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Solar cells parameters evaluation considering the series and shunt resistance

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Abstract

This paper presents a new technique for the evaluation of the parameters of illuminated solar cell with a single diode lumped circuit model and considering the series and shunt resistances. This method includes the presentation of the standard $I = f(V)$ function as $V = f(I)$ and the determination of the factors C_0, C_1, C_2 of this function that provide the calculation of the illuminated solar cell parameters. These parameters are usually the saturation current (I_s), the series resistance (R_s), the ideality factor (n), the shunt conductance ($G_{sh} = 1/R_{sh}$) and the photocurrent (I_{ph}).

Parameter values were extracted using the present method from experimental I–V characteristics of commercial solar cells and modules. The method proposed below appears to be accurate even in the presence of noise and/or random errors during measurement and it needs no a prior knowledge of the parameters compared to other methods.

Keywords: Solar cells; Parameters extraction; Illumination

1. Introduction

An accurate knowledge of solar cell parameters from experimental data is of vital importance for the design, quality control of solar cells and for estimates of their performance.

Several methods for the determination of G_{sh}, I_{ph}, R_s, I_s, and n are proposed by several authors [1–15]. Some of the methods involve measurement of illuminated I–V characteristics at single or different levels of illumination [1–6], some use dark conditions [7–10], while other utilizes dark and illumination measurements [9–12]. Recent methods use the measured current voltage characteristics and the subsequently calculated conductance of the device [13,14].

A review of techniques to determine the ideality factor and or the series resistance of solar cells has been given by Mialhe et al. [15] and Bashahu et al. [16]. In addition a comparative study of extraction methods for solar cell parameters has been dealt with in a previous paper [17].

Recent works have been published [18–22] and present new methods in order to compute the different parameters of interest. Authors [18] have presented interesting mathematical techniques that introduce new formulations to extract the single exponential model parameters of plastic solar cells. The high performance of these methods is inferred after application to devices with very high series and shunt lost. A study in simulation [20] is concerned with organic solar cells, which are generally characterized by 2–4 order of magnitude larger series resistance values and by relatively small shunt resistance values and where the photocurrent is generally about 1000 times smaller than for classical silicon cells. The study considers the effects on the IV characteristic, of any changes in the parameters values. Recently, a numerical method using a combination of lateral and vertical optimization was used [22] to extract the parameters of an illuminated solar cell.

In addition, least-squares numerical techniques [23–30] have been proposed. Among the latter and of interest for us here for the sake of comparison, is a non-linear least-squares optimization algorithm based on the Newton

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method modified by introducing the so-called Levenberg parameter [29].

Gromov et al. [31] proposed a method based on the function $V=f(I)$ of the PtSi/Si Schottky-diodes of different quality in order to extract the relevant device parameters. In this paper this technique has been adequately modified, extended to cover the case of solar cells, and used to extract the parameters of interest. The problem to be solved in this paper is the evaluation of a set of five parameters (G_{sh}, I_{ph}, n, R_s and I_s) in order to fit a given experimental current–voltage characteristics using a single diode lumped circuit.

The method is first applied to noise-free computer-calculated I–V curves 1%, 5% and 10% electronic noise is subsequently generated by the computer and added to the values of the current. The parameters are then extracted from the noisy I–V curves. The influence of the noise on the I–V curves and the extracted parameters is discussed below as well as the test used to check reliability, robustness and accuracy of the method in evaluating the parameters.

2. Theory and analysis

The current–voltage characteristic of the solar cell can be presented by either a two diode model [8,32,33] or by a single diode model [13,14,17,34]. Under illumination and non stressed operating conditions, the single diode model is however the most popular model for solar cells.

At a given illumination, the current–voltage relation for a solar cell is given by

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

where I_{ph}, I_d and I_p, being the photocurrent, the diode current and the shunt current; I_s, n, R_s and $G_{sh}(=1/R_{sh})$ are the diode saturation current, the diode ideality factor, the series resistance, and the shunt conductance, respectively. R_{sh} is the shunt resistance and $\beta = q/kT$ is the usual inverse thermal voltage. Eq. (1) is implicit and not solvable analytically.

The model can also be used for modules where the cells are connected in series and /or parallel, provided that the cell variations are small enough.

Eq. (1) can be written as

$$I = I_{pA} - I_0\left[\exp\left(\frac{\beta}{n}(V+IR_s)\right) - 1\right] - G_A V, \quad (2)$$

where

$$\begin{cases} I_{pA} = \frac{I_{ph}}{1+G_{sh}R_s} \\ I_0 = \frac{I_s}{1+G_{sh}R_s} \\ G_A = \frac{G_{sh}}{1+G_{sh}R_s} \end{cases}. \quad (3)$$

For low bias voltages, the linear part dominates and Eq. (2) can be written as

$$I = I_{PA} - G_A V, \quad (4)$$

where G_A, I_{pA} are evaluated from Eq. (4) by a simple linear fit.

The calculated value of G_A gives the product $(G_A V)$ which can be added in turn to the measured current to yield the corrected current across the solar cell and is given by

$$I_c = I + G_A V. \quad (5)$$

Under forward bias for $(V+R_sI) \gg kT$ the current across the device is given by

$$I_c = I_{pA} - I_0\left[\exp\left(\frac{\beta}{n}(V+IR_s)\right)\right]. \quad (6)$$

To evaluate the series resistance, the ideality factor and the diode saturation current, we use (I) instead of (V) as the independent variable in Eq. (6), we obtain

$$V = \frac{n}{\beta}\ln\frac{I_{pA}}{I_0} + \frac{n}{\beta}\ln\left(1 - \frac{I_c}{I_{pA}}\right) - R_s I. \quad (7)$$

This expression can be presented in the common form

$$f(I) = C_0 + C_1 I + C_2 \ln\left(1 - \frac{I_c}{I_{pA}}\right). \quad (8)$$

The values of factors C_0, C_1, C_2 can be obtained by means of the experimental current–voltage data array using a least-squares method. This results in the system of equations.

$$\begin{cases} C_1 \sum_{i=1}^{N} I_i^2 + C_2 \sum_{i=1}^{N} I_i \ln\left(1 - \frac{I_{ci}}{I_{pA}}\right) + C_0 \sum_{i=1}^{N} I_i = \sum_{i-1}^{N} I_i V_i \\ C_1 \sum_{i=1}^{N} I_i + C_2 \sum_{i=1}^{N} \ln\left(1 - \frac{I_{ci}}{I_{pA}}\right) + C_0 N = \sum_{i-1}^{N} V_i \\ C_1 \sum_{i=1}^{N} I_i \ln\left(1 - \frac{I_{ci}}{I_{pA}}\right) + C_2 \sum_{i=1}^{N} \ln^2\left(1 - \frac{I_{ci}}{I_{pA}}\right) \\ \quad + C_0 \sum_{i=1}^{N} \ln\left(1 - \frac{I_{ci}}{I_{pA}}\right) = \sum_{i-1}^{N} V_i \ln\left(1 - \frac{I_{ci}}{I_{pA}}\right) \end{cases}. \quad (9)$$

The given system can be easily solved by means of Kramer's rule. $(I_i$–$V_i)$ are the measured values of the current–voltage at the ith point among N data points and I_{ci} is the corrected measured current. The series resistance, the ideality factor and the current, I_0, values are then determined from the following equations:

$$\begin{cases} R_s = -C_1 \\ n = \beta C_2 \\ I_0 = I_{pA}\exp(-C_0/C_2) \end{cases}. \quad (10)$$

Substituting the values of R_s and I_0 obtained in Eq. (10), the shunt conductance, the photocurrent, and the diode saturation current values are determined from

$$\begin{cases} G_{\mathrm{sh}} = \frac{G_{\mathrm{A}}}{1-G_{\mathrm{A}}R_{\mathrm{s}}} \\ I_{\mathrm{ph}} = \frac{I_{\mathrm{pA}}}{1-G_{\mathrm{A}}R_{\mathrm{s}}} \\ I_{\mathrm{s}} = \frac{I_0}{1-G_{\mathrm{A}}R_{\mathrm{s}}} \end{cases}. \tag{11}$$

For the sake of comparison, a non-linear least-squares optimisation algorithm based on the Newton method modified by introducing the so-called Levenberg parameter is used. This was proposed by Easwarakhantan et al. [29] and used to extract the five illuminated solar cell parameters mentioned above.

The problem consists to minimize the objective function S with respect to the set of parameters P:

$$S(P) = \sum_{i=1}^{N}[I_i - I_i(V_i, P)]^2, \tag{12}$$

where P is the set of unknown parameters $P = (G_{\mathrm{sh}}, I_{\mathrm{ph}}, n, R_{\mathrm{s}}, I_{\mathrm{s}})$ and I_i, V_i are respectively the measured current and voltage at the ith point among N measured data points.

Newton's method is used to obtain an approximation to the exact solution for the non linear resulting set of equations $F(P) = 0$, derived from multivariate calculus for a minimum to occur. The Newton functional iteration procedure evolves from

$$(P_j) = (P_{j-1}) - [J(P)]^{-1}F(P), \tag{13}$$

where $J(P)$ is the Jacobean matrix.

3. Results and discussion

The measured I–V data of different solar cells and modules are considered in this work. The data of a 57 mm diameter commercial silicon solar cell and a solar module in which 36 polycrystalline silicon cells are connected in series are taken from the work of Easwarakhanthan et al. [29]. Other measured data, of a CIS solar module of 734 cm^2 area and a mono-Si solar cell of 100 cm^2 area, are also considered. The series resistance and the ideality factor are evaluated from Eq. (10). Then the shunt conductance, the photocurrent and the saturation current are evaluated using Eq. (11).

To test the quality of the fit to the experimental data, statistical analysis of the results was performed. The root mean squared 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

$$\begin{cases} \mathrm{RMSE} = \left[(1/m)\sum_{1}^{m}(I_i/I_{\mathrm{cal},i} - 1)^2\right]^{1/2} \\ \mathrm{MBE} = (1/m)\sum_{1}^{m}(I_i/I_{\mathrm{cal},i} - 1) \\ \mathrm{MAE} = (1/m)\sum_{1}^{m}\left|(I_i/I_{\mathrm{cal},i} - 1)\right| \end{cases}, \tag{14}$$

where $I_{\mathrm{cal},i}$ is the current calculated for each V_i, by solving the implicit Eq. (1) with the determined set of parameters $P = (G_{\mathrm{sh}}, I_{\mathrm{ph}}, n, R_{\mathrm{s}}, I_{\mathrm{s}})$. (I_i, V_i) are, respectively, the measured current and voltage at the ith point among m considered measured data points avoiding the measurement close to the open circuit condition where the current is not well defined [29].

Table 1 resumes the extracted parameters from experimental data of a silicon solar cell and a module at 33 and 45 °C, respectively. The obtained results are compared with published data related to the same devices [29]. The agreement between the obtained results and those published previously are remarkable. Note that the proposed technique has the advantage that it needs no a prior knowledge of the parameters compared to non-linear least-squares optimisation method. The statistical indicators of accuracy show better results of the presented method.

Figs. 1 and 2 show a comparison between the experimental I–V data of the mono-Si solar cell and the CIS solar module at 25 °C and the fitted curves derived from Eq. (1) with the parameters extracted using our method.

Table 1
Extracted parameters obtained in this work and in Ref. [29] for a solar cell and a module

Parameters	Cell (33 °C)		Module (45 °C)	
	In Ref. [29]	In this work	In Ref. [29]	In this work
G_{sh} (Ω^{-1})	0.0186	0.0166	0.00182	0.00181
R_{s} (Ω)	0.0364	0.0364	1.2057	1.2030
n	1.4837	1.4816	48.450	48.1862
I_{s} (μA)	0.3223	0.3267	3.2876	3.0760
I_{ph} (A)	0.7608	0.7607	1.0318	1.0339
RMSE (%)	0.6251	0.3161	0.7805	0.6130
MBE (%)	–	0.0418	–	−0.2757
MAE (%)	–	0.1786	–	0.3484

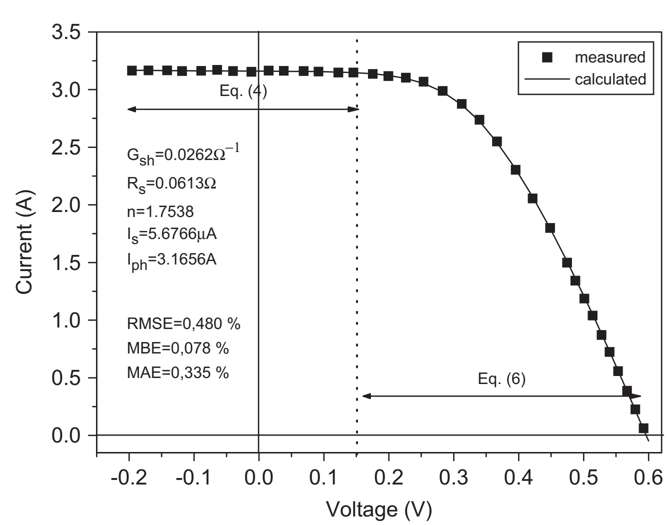

Fig. 1. Experimental (■), data and the fitted curve (—) for a silicon solar cell.

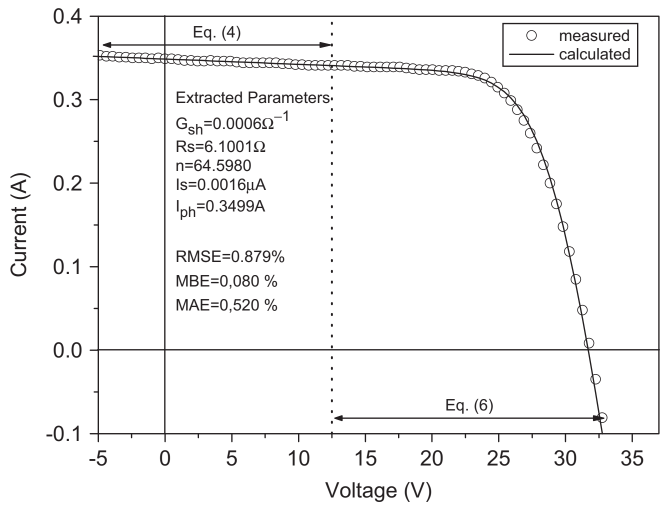

Fig. 2. Experimental (○), data and the fitted curve (—) for a CIS solar module.

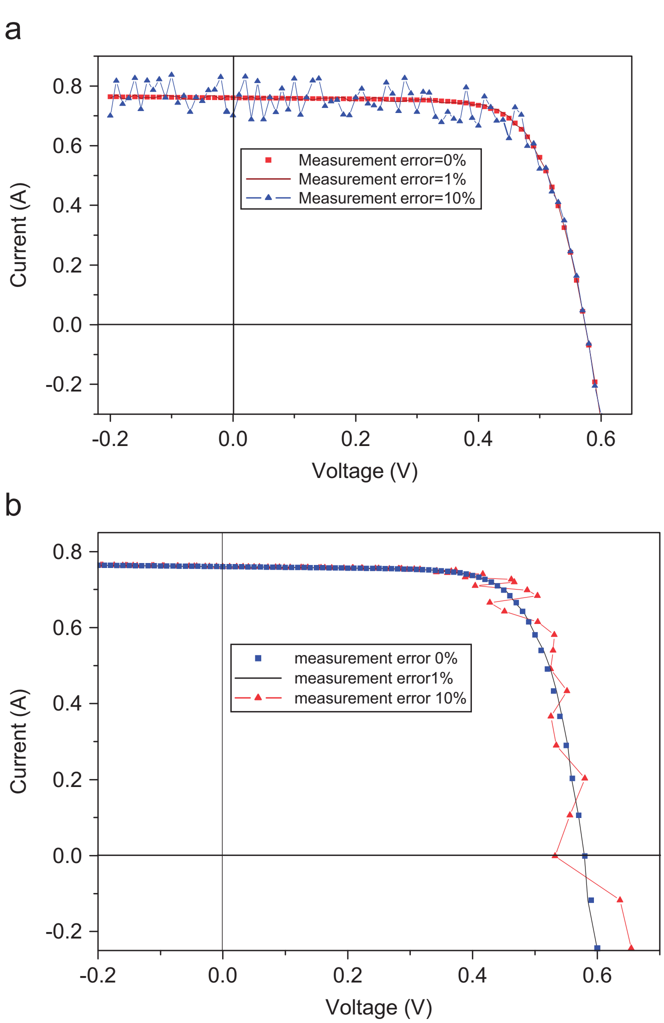

Fig. 3. I–V characteristics with and without measurement errors (i.e. noise). For this particular plot ($I_s = 0.3223\,\mu A$, $n = 1.4837$, $G_{sh} = 0.0186\,\Omega^{-1}$, $R_s = 0.0364\,\Omega$ and $I_{ph} = 0.7608\,A$ and noises of 0%, 1% and 10% are used). (a) Measurement errors on the current; (b): measurement errors on the voltage.

To check the accuracy, robustness and reliability of the present method, tests are carried out to extract the different parameters of interest considering possible electronic noise or random errors during measurements, the current or the voltage can be written as [35,36].

$$X_{\text{with noise}} = X_{\text{without noise}}(1 + \text{percent} \times \text{random}), \tag{16}$$

where $X_{\text{without noise}}$ is the simulated current or voltage and $X_{\text{with noise}}$ is the current or voltage including noise used in the procedure of extraction, percent is the relative percentage of error to be added and random is a randomly generated number between -1 and $+1$. A typical plot of the I–V data with and without measurement errors (i.e. noise) is presented in Fig. 3 with $I_s = 0.3223\,\mu A$, $n = 1.4837$, $G_{sh} = 0.0186\,\Omega^{-1}$, $I_{ph} = 0.7608\,A$ and $R_s = 0.0364\,\Omega$ for noises of 0%, 1% and 10%.

Fig. 4 shows the results obtained for the absolute relative errors of n, I_s, R_s, G_{sh} and I_{ph} extracted for various levels of measurement errors. The absolute relative error is defined as

$$\Delta P/P = \left|1 - P_{\text{noisy}}/P_{\text{exact}}\right|, \tag{17}$$

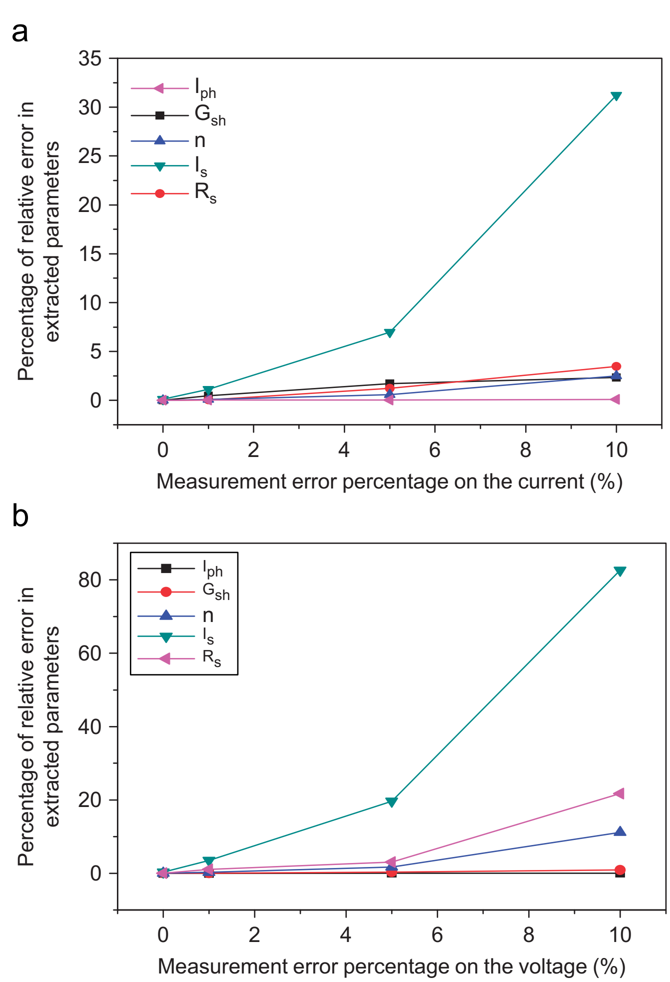

Fig. 4. The absolute relative errors of the extracted parameters resulting for various levels of noise measurements added to the original synthetic data. (a) Measurement errors on the current; (b): measurement errors on the voltage.

where P is the set of parameters $P = (G_{sh}, I_{ph}, n, R_s, I_s)$, $P_{exact} = (G_{sh} = 0.0186\,\Omega^{-1}, \quad I_{ph} = 0.7608\,A, \quad n = 1.4837, I_s = 0.3223\,\mu A$, and $R_s = 0.0364\,\Omega)$ and P_{noisy} is the set of parameters extracted from the noisy I–V characteristics using our method.

It is observed that the extracted n, R_s, G_{sh} and I_{ph} have very small absolute relative errors when the measurements are within the tolerance of a typical experimental setup. The extracted I_s has small absolute relative errors when the noise level is below 3% and becomes questionable when the noise exceeds this value.

4. Conclusion

This paper presents a simple method to extract the model parameters of illuminated solar cells containing a series resistance and a shunt conductance. The proposed technique is based on the measured or theoretical current–voltage characteristics. The results obtained are in good agreement with those published previously and with the experimental data. The method is quite accurate even when electrical noise or random errors are part of the measured I–V characteristics. The proposed method is easy, straightforward, does not require prior knowledge of any of the parameters of interest, less critical to the measurement device fidelity and allows automation of the measurement process.

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