}$ is the calculated voltage and N the number of variables. It can be noticed that by replacing the parameters calculated in (1) or (2), the variable used as the independent variable is the current *(I)*, so that $V = f(I)$.

A. Single exponential model

For the single exponential model the initial conditions are laid down in (13)

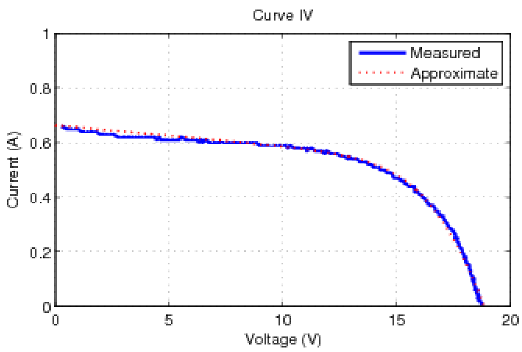
$$\left[I_{ph}, I_0, A, R_s, R_{sh}\right] = \left[1.5, 1e^{-9}, 50, 1.5, 100\right] \quad (13)$$

Table III shows the results obtained by the Trust Region Method.

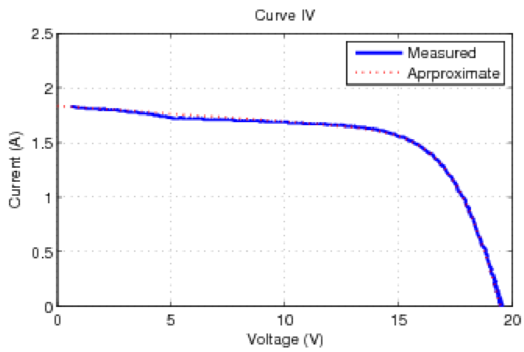
Table III - Obtained parameters with single exponential

Curve	Parameters				
	I_{ph} [A]	I_o [μA]	A	R_s [Ω]	R_{sh} [Ω]
1	0.6736	2.4258	48.2045	2.0364	129.8172
2	1.8498	0.1632	37.4816	0.5282	69.1844
3	2.2006	0.9783	36.1223	0.5497	57.7150
4	2.7577	0.6358	36.0000	0.5692	50.5662

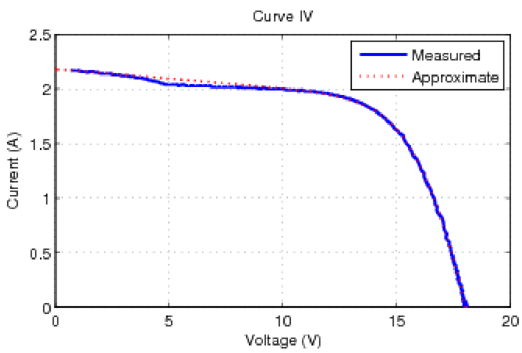
Replacing the values found in equation (1) the IV curve was draw up for each measurement curve and a comparison was made with the experimental curve, as in Figure 4.



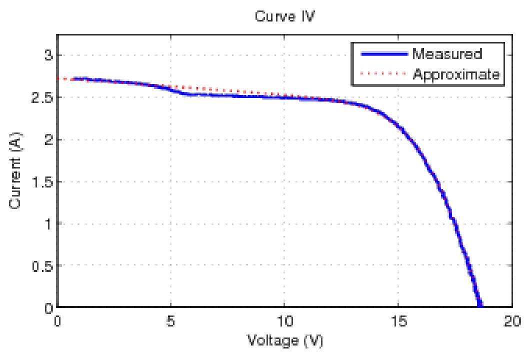
(a) Curve 1



(b) Curve 2



(c) Curve 3



(d) Curve 4

Fig. 4. Approximated curves using the single diode model

Table IV shows the errors in the approximations obtained using the model with an exponential. It is observed that by using the approximate parameters (I_{ph}, I_o, A, R_s, R_{sh}) errors obtained were less than 1%

indicating a good approximation to the desired parameters.

Table IV – Errors in approximated curves with single exponential

Curve	RMSE	MBE	MAE
1	0.20%	-0.10%	0.11%
2	0.11%	-0.04%	0.06%
3	0.13%	-0.04%	0.06%
4	0.31%	0.01%	0.11%

B. Double exponential model

The values for initialization of the method in the model with two exponentials are shown in (14)

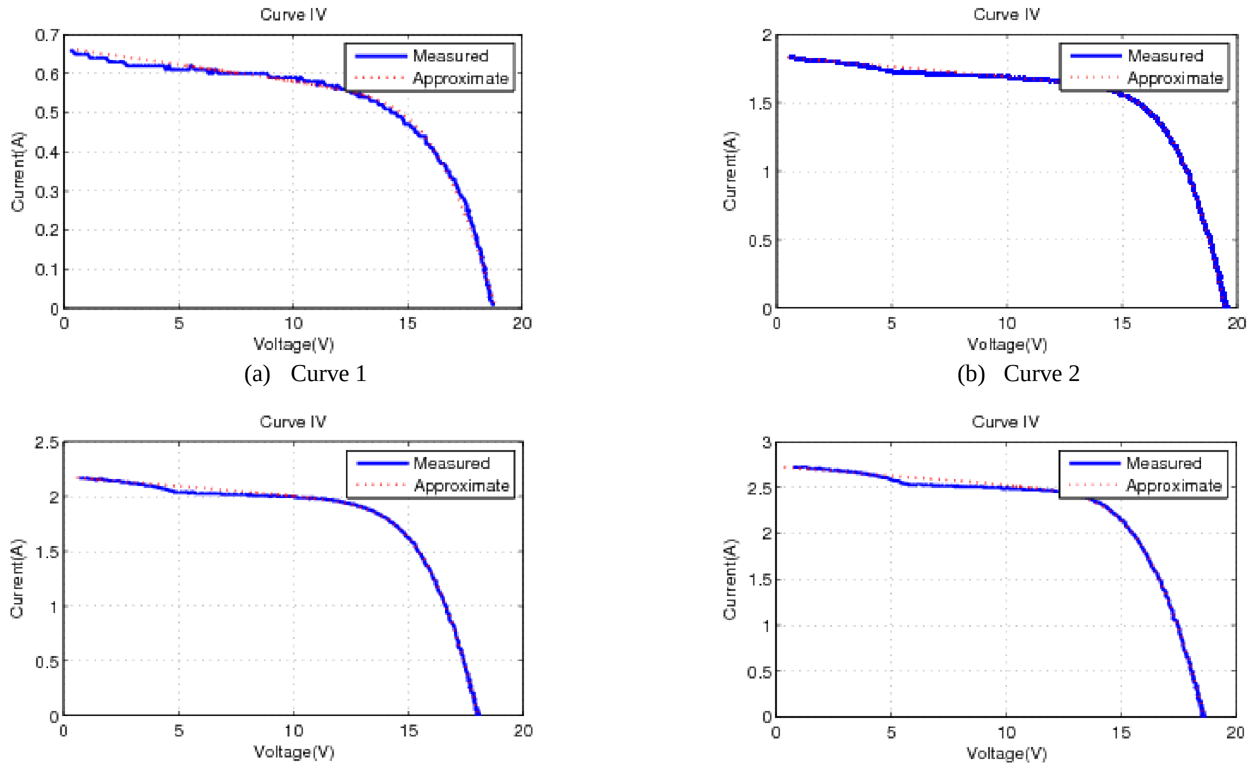
$$\left[I_{ph}, I_{01}, I_{02}, R_s, R_{sh}\right] = \left[1.5, 1e^{-7}, 1e^{-12}, 1.5, 100\right] \qquad (14)$$

Table V shows the results obtained by the Trust Region Method for this model.

Table V – Obtained parameters with double exponential

Curve	Parameters				
	I_{ph} [A]	I_{01} [uA]	I_{02} [pA]	R_s [Ω]	R_{sh} [Ω]
1	0.6821	0.00026	10.000	2.9734	115.4228
2	1.8521	0.08063	0.1260	0.5657	67.5704
3	2.2009	0.92799	0.1300	0.5525	57.5792
4	2.7576	0.63582	0.1220	0.5692	50.5665

Proceeding the same way as the previous model, the values found were replaced in Eq (2) and the approximated curves were plotted. Figure 5 shows the comparison between the measured and approximated curves.



(a) Curve 1

(b) Curve 2

(c) Curve 3

(d) Curve 4

Fig. 5. Approximated curves using the double diode model

Table VI indicate the errors calculated for the approximate curves using the double exponential. It can be observed that the errors obtained at the two exponential model are very close to those obtained previously. However, for curve 4 which shows the highest rate for the RMSE, the model with two diodes was more appropriate.

Table VI –Errors in approximated curves with double exponential

Curve	RMSE	MBE	MAE
1	0.19%	-0.07%	0.10%
2	0.11%	-0.04%	0.06%
3	0.13%	-0.04%	0.06%
4	0.13%	-0.03%	0.07%

5. Conclusion

The use of iterative methods for the extraction of parameters for PV panels allows obtaining these parameters from the use of only five known points on the curve VI of a PV module. Moreover, it was found that the proposed method allows the extraction of parameters for curves that have a large variation in the behavior of current when it approaches the point of short circuit. In this context, by calculating the statistical errors, we observe that the method of trust region allows us to obtain parameters that approximate satisfactorily IV curves measures for both exponential models.

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References

[1] F. B. Matos. "Computational modeling of the behavior of photovoltaic cells based on physical properties of materials" Uberlândia, 2006. 125p. Dissertation (MSc in Electrical Engineering) – School of Electrical Engineering, Universidade Federal de Uberlandia, Minas Gerais, Brazil. (*In Portuguese*). Electronic document available in: <http://www.camacho.prof.ufu.br/dissertacao_fernando.pdf>. Accessed in August 18, 2010.

[2] J. Thongpron, K. Kirtikaraa, C. Jivacate, "A method for the determination of dynamic resistance of photovoltaic modules under illumination". *Sol. Energy Mater. Sol. Cells*, Vol. 90, pp. 3078-3084 (2006).

[3] M. Haouari-Merbaha, M. Belhamelb, I. Tobías, J. M. Ruiz, "Extraction and analysis of solar cell parameters from the illuminated current–voltage curve". *Sol. Energy Mater. Sol. Cells*, Vol. 87, pp. 225-233 (2005).

[4] Adelmo Ortiz-Conde, Francisco J. García Sánchez and Juan Muci. "New method to extract the model parameters of solar cells from the explicit analytic solutions of their illuminated I–V characteristics". *Sol. Energy Mater. Sol. Cells*, Vol. 90 pp. 352–361 (2006).

[5] Priyanka, Mohan Lal and S.N. Singh, "A new method of determination of series and shunt resistances of silicon solar cells". *Sol. Energy Mater. Sol. Cells*, Vol. 91, pp. 137-142 (2007).

[6] Z. Ouennoughi and M. Chegaar, "A simpler method for extracting solar cell parameters using the conductance method". *Solid-State Electron.*, Vol. 43, pp. 1985-1988 (1999).

[7] M. Tivanov, A. Patryn, N. Drozdov, A. Fedotov and A. Mazanik, "Determination of solar cell parameters from its current–voltage and spectral characteristics". *Sol. Energy Mater. Sol. Cells*, Vol. 87, pp. 457-465 (2005).

[8] Ewa Radziemska. "Dark I–U–T measurements of single crystalline silicon solar cells". *Energy Convers. Manage.*, Vol. 46, pp. 1485-1494 (2005).

[9] R. Hussein, D. Borchert, G. Grabosch and W.R. Fahrner. "Dark I–V–T measurements and characteristics of (n) a-Si/(p) c-Si heterojunction solar cells". *Sol. Energy Mater. Sol. Cells*, Vol. 69, pp. 123-129 (2001).

[10] Erees Q.B. Macabebe and E. Ernest van Dyk. "Parameter extraction from dark current–voltage characteristics of solar cells". *S.Afr. J. Sci.*, Vol. 104, pp. 401-404 (2008). Electronic document available in: http://www.scielo.org.za/pdf/sajs/v104n9-10/a1710410.pdf. Accessed in August 18, 2010.

[11] J. Salinger, "Measurement of Solar Cell Parameters with Dark Forward I-V Characteristics". *Acta Polyt.*, Vol. 46 No. 4, pp. 25-27 (2006).

[12] A. Vishnoi, R. Gopal, R. Dwivedi and S. K, Srivastava, "Distributed parameter analysis of dark I-V characteristics of the solar cell - estimation of equivalent lumped series resistance and diode quality factor". *Circuits, Devices and Systems, IEE Proceedings G*, Vol. 140, No. 3, pp. 155-164 (1993).

[13] M. K. El-Adawi and I. A. Al-Nuaimvacate, "Methods to determine the solar cell series resistance from a single I–V". Characteristic curve considering its shunt resistance - new approach". *J. Vac. Sci. Technol., A*, No. 64, pp. 33-36 (2002).

[14] E. Q. B. Macabebe and E. E. Van Dyk. "Parameter extraction from dark current–voltage characteristics of solar cells". *S.Afr. J. Sci.*, Vol. 104, September/October, pp. 401-404 (2008).

[15] S. Dib, M. De La Bardonnie, A. Khoury, F. Pelanchon and P. Mialhe. "A new method for the extraction of diode parameters using a single exponential model". *Act. Passive Electron. Compon*, Vol. 22, pp. 157-163 (1999).

[16] M. A. de Blas, J. L. Torres, E. Prieto and A. García, "Selecting a suitable model for characterizing photovoltaic devices". *Renew. Energy*, Vol. 25, pp. 371-380 (2002).

[17] D. Chan and J. Phang, "Analytical method for the extraction of solar cell single and double-diode". *IEEE Trans. Electron Devices*, Vol. Ed-34, No. 2, pp. 286-293 (1987).

[18] M. Wolf, G. T. Noel, and Richard J. Stirn, "Investigation of the double exponential in the current–voltage characteristics". *IEEE Trans.Electron Devices*, Vol. Ed-24, No. 4, pp. 419-428 (1977).

[19] J. Nocedal and S.J. Wright. "Numerical Optimization". Second Edition. Springer Series in Operations Research, Springer Verlag, 2006.

[20] Mencke & Tegtmeyer. "Mini I-V Curve Analyzer". Electronic document available in: <http://www.ib-mut.de/en/produkt_detail.php4?id=22>. Accessed in August 18, 2010.

[21] K. Bouzidi, M. Chegaar and A. Bouhemadou, "Solar cells parameters evaluation considering the series and shunt resistance". *Sol. Energy Mater. Sol. Cells*, Vol. 91 pp. 1647-1651 (2007).