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A new method for evaluating illuminated solar cell parameters

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Abstract

A new method to evaluate the five illuminated solar cell parameters (series resistance R_s, the ideality factor n, the photocurrent I_{ph}, the shunt conductance G_{sh} and the diode saturation current I_s) is described. The method uses the measured current–voltage data and the resulting calculated conductance of the device.

By using the conductance, the number of parameters which has to be calculated is reduced and then only four parameters have to be extracted. A nonlinear least squares optimization algorithm based on the Newton model is hence used to evaluate these parameters. To overcome the difficulty in initializing the cell parameters, the simple conductance technique is used. When incorporated into microcomputer-based data acquisition software, the program allows theoretical modeling of solar cells. Results obtained for a commercial solar cell and a module are given. Comparison with other commonly used methods is also discussed. © 2001 Published by Elsevier Science Ltd.

1. Introduction

An accurate knowledge of solar cell parameters from experimental data is of vital importance for the design of solar cells and for estimates of their performance. The major parameters are usually the diode saturation current, the series resistance, the ideality factor, the photocurrent and the shunt conductance.

The evaluation of these parameters has been the subject of investigation of several authors [1–14]. Some of the methods involve measurements of illuminated *I–V* characteristics at single or different levels of illumination [1–8], some use dark conditions [9–11], while others utilize dark and illumination measurements [12–14].

Over the years several methods have been suggested for extracting the series resistance of a solar cell, but the other parameters have not received the same amount of attention and few methods of extracting the other parameters have been proposed.

A review of techniques to determine 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].

2. Theory and application

The *I–V* characteristics of the solar cell can be presented by either a two diode model [11,18–22] or by a single diode model [23]. Under illumination and normal operating conditions, the single diode model is however the most popular model for solar cells [24].

In this case, the current voltage (*I–V*) relation of an illuminated solar cell is given by:

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

Here I_d is the diode current and I_p describes the shunt current through the parallel conductance G_{sh}. I_{ph}, I_s, n and R_s being the photocurrent, the diode saturation current, the ideality factor and the series resistance, respectively. $\beta = q/kT$ is the usual inverse thermal voltage.

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

Eq. (1) is implicit and cannot be solved analytically. The proper approach is to apply least squares techniques by taking into account the measured data over the entire experimental I–V curve and a suitable nonlinear algorithm in order to minimize the sum of the squared errors.

Several methods [19,25,26] have been used, but Newton's method remains attractive with the number of variables being limited and their partial derivatives easily obtainable. Of interest for the sake of comparison, is a nonlinear least-square optimization algorithm based on the Newton method modified by introducing the so-called Levenberg parameter. This was proposed by Easwarakhantan et al. [26] and used to extract the five illuminated solar cell parameters mentioned above.

In this work the measured current–voltage curve and its derivative are used [27–29]. A nonlinear least squares optimization algorithm based on the Newton model is hence used to evaluate the solar cell parameters. The problem is then to minimize the objective function S with respect to the set of parameters P :

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

where P is the set of unknown parameters $P = (I_s, n, R_s, G_{sh})$ and I_i, V_i are the measured current, voltage and the computed conductance $G_i = \mathrm{d}I_i/\mathrm{d}V_i$ respectively at the ith 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 [30].

The conductance G can be written as :

$$G = -\frac{\chi}{1 + R_s\chi} \tag{3}$$

where χ is given by:

$$\chi = \frac{\beta}{n}\left\{I_{ph} + I_s - I - G_{sh}(V + R_s I)\right\} + G_{sh} \tag{4}$$

The term between brackets is equal to $I_s \exp(\beta/n\,(V + IR_s))$ and when replaced in Eq. (4), the conductance G will be independent of the photocurrent I_{ph}. Consequently, by minimizing the sum of the squares of the conductance residuals instead of minimizing the sum of the squares of current residuals as in Ref. [26], the number of parameters to be calculated is reduced from five $P = (I_s, n, R_s, G_{sh}, I_{ph})$ to only four parameters $P = (I_s, n, R_s, G_{sh})$ which is the main idea developed in this contribution. The fifth parameter, the photocurrent, can be easily deduced using Eq. (1) at $V = 0$, which yields to the following equation (Eq. (13) in Ref. [17]):

$$I_{ph} = I_{sc}(1 + R_s G_{sh}) + I_s\left(\exp\frac{\beta I_{sc} R_s}{n} - 1\right) \tag{5}$$

where I_{sc} is the short circuit current.

It is therefore necessary to emphasize that the here 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 [27].

For minimizing the sum of the squares, it is necessary to solve the equations

$$F(P) = \frac{\partial S}{\partial P} = 0 \tag{6}$$

Newton's method is used to obtain an approximation to the exact solution for the nonlinear resulting set of equations $F(P) = 0$, derived from multivariate calculus for a minimum to occur:

$$(P_j) = (P_{j-1}) - [J(P)]^{-1}F(P) \tag{7}$$

where $J(P)$ is the Jacobian matrix which elements are defined by:

$$J = \frac{\partial F}{\partial P} \tag{8}$$

Although the Newton procedure converges rapidly, it has a major difficulty in converging to the solution unless a sufficient accurate starting point for P is found. To overcome this problem the simple conductance technique recently published by the authors has been used [29]. Hence, these initial values are injected in the optimization program in order to determine the model parameters.

As test examples, the measured I–V data of a 57 mm diameter commercial (RTC France) silicon solar cell and a solar module (Photowatt-PWP 201) in which 36 polycrystalline silicon cells are connected in series are considered [26].

The program converges rapidly and the obtained four cell and module optimal parameters are given in Table 1.

Using the method proposed here for both the solar cell and the module, the obtained results are compared with published data related to the same devices [26]. The agreement between the obtained results and those published previously is remarkable particularly in the case of the solar cell. In Fig. 1, the solid squares are the experimental data for the solar cell and the solid line is the fitted curve derived from Eq. (1) with the parameters shown in Table 1. Fig. 2 shows similar results for the solar module.

The method also avoids the problems of undesired oscillations because starting values are close enough to

Table 1
Optimal parameters obtained in Ref. [26] and in this work

P	Cell (33°C)		Module (45°C)	
	In Ref. [26]	In this work	In Ref. [26]	In this work
$G_{sh}(\Omega^{-1})$	0.0186	0.0202	0.00182	0.005
R_s (Ω)	0.0364	0.0364	1.2057	1.146
n	1.4837	1.5039	48.50	51.32
I_s (μA)	0.3223	0.4039	3.2876	6.77
I_{ph} (A)	0.7608	0.7609	1.0318	1.0359

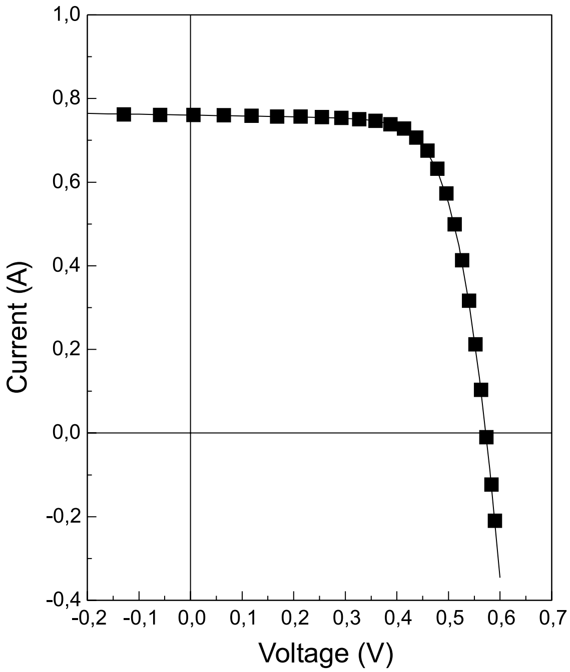

Fig. 1. Experimental (■) data and the fitted curve (—) for the commercial (RTC France) solar cell.

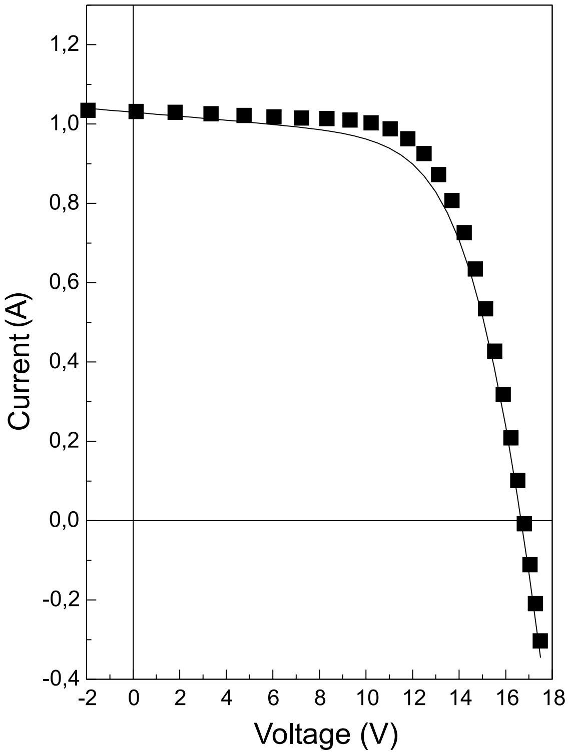

Fig. 2. Experimental (■) data and the fitted curve (—) for the commercial (Photowatt-PWP 201) solar module.

the optimal parameters. The parameters precision and the quality of the fit can obviously be improved using a small voltage step ($\approx$1 mV or less) when numerically deriving the measured *I–V* data to get more accurate values for *G*.

It should be noted that in the case of a module, although the theoretical model fits with the experimental data except around the maximum power point, the model parameters (particularly the ideality factor), are not well related to the physical phenomena which are intrinsically existing. This is due to the differences between the cells which are connected in series and/or parallel to form modules.

3. Conclusion

This contribution presents and examines an alternative method for computing the series resistance, ideality factor, diode saturation current and shunt conductance in solar cells. In contrast to numerical techniques that have already been developed for this purpose, the proposed technique is not only based on the *I–V* characteristic but also on the derivative of this curve, i.e. the conductance *G*. By using this method , the number of parameters which should be extracted is reduced. To the best of our knowledge, it is the first time that the minimization is done on the *G–V* curve instead of the *I–V* characteristic generally used. Furthermore the present method, tested for selected cases, is easy and straightforward. The fitted curve obtained for a solar cell show a complete coincidence with experimental curve. The parameter precision can obviously be improved using a small voltage step in order to obtain a better approximation of the real derivative of the *I–V* curve.

The method can be applied to pn junctions as well as Schottky diodes since Eq. (1) is representing both cases with $I_{ph} = 0$.

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