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Contribution to the evaluation of the illuminated solar cells parameters

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Abstract. A contribution to the evaluation of the illuminated solar cells parameters (the series resistance Rs, the ideality factor n, the saturation current Is, the photocurrent Iph, and the shunt conductance Gsh) is dealt with in this paper. The suggested method uses the illuminated current–voltage (I –V) characteristics and the voltage dependent differential slope curve δ of solar cells. The procedure is verified using simulated and experimental I-V curves of different solar cells and modules. The extracted values are in good agreement when compared to the calculated values obtained by other published methods.

Key words: Solar cells, series resistance, shunt conductance, extraction.

1. Introduction

The simulation and design calculation of solar cell systems require an accurate knowledge of the parameters that describe the nonlinear electrical model of solar cells. These parameters are usually the saturation current, the series resistance, the ideality factor, the shunt conductance and the photocurrent. These parameters could be determined from the measured current–voltage (I–V) characteristics. Extracting these parameters is of vital importance for quality control and evaluation of the performance of solar cells when elaborated and during their normal use on site under different conditions of temperature and illumination.

Recent published works [1-16] have been proposed by several authors to determine the values of Rs, n, Is, I_{ph}, and Gsh. Some use the illuminated and dark I-V conditions [1,2], while others use dynamic measurements [3, 4] or integration procedures [5] based on computation of the area under the current-voltage curves.

Authors [6-7] have presented a review of techniques to determine the ideality factor and the series resistance of solar cells. Priyank et al [8] have proposed a method to extract the series resistance R_s and the shunt resistance R_{sh} using illuminated I-V characteristics in third an fourth quadrants and the Voc-Isc characteristics of the cell. An accurate method using Lambert W-function was presented by Jain and Kapoor [9].

Another method uses an auxiliary function to evaluate the five parameters has recently been presented [10]. Numerical techniques have been also used to calculate the parameters. These are based on the application of algorithms to optimize functions defining the difference between the experimental characteristics and the theoretical model [11, 12, 14], however, the optimisation techniques need prior knowledge of the parameters of interest, i.e. initial guesses, they present some disadvantages. For example, the five-point method [14] gives parameter values that are close to those obtained by the optimization methods. Although it seems faster and simpler, the uncertainties prevailing in measuring the open circuit voltage and the short circuit current, in locating the maximum power point and in graphically determining the two slopes impede an accurate solution for the parameters, and thus, a constructed fit may not accurately represent the I–V characteristics over its whole range. The simple conductance technique [15] has the advantage that it needs no prior knowledge of the parameters. However, the drawbacks of this method are that in the case of the module, the calculated saturation current is far higher than that obtained using the other techniques, and it does not give all the parameters simultaneously.

Mikhelashvili et al [13] proposed a method based on the current–voltage (I –V) characteristics and the voltage-dependent differential slope in order to extract the relevant device parameters of the nonideal Schottky barrier, p-n and p-i-n diodes.

Here this method 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, Rs and Is) in order to fit a given experimental current-voltage characteristics using a single diode lumped circuit.

2. Description of the method

For an individual solar cell, or for a module consisting of several cells under illumination, the current–voltage characteristic is modeled with the standard one diode model consisting of single series and shunt resistance, and the current–voltage (I–V) relation is given by

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

The five parameters to be determined are the photocurrent I_{ph}, the series resistance Rs, the shunt conductance G_{sh}, the saturation current Is, and the ideality factors n. β=q/kT is the thermal voltage.
Equation (1) may be written as:

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

Where

$$\begin{cases} I_{pk} = \dfrac{I_{ph}}{1 + G_{sh}R_s} \\ I_0 = \dfrac{I_s}{1 + G_{sh}R_s} \\ G_k = \dfrac{G_{sh}}{1 + G_{sh}R_s} \end{cases} \quad (3)$$

For low bias voltages, the exponential part is negligible and equation (2) can be written as:

$$I = I_{pk} - G_k V \quad (4)$$

G_k, I_{pk} are evaluated from (4) by a simple linear fit.
The measured current –voltage are corrected considering the product (G_kV) which can be added in turn to the measured current, and we obtain the corrected current :

$$\mathrm{I_c} = \mathrm{I} + \mathrm{G_k V} \quad (5)$$

For (V+RsI)>>kT the current–voltage (I–V) relation becomes:

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

To extract the series resistance, the ideality factor and the diode saturation current, the expression (6) can be presented in the common form:

$$V = \frac{n}{\beta}\ln(I_{pk} - I_c) - \frac{n}{\beta}\ln I_0 - R_s I_c \quad (7)$$

The proposed technique makes use of the parameter (δ) defined by:

$$\delta = \frac{d\ln(I_{pk} - I_c)}{d\ln V} \quad (8)$$

A simple manipulation of eq (8) using eq (7), this parameter takes the form:

$$\delta = \frac{qV}{nkT + qR_s(I_{pk} - I_c)} \quad (9)$$

Figure 1 shows the plot of δ versus the voltage V. At low bias, the δ–V curve increases reaching a maximum δm before decreasing. For the maximum value δm of δ corresponding to the corrected current Icm, and the tension Vm, these values (δm, Icm and Vm) are easily found by differentiating Eq. (9) and setting dδ/dV=0. They are uniquely related to the parameters to be extracted as follows

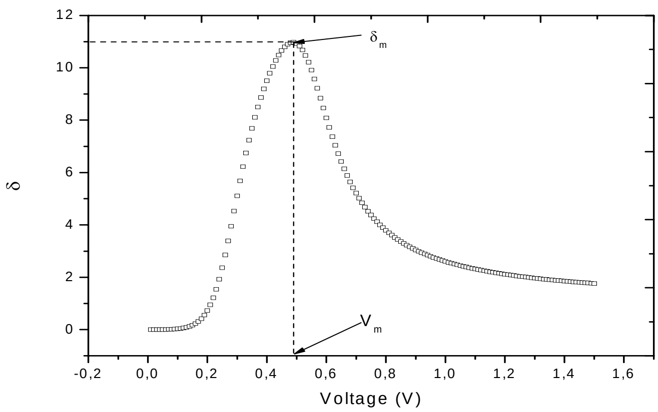

Fig. 1: Calculated δ–V characteristics of a solar cell with: Rs=0.0364Ω, n=1.48, Is=0.3223μA, G_{sh}=0.0186 Ω-1 and I_{ph}=0.7608A.

$$\begin{cases} R_s = \dfrac{V_m}{(I_{pk} - I_{cm})\delta_m^2} \\ n = \dfrac{qV_m(\delta_m - 1)}{kT\delta_m^2} \\ I_0 = (I_{pk} - I_{cm})\exp\left[\dfrac{1}{1-\delta_m}\left(\delta_m + \dfrac{I_{cm}}{I_{pk} - I_{cm}}\right) - \delta_m\right] \end{cases} \quad (10)$$

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

$$\begin{cases} G_{sh} = \dfrac{G_k}{1 - G_k R_s} \\ I_{ph} = \dfrac{I_{pk}}{1 - G_k R_s} \\ I_s = \dfrac{I_0}{1 - G_k R_s} \end{cases} \quad (11)$$

3. Results and discussion

This technique has been applied to different solar cells and modules using experimental data of Easwarakhanthan et al. [11]. This consists of a 57 mm diameter commercial silicon solar cell (cell1) and a solar module in which 36 polycrystalline silicon cells are connected in series (Module1). Other measured data of a mono-Si solar cell of a 100 cm2 area (cell2) and a CIS solar module of 734 cm2 area (Module2) are also considered. In order to check the consistency of the curve fit obtained from eq (1) with the measured values, the root mean squared error was calculated from the following eq.

$$\sigma = \left[(1/N)\sum_{1}^{N}\left(I_{meas,i}/I_{cal,i} - 1\right)^2\right]^{1/2} \quad (12)$$

Where N is the total number of measured points, Imeas,i is the measured current value and Ical,i is the calculated current value. The measured points close to the open circuit condition have been avoided because the current is not well-defined [11].

The values of the extracted parameters for two experimental data, (Cell1 and module1 at 33°C and 45°C), are given in Table 1. For comparison, the resulting parameters extracted by three other methods are also given. These methods are the vertical optimization method [11] which consists of a non linear least-squares optimization algorithm based on the Newton method. The second one [14] is the modified analytical five-point method. The third method [10] is based on the I –V curve and the use of an auxiliary function to evaluate the five illuminated parameters. It is clear that all the parameters extracted with the proposed method are in excellent agreement with those published using previous methods.

Figures 2 and 3 show a comparison between the experimental I-V characteristics and the fitted curves using relation (1) are presented in. This shows a good agreement between the calculated values and the obtained for the two cases (cells and modules) are with standard deviation σ less than 1%.

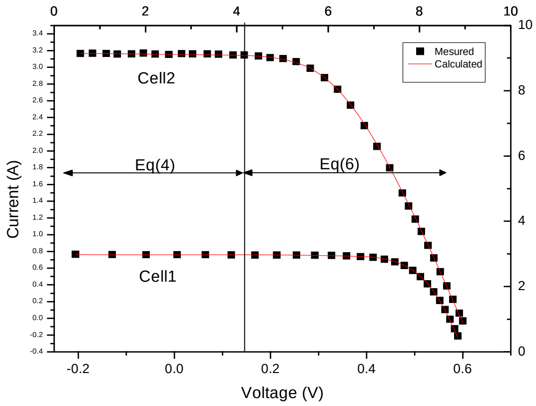

Fig.2. Experimental data (■) and the fitted curve for different silicon solar cells.

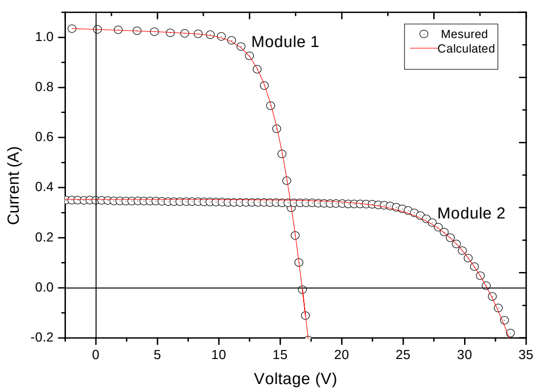

Fig.3. Experimental data (○) and the fitted curve for different solar modules

4. Conclusion

In this paper, we have described a simple, reliable, and accurate method, which can be applied to extract the fundamental parameters of solar cell (series resistance Rs, the ideality factor n, the saturation current Is, the photocurrent I_{ph}, and the shunt conductance G_{sh}) from the measured data under illumination. The proposed technique is based on the current-voltage characteristic, and on the voltage dependent differential slope curve δ(V). The suggested procedure was applied to different experimental illuminated I-V characteristics of solar cells and modules. The method is convenient to use and easy applicable to parameters extraction for illuminated solar cells. The obtained results are in good agreement with those published previously.

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Table1: Extracted parameters values of a solar cell1 and a module1 using various methods

parameters	**Cell 1 (33°C)**				**Module1 (45°C)**			
	Method [11]	Method [14]	Method [10]	Our Method	Method [11]	Method [14]	Method [10]	Our Method
G_{sh} (Ω^{-1})	0.0186	0.094	0.0094	0.0166	0.00182	0.00145	0.00145	0.00181
R_s (Ω)	0.0364	0.0422	0.0376	0.0328	1.2057	1.2226	1.1619	1.1922
n	1.4837	1.4513	1.4841	1.4983	48.450	47.533	50.99	47.1922
Is (µA)	0.3223	0.2417	0.3374	0.3943	3.2876	2.5908	6.3986	2.3528
I_{ph} (A)	0.7608	0.7606	0.7603	0.7607	1.0318	1.0320	1.030	1.0339
σ (%)	0.6251	0.216	-	0.3381	0.7805	0.110	-	0.7314