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Extracting dc parameters of solar cells under illumination

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Abstract

This paper presents a comparative study of four methods for extracting solar cell parameters of the single diode lumped circuit model. These parameters are usually the saturation current, the series resistance, the ideality factor, the shunt conductance and the photocurrent. The methods are the vertical optimization method, the modified analytical five-point method, and two methods we have proposed, are based on the current–voltage characteristics and the subsequently calculated conductance. Parameter values were extracted using these different methods from experimental I–V characteristics of a commercial solar cell and a module.

Keywords: Illuminated conditions; Solar cell; Solar cell parameters

1. Introduction

The knowledge of solar cell model parameters from measured current–voltage (I–V) characteristics is of vital importance for the quality control and evaluation of the performance of the solar cells. Several authors [1–16,32] proposed methods to devise ways for extracting the parameters that describe the non-linear electrical model of solar cells. These parameters are usually the saturation current, the series resistance, the ideality factor, the shunt conductance and the photocurrent. Some of the suggested methods involve both illuminated and dark I–V characteristics [1,2], while others use dynamic measurements [3,4] or integration procedures [5] based on the computation of the area under the current–voltage curves.

In addition, least-squares numerical techniques [14–23] 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 method modified by introducing the so-called Levenberg parameter [24].

Another method [26], that we have slightly modified, is based on the experimental voltage and slope at the open-circuit point, the maximum power point, and the current and slope at the short-circuit point, is also dealt with.

Werner [25] proposed a method based on the current and the conductance of both Schottky

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diodes and pn junctions [27,29] to extract relevant device parameters. This technique has been adequately modified, extended to cover the case of solar cells, and used to extract the parameters of interest [28]. The second method we have proposed is a non-linear least-squares optimization algorithm [31] based on the Newton model using the measured current–voltage data and the subsequently calculated conductance of the device.

2. Theory and analysis

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

$$\begin{aligned} I &= I_{\mathrm{ph}} - I_{\mathrm{d}} - I_{\mathrm{p}} \\ &= I_{\mathrm{ph}} - I_{\mathrm{s}}\left[\exp\left(\frac{\beta}{n}(V + IR_{\mathrm{s}})\right) - 1\right] \\ &\quad - G_{\mathrm{sh}}(V + IR_{\mathrm{s}}), \end{aligned} \tag{1}$$

I_{ph}, I_{d}, I_{s}, n, R_{s} and G_{sh} ($=1/R_{\mathrm{sh}}$) being the photocurrent, the diode current, the diode saturation current, the diode quality factor, the series resistance and the shunt conductance, respectively. I_{p} is the shunt current and $\beta = q/kT$ is the usual inverse thermal voltage. Eq. (1) is implicit and nonsolvable analytically.

2.1. *The vertical optimization method*

This method consists of a non-linear least-squares optimization algorithm based on the Newton method modified by introducing the so-called Levenberg parameter. This was proposed by Easwarakhanthan et al. [24] and used to extract the five illuminated solar cell parameters mentioned above.

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

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

where P is the set of unknown parameters $P = (I_{\mathrm{ph}}, I_{\mathrm{s}}, n, R_{\mathrm{s}}, G_{\mathrm{sh}})$ 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

$$(P_j) = (P_{j-1}) - [J(P)]^{-1} F(P), \tag{3}$$

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

2.2. *The modified analytical five-point method*

Using this method the characteristic parameters of the solar cell are computed from the values of the open-circuit voltage V_{oc}, the short-circuit current I_{sc}, the voltage at maximum power point V_{m}, the current at maximum power point I_{m}, the slope at open-circuit point R_{s0}, and the slope at short-circuit point R_{sh0} measured from the I–V characteristic. The following expressions are derived [26].

$$R_{\mathrm{sh}} = R_{\mathrm{sh0}} = -\left.\frac{\mathrm{d}V}{\mathrm{d}I}\right|_{I=I_{\mathrm{sc}}} \tag{4}$$

$$n' = \frac{\beta A}{B + C}, \tag{5}$$

where

$$\begin{aligned} A &= V_{\mathrm{m}} + R_{\mathrm{s0}} I_{\mathrm{m}} - V_{\mathrm{oc}}, \\ B &= \ln\left(I_{\mathrm{sc}} - \tfrac{V_{\mathrm{m}}}{R_{\mathrm{sh0}}} - I_{\mathrm{m}}\right) - \ln\left(I_{\mathrm{sc}} - \tfrac{V_{\mathrm{OC}}}{R_{\mathrm{sh}}}\right), \\ C &= \frac{I_{\mathrm{m}}}{I_{\mathrm{sc}} - V_{\mathrm{oc}}/R_{\mathrm{sh0}}}, \end{aligned}$$

$$I_{\mathrm{s}} = \left(I_{\mathrm{sc}} - \frac{V_{\mathrm{oc}}}{R_{\mathrm{sh}}}\right)\exp\left(-\beta\frac{V_{\mathrm{oc}}}{n'}\right), \tag{6}$$

$$R_{\mathrm{s}} = R_{\mathrm{s0}} - \frac{n'}{\beta I_{\mathrm{s}}}\exp\left(-\beta\frac{V_{\mathrm{co}}}{n'}\right), \tag{7}$$

$$I_{\mathrm{ph}} = I_{\mathrm{sc}}\left(1 + \frac{R_{\mathrm{s}}}{R_{\mathrm{sh}}}\right) + I_{\mathrm{s}}\left(\exp\beta\frac{I_{\mathrm{sc}}R_{\mathrm{s}}}{n'} - 1\right), \tag{8}$$

where

$$R_{\mathrm{s0}} = -\left.\frac{\mathrm{d}V}{\mathrm{d}I}\right|_{V=V_{\mathrm{oc}}}. \tag{9}$$

R_{s0} and R_{sh0} are obtained from the measured characteristic by a simple linear fit.

We have slightly modified the expression of the ideality factor and is given by

$$n = 10\,n'. \tag{10}$$

2.3. Our methods

The techniques we have developed use the measured current voltage characteristics and the subsequently calculated conductance of the device.

2.3.1. The conductance optimization method

A non-linear least-squares optimization algorithm based on the Newton model is used to evaluate the different solar cell parameters. The problem consists of minimizing the objective function S with respect to the set of parameters P [31]

$$S(P) = \sum_{i=1}^{N}[G - G_i(V_i, I_i, P)]^2, \tag{11}$$

where P is the set of unknown parameters $P=(I_s, n, R_s, G_{sh})$ and I_i, V_i are respectively the measured current, voltage and the computed conductance $G_i= \mathrm{d}I_i/\mathrm{d}V_i$ at the ith point among N measured data points. Note that the differential conductance was determined numerically for whole I/V curve using a method based on the least-squares principle and a convolution [30].

The conductance can be written as

$$G = -\frac{\chi}{1 + R_s\chi}, \tag{12}$$

where χ is given by

$$\chi = \frac{\beta}{n}\{I_{ph} + I_s - I - G_{sh}(V + R_s I)\} + G_{sh}. \tag{13}$$

The term between the curly brackets is equal to $I_s \exp(\beta/n(V + IR_s))$ is substituted into Eq. (13) and χ is then substituted into Eq. (12), 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 the first method, 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 $P=(I_s, n, R_s, G_{sh})$. The fifth parameter, the photocurrent, can be easily deduced.

It is therefore stressed that the method proposed here is not based on the I–V characteristics alone, but also on the slope of this curve, i.e. the conductance G. 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 [25].

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

$$\frac{\partial S}{\partial x} = 0, \tag{14}$$

where x stands for all free parameters that are used for characterizing the I–V curve. The solution of these equations can be found using the Newton's method. Although Newton's procedure converges rapidly, it has a major difficulty in converging to the solution unless a sufficiently accurate starting point for P should be found.

To overcome this problem the simple conductance technique [28] has been used.

2.3.2. The simple conductance technique

This method is based on Werner's method [25] that uses the current and the conductance of both Schottky diodes and pn junctions to extract relevant device parameters. This method has been adequately modified and extended to cover the case of solar cells, and used to extract the parameters of interest. For large negative bias voltages $-qV \gg kT$, with shunt resistance $R_{sh} = 1/G_{sh} \gg R_s$, which is usually true, the shunt conductance G_{sh} is evaluated from the reverse bias characteristics by a simple linear fit. The calculated value of G_{sh} gives the shunt current $I_p = G_{sh}V$ which can be subtracted in turn from the measured current to yield the current across the solar cell.

Under forward bias for $V + R_s I \gg kT$ the current across the diode is given by

$$I = I_{ph} - I_S \exp\left(\frac{\beta}{n}(V + IR_s)\right) \tag{15}$$

from which the conductance $G = \mathrm{d}I/\mathrm{d}V$ of the diode is obtained

$$G = -\frac{\beta}{n}(1 + R_s G)(I_{ph} - I). \tag{16}$$

The above equation can be written in a more convenient form as

$$\frac{G}{(I_{ph} - I)} = -\frac{\beta}{n}(1 + R_s G). \tag{17}$$

Eq. (17) shows that a plot of $G/(I_{ph} - 1)$ versus the conductance G should give a straight line that yields $-\beta/n$ from the intercept with the y-axis and slope $-\beta R_s/n$. For most practical solar cells, we usually have $I_s \ll I_{ph}$ such that the approximation $I_{ph} \cong |I_{sc}|$ (I_{sc} is the short-circuit current) is highly acceptable and introduces no significant errors in subsequent calculations.

The saturation current I_s was evaluated using a standard method based on the forward I–V data [30]. Prior to this, the I–V data were corrected by taking into account the effect of the series resistance as obtained from the linear plot of $G/(I_{ph} - 1)$ versus G.

The values obtained are then taken as initial values and entered 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 taken from the work of Easwarakhanthan et al. [24].

In order to test the quality of the fit to the experimental data, the standard deviation σ is calculated as

$$\sigma = \left[(1/m)\sum_{m=1}^{25}(I_{cal,i}/I_i - 1)^2\right]^{1/2}, \tag{18}$$

where $I_{cal,i}$ is the current caculated for each V_i, by solving the implicit Eq. (1) with the determined set of parameters $P = (I_{ph}, I_s, n, R_s, G_{sh})$. (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 [24].

The results obtained using the different methods proposed here for both the solar cell and the module are given in Table 1. The agreement between the results obtained is remarkable particularly for the solar cell. Figs. 1 and 2 show a comparison between the experimental data and the fitted curves derived from (1) with the parameters shown in Table 1.

Table 1
Extracted parameters using different methods for a solar cell and a module

Parameter	Vrt Opt.	An.5-Pt.	CndOpt	SmpCnd
Cell (33°C)				
$G_{sh}(\Omega^{-1})$	0.0186	0.0094	0.0202	0.02386
$R_s(\Omega)$	0.0364	0.0422	0.0364	0.0385
n	1.4837	1.4513	1.5039	1.456
I_s (μA)	0.3223	0.2417	0.4039	0.46
I_{ph} (A)	0.7608	0.7606	0.7608	0.7603
σ (%)	0.0303	0.0216	0.0102	0.6284
Module (45°C)				
$G_{sh}(\Omega^{-1})$	0.00182	0.00145	0.005	0.00145
$R_s(\Omega)$	1.2057	1.2226	1.146	1.2293
n	48.450	47.533	51.32	48.93
I_s (μA)	3.2876	2.5908	6.77	46
I_{ph} (A)	1.0318	1.0320	1.035	1.030
σ (%)	0.0149	0.0110	0.1384	5.312

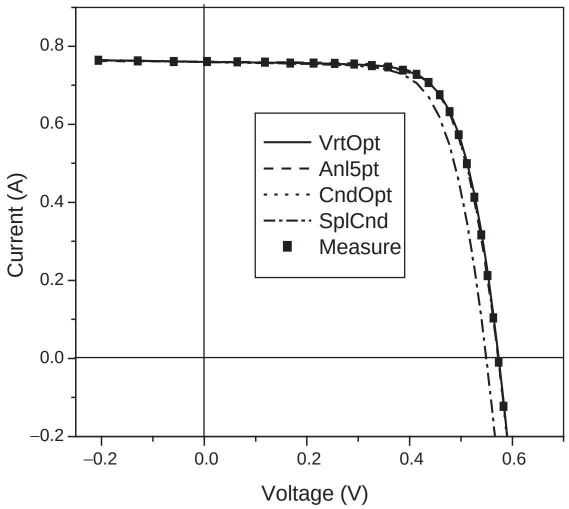

Fig. 1. Experimental data (■) and the fitted curves for the commercial (RTC France) solar cell.

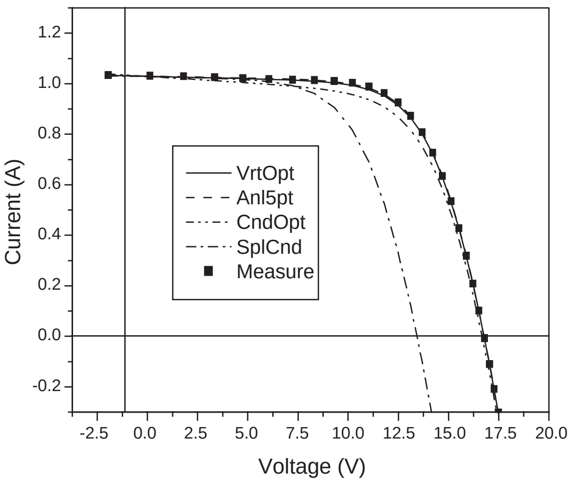

Fig. 2. Experimental data (■) and the fitted curves for the commercial (Photwatt-PWP 201) solar module.

3. Conclusion

We have compared four methods to extract the solar cells parameters: our methods, the modified analytical five-point method and the vertical optimization method. The modified analytical five-point method gives parameter values that are close to those obtained by the optimization techniques. 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. Our simple conductance technique has the advantage that it needs no prior knowledge of the parameters. Note however, the drawbacks of the method are that in the case of the module, our calculated saturation current is far higher than that obtained numerically [28] and it does not give all the parameters simultaneously which is the main advantage of non-linear least-squares methods. We believe that the modified procedure used here is more reliable to obtain physically meaningful parameters. The parameter precision can obviously be improved using a small voltage steps (typically less than 1 mV) when numerically deriving the measured *I–V* data to get more accurate values. Indeed, by minimizing the sum of the squares of the conductance residuals, which is the case of our second method, instead of minimizing the sum of the squares of current residuals as in [24], the number of parameters to be calculated is reduced from five to only four parameters. The fifth parameter, the photocurrent, can easily be deduced and it is therefore to be emphasized that our proposed method is not based on the *I–V* characteristics alone, but also on the slope of this curve, i.e. the conductance *G*. The method also avoids the problems of undesired oscillations because starting values are close enough to the optimal parameters.

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