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A simple solar cell series resistance measurement method

J. Cabestany and L. Castañer

E.T.S.I. Telecomunicacion, P.O. Box 30002, Barcelona, Spain. Telex 528281.

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Résumé. — On décrit une technique nouvelle et simple pour mesurer la résistance série d’une Cellule Solaire. Ce procédé ne demande que des mesures I(V) à l’obscurité et un dispositif expérimental simple, comprenant une résistance standard étalonnée. On discute aussi cette méthode par rapport à d’autres utilisées couramment.

Abstract. — A new and simple technique to evaluate the series resistance of a solar cell is described. This procedure only needs dark I(V) measurements and a simple experimental-arrangement including a calibrated standard resistor. Comparison with other commonly used methods is also discussed.

The series resistance of a solar cell is a parameter of special interest because of its influence in the maximum available power and fill factor. It is also a parameter that indicates in some way the quality of the device and can be used as production test.

There exists a number of methods to evaluate the series resistance of the cells based on I(V) characteristics, most of them using more than one I(V) curve (Refs. 1, 2).

The new method is based on the dark I(V) characteristics model that can be written with the help of figure 1, where \( R_s \) is the series resistance, \( R_{sh} \) is the shunt resistance and D1 and D2 — are the two diodes accounting for Shockley diffusion term (D1), and Space Charge Region recombination term (D2).

\[
I = \sum_{i=1}^{2} I_0 \left[ \exp \left( \frac{q(V - IR_s)}{n_i kT} \right) - 1 \right] + \frac{V - IR_s}{R_{sh}} \tag{1}
\]

where the first term, \( i = 1 \), is the current flowing through D1 and the second, \( i = 2 \), is the current that flows through D2. The last term takes into account the shunt current which can be an important effect for low bias levels.

Our method is based in the experimental arrangement shown in figure 2 where only the addition of an external calibrated resistor \( R_{\text{ext}} \) is needed. Obviously, the model given in equation 1 is still valid and only \( R_s \) must-be replaced by \( (R_s + R_{\text{ext}}) \). Series resistance effects appears for the higher voltage values where the term given by \( i = 2 \) and the last one can be neglected in front of the diffusion term modified by the series resistance effect.

Equation 1 can now be written as follows:

\[
\frac{I}{I_{01}} = \exp \left[ \frac{q(V - IR_s + R_{\text{ext}})}{KT} \right]. \tag{2}
\]

For several given values of the external resistor \( R_{\text{ext}} \), a set of I(V) curves is obtained being \( R_{\text{ext}} \) the parameter. Figure 3 shows a set of experimentally obtained I(V) curves in dark conditions.

In order to obtain the series resistance \( R_s \), two
strategies are possible, giving origin to two methods: A (constant voltage) and B (constant current).

Method A: Let us consider two \( I(V) \) characteristics of figure 3, corresponding to \( R_{\text{ext1}} \) and \( R_{\text{ext2}} \). We can easily determine the current values \( I_1 \) and \( I_2 \) of each characteristic corresponding to the same voltage value \( V_A \).

With the help of equation 2 it can be written that
\[
R_s = \frac{KT}{q} \ln \left( \frac{I_2}{I_1} \right) + \frac{I_2 R_{\text{ext2}} - I_1 R_{\text{ext1}}}{I_1 - I_2}.
\] (3)

Equation 3 gives \( R_s \) for a given value of \( I_1, I_2, R_{\text{ext1}} \) and \( R_{\text{ext2}} \). This method needs only two experimental dark measurements for constant voltage. Obviously, one resistor can be null (\( R_{\text{ext1}} = 0 \), for example).

Method B: Conversely the shape of the curves of figure 3 suggest that \( R_s \) could be also measured taking the voltage values corresponding to different \( I(V) \) curves for the same current-value. In such conditions equation 2 can be written as follows
\[
R_{\text{ext}} + R_s = \frac{1}{I} \left[ V + \frac{KT}{q} \ln \left( \frac{I_1}{I} \right) \right]
\] (4)

for several values of \( R_{\text{ext}} \), the function \( R_{\text{ext}} \) vs. \( V \) is a straight line with slope \( 1/I \). If, further, we take two current values, two sets of points are obtained that can be plotted as it is shown in figure 4. There are two

Fig. 4. — Implementation of method B.

straight lines of slopes \( 1/I \) and \( 1/I' \) intersecting at point Q. The ordinate of this point is
\[
R' = -R_s + \frac{KT}{q(I' - I)} \ln \left( \frac{I'}{I} \right)
\] (5)

\( R' \) can be easily and accurately calculated using a simple interpolation technique, then \( R_s \) value can be obtained from equation 5.

Table I shows the results obtained with methods A and B, on a commercially available cell indicating in each case the values of the parameters \( R_{\text{ext1}}, R_{\text{ext2}}, V_A, I, I' \) involved.

The same cell has been analysed using the Wolf and Handy methods (Ref. 1.2) and a numerical method.

<table>
<thead>
<tr>
<th>Method</th>
<th>Constant voltage ( V_A ) (V)</th>
<th>( R_{\text{ext1}} ) (Ω)</th>
<th>( R_{\text{ext2}} ) (Ω)</th>
<th>( R_s ) (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0'8</td>
<td>0</td>
<td>1</td>
<td>0'356</td>
</tr>
<tr>
<td></td>
<td>0'8</td>
<td>2</td>
<td>3</td>
<td>0'374</td>
</tr>
<tr>
<td></td>
<td>0'9</td>
<td>1</td>
<td>2</td>
<td>0'378</td>
</tr>
<tr>
<td></td>
<td>0'925</td>
<td>1</td>
<td>2</td>
<td>0'385</td>
</tr>
<tr>
<td>B</td>
<td>( I ) (A)</td>
<td>( I' ) (A)</td>
<td>( R_s ) (Ω)</td>
<td>Method</td>
</tr>
<tr>
<td></td>
<td>0'1375</td>
<td>0'1</td>
<td>0'34</td>
<td>Wolf</td>
</tr>
<tr>
<td></td>
<td>0'275</td>
<td>0'1375</td>
<td>0'364</td>
<td>Handy</td>
</tr>
<tr>
<td></td>
<td>0'275</td>
<td>0'25</td>
<td>0'404</td>
<td>Numerical</td>
</tr>
</tbody>
</table>
based on optimization algorithms (Ref. 3). Table I, also, includes these results.

We have checked the methods A and B with a terrestrial silicon solar cell. In such a device, series resistance values of the order of 0.01 Ω are expected. This fact makes very inaccurate the results obtained with the Wolf and Handy methods. The results are shown in table II.

Table II. — Results on a terrestrial solar cell.

<table>
<thead>
<tr>
<th>Method</th>
<th>Series resistance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method A</td>
<td></td>
</tr>
<tr>
<td>( V_A = 0.575 \text{ V} )</td>
<td></td>
</tr>
<tr>
<td>( R_{\text{ext}} = 0 \Omega )</td>
<td>0.0407</td>
</tr>
<tr>
<td>( R_{\text{ext}} = 1 \Omega )</td>
<td></td>
</tr>
<tr>
<td>Method B</td>
<td></td>
</tr>
<tr>
<td>( I = 0.175 \text{ A} )</td>
<td>0.0452</td>
</tr>
<tr>
<td>( I' = 0.15 \text{ A} )</td>
<td></td>
</tr>
<tr>
<td>Numerical (Ref. 3)</td>
<td>0.0392</td>
</tr>
</tbody>
</table>

The precision of the current and voltage measurements is ± 0.5% in the range of measurement. Those precisions and tolerances allow to say that a ± 3% accuracy is predicted for method A around the values given in the tables I and II.

The evaluation of the accuracy of the method B is not as simple than that of method A because the calculation procedure uses a numerical routine. Nevertheless the experimental arrangement uses the same equipments and the results obtained with method B are inside the tolerance of the values obtained with method A.

b) The values of \( R_s \) obtained by the two methods present a certain dispersion that can not be atributed to measurement inaccuracies. It is well known (Ref. 4) that the series resistance depends on the value of the current used in the measurement, more precisely, \( R_s \) increases when the current increases. This behaviour can be seen in our results of table I.

Conclusions.

We can conclude that the use of the two proposed methods is simple and the experimental complexity is lower than the other methods commonly used. The limitations of our methods are mainly two. First, these methods are not applicable when the series resistance is influenced by the photoconductivity of the upper solar cell layer. On the other hand, the methods applies only to the solar cells with \( I(V) \) characteristics that can be represented by equation 1 with the diode factor of the diffusion term equal to the unity.

References