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A simpler method for extracting solar cell parameters using the conductance method

Z. Ouennoughi*, M. Chegaar

Institut de Physique, Université Ferhat Abbas, Setif 19000, Algeria

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Abstract

This paper presents and examines an alternative method for determining the series resistance, the ideality factor, the saturation current and the shunt conductance in solar cells. The technique uses the measured current voltage characteristics and the subsequently calculated conductance of the device. Although numerical techniques have been readily developed for such purposes, the alternative technique presented here avoids the difficulties and problems that are likely to arise when using very specialized numerical methods. Furthermore the present method, tested for selected cases, is easy, straightforward and requires no prior knowledge of any of the parameters of interest. The results obtained for a solar cell and a module are in good agreement with previously published data.

1. Introduction

Based mainly on the measured current-voltage (I–V) characteristics, a variety of methods have been proposed by several authors [1–13] in the past to devise ways for determining the parameters which 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. 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.

Warashina and Ushirokawa [6] have developed an elegant graphic method to obtain R_s and n. These authors take the dynamic resistance instead of the dynamic conductance considered here. Another paper which discusses these matters is by Miahle et al. [7]. Other parameters are usually computed with classical approximations near the short-circuit region. These approximations have been elaborated in several papers [8–13].

In addition least-square numerical techniques [14–23] have been proposed. Among the latter, and of interest for us here 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 [24] and used to extract the five illuminated solar cell parameters mentioned above.

A related calculation method, based on the current and the conductance of both Schottky diodes and pn junctions, was suggested recently [25] and was applied successfully to Pt/Si [25], Au/InP [26] and W/n-Si Schottky diodes [27] as well as MIS tunnel diodes [28], to extract relevant device parameters.

Here, Werner's method [25] has been adequately modified, extended to cover the case of solar cells, and

* Corresponding author. Fax: +213-5-912-859.

E-mail address: physique@elhidhab.cerist.dz (Z. Ouennoughi)

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used to extract the parameters of interest. The results obtained are compared with previously published data related to the same devices [24].

2. Model and method of analysis

The current-voltage relation for a solar cell under illumination is given by

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

I_{ph}, I_s, n, R_s and G_{sh} being the photocurrent, the diode saturation current, the diode quality factor, the series resistance and the shunt conductance, respectively. $\beta = q/kT$ is the usual inverse thermal voltage. 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 $V + R_sI \gg kT$ the current across the diode is given by

$$I = I_{ph} - I_s\exp\left(\frac{\beta}{n}(V + IR_s)\right) \quad (2)$$

from which the conductance $G = dI/dV$ of the diode is obtained:

$$G = -\frac{\beta}{n}(1 + R_sG)(I_{ph} - I) \quad (3)$$

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

$$\frac{G}{(I_{ph} - I)} = -\frac{\beta}{n}(1 + R_sG). \quad (4)$$

Eq. (4) shows that a plot of $G/(I_{ph}-I)$ versus the conductance G should give a straight line that yields -β/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 [29]. Prior to this, the I–V data was corrected by taking into account the effect of the series resistance as obtained from the linear plot of $G/(I_{ph}-I)$ versus G above (Eq. 4).

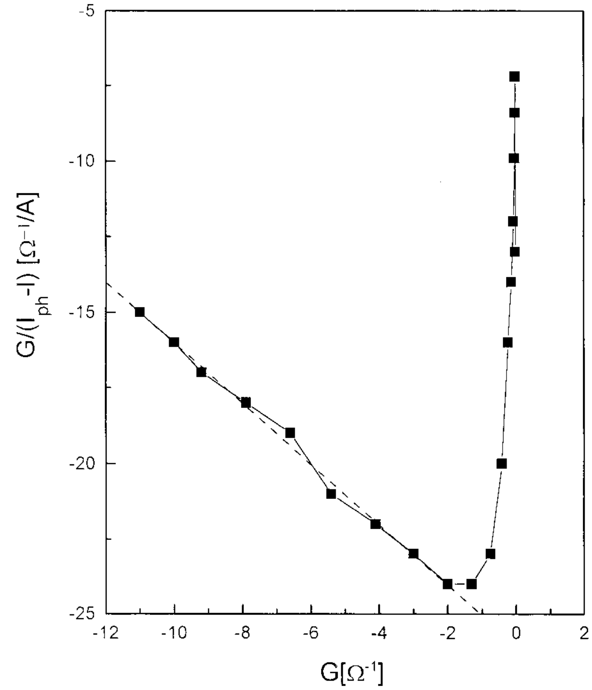

Fig. 1. Variation of $G/(I_{ph}-I)$ as a function of G for a commercial (R.T.C. France) solar cell. The y-axis intercept gives the value of -β/n. The slope is -$\beta R_s/n$. The dashed line represents the best linear fit.

The procedure proposed here is quite different from the method proposed by Warashina and Ushirokawa [6]. They have used the plot $-dU/dI$ versus $(I_{sc}-I)^{-1}$ and the R_s value has been obtained from the intersection point of the extrapolated line with the vertical axis. This plot is particularly unreliable because it uses the inverse current as abscissa and the differential resistance in a linear ordinate and the linear extrapolation yields unreliable fit results for the series resistance as shown by Werner [25]. Even though the relation found by Warashina and Ushirokawa [6] and our relation Eq. (4) seem to be mathematically similar, when applied to physical systems our approach will yield the best basis for a reliable evaluation of I–V data. The slight advantage is based on the use of conductance G as abscissa which varies even less with voltage than the current I. Moreover, their method [6] has been criticized by other authors [7]. They confirm that the application of Warashina's method needs very low R_s values (about 0.01 Ω) and/or low shunt circuit current.

In the case of the examined solar cells, the plot G/I vs. G does not yield a straight line as it is suggested by

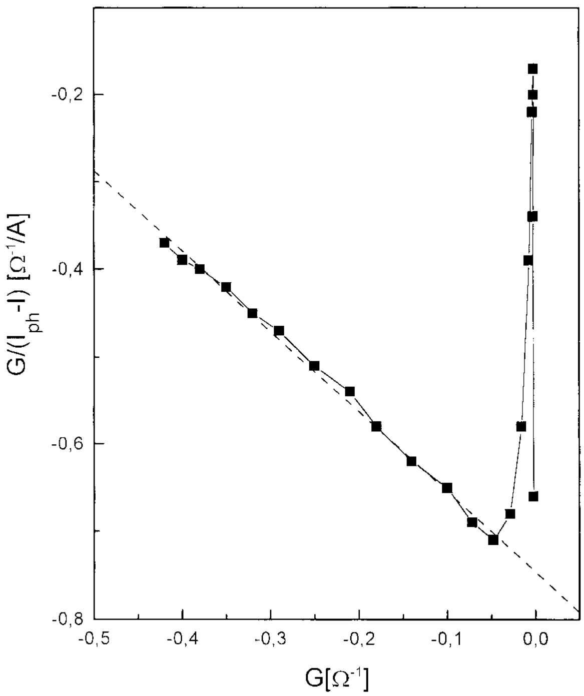

Fig. 2. Variation of $G/(I_{ph}-I)$ as a function of G for a commercial (Photowatt PWP 201) solar module. The y-axis intercept gives the value of $-\beta/n$. The slope is $-\beta R_s/n$. The dashed line represents the best linear fit.

Werner [25] and verified on Schottky diodes and pn junctions [25–27]. The modified plot $G/(I_{ph}-I)$ vs. G gave, however a fairly straight line over more than two decades. It is to be noted that when $I_{ph}=0$, Eq. (4) is similar to Eq. (8) in Werner's work defined and known therein as plot A. It is this modified equation ($I_{ph} \neq 0$) that was used to yield the relevant parameters of commercial solar cells.

3. Results and discussion

Experimental current-voltage (I–V) data were taken from Easwarakhantan work [24]. The photocurrent has been taken directly as the short circuit current according to the approximation $I_{ph} \cong |I_{sc}|$. The reverse bias characteristics have been used to calculate the shunt conductance $G_{sh}=1/R_{sh}$ using a simple linear fit. The differential conductance was then determined numerically for voltages in the forward region. We used a method based on the least squares principle and a convolution [30].

Figures 1 and 2 show the plots of $G/(I_{ph}-I)$ vs. G for the solar cell and the module, respectively. It is clear that the plots are reasonably linear over an extended region which justifies the use of our modified model. We can also notice that $G/(I_{ph}-I)$ vs. G plots reach both a minimum as G approaches zero. Such a behavior was noticed in Werner's plots [25] and was ascribed to the effect of an incomplete correction of the current across a cell due to the shunt current I_p.

The series resistance and the ideality factor were, in fact, obtained from linear least square fits to the data between two conductance boundaries - the two points respectively to the left and to the right of the linear portion and beyond which linearity is lost. For the solar cell a fit between $-11\ \Omega^{-1}$ and $-2\ \Omega^{-1}$ yields $R_s=0.0385\ \Omega$ and n = 1.456 for the series resistance and the ideality factor respectively. It turns out from our calculations that neither the variations of the lower (left) and upper (right) boundary conductance nor the correction for the shunt current (I_p) are critical for the fits carried out here and consequently do not have significant influence on the determination of R_s and n. Naturally, additional ideality factors are also obtained from the slope of the corrected plot. The values obtained are close to those obtained initially from the $G/(I_{ph}-I)$ vs. G plots. The results are summarized in Table 1. These values are in good agreement with those obtained by the numerical method of

Table 1
Obtained parameters in Ref. [24] and when using the method proposed here for both the solar cell and the module

	Cell (33°C)		Module (45°C)	
	method used by (Easwarakhantan et al. [24])	method of this work	method used by (Easwarakhantan et al. [24])	method of this work
G_{sh} (Ω^{-1})	0.0186	0.02386	0.00182	0.00145
R_s (Ω)	0.0364	0.0385	1.2057	1.2293
n	1.4837	1.456	48.450	48.93
I_s (μA)	0.3223	0.46	3.2876	46
I_{ph} (A)	0.7608	0.7603	1.0318	1.030

Easwarakhantan et al [24]. The small discrepancies observed between G_{sh} and I_s of this work and those obtained elsewhere [24] can be explained by the nature of the procedures used. Our G_{sh} value was calculated form the reverse bias and I_s was determined under forward bias while G_{sh} and I_s in ref. [24] were computed over the entire range of the I–V curves. The obtained values for the series resistance and the ideality factor are, however, practically identical. It should be noted that in the case of the module our calculated I_s is far higher than that obtained numerically. Although we do not understand and hence explain the reason of such a big discrepancy, we believe that the modified procedure used here is more reliable to obtain physically meaningful parameters. The parameters 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 for G. The effect of noise will be reduced consequently. The values of the so determined solar cell parameters are good estimation of the real quantities and could be taken as they are or used as good initial values in methods based on numerical routines which will possibly and logically result in further reductions of computation time and better accuracy.

4. Conclusion

We have applied a simple method, for the determination of the solar cell parameters, based on the computation of the derivative of the measured current–voltage characteristics. The method has been successfully applied to commercial solar cells and the results obtained are in good agreement with those published previously. Except the case of the photocurrent which can be measured directly, no a priori knowledge of parameters is required. Note however, the drawback of the method is that it does not give all the parameters simultaneously (in particular the dark current) which is the main advantage of nonlinear least squares methods. Also the use of the derivative G of the I–V curve instead of the I–V curve itself introduces extra noise resulting in uncertainties in the fitted parameters compared to nonlinear least squares methods. Nevertheless, the values of the so determined solar cell parameters are very close to the real parameters. The simple procedure described herein is easily adapted to microcomputer-based data acquisition software in laboratories.

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