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Université de Dakar, Ecole Normale Supérieure, Dakar-Fann[1] *(a),*
Lebanon University II, Mansourieh[2] *(b),*
and Centre d'Electronique de Montpellier,
Université des Sciences et Techniques du Languedoc[3] *(c)*

A Review of Techniques to Determine the Series Resistance of Solar Cells

By

P. MIALHE (a), A. KHOURY (b), and J. P. CHARLES (c)

A review of solar cell series resistance determinations is discussed from a theoretical point of view and from a confrontation with experimental results. The cell diode model is then considered to determine the limitation of each approximated method.

Les méthodes expérimentales conduisant à une détermination approchée de la résistance série d'une cellule solaire sont rapidement indiquées à travers une étude bibliographique. Les descriptions théoriques sont comparées à des résultats expérimentaux qui permettent de préciser les limites d'application de chaque méthode.

1. Introduction

The primary difficulty with high intensity operation in silicon photovoltaic cells of the standard sort has been their resistance to current flow. It is well known that the series resistance R_S is a power loss factor that decreases the maximum output power. Hence, R_S is an important parameter for concentrator solar cells. The introduction of a lumped series resistance depends on an approximate model, but it provides a practical method to estimate the losses and to characterize solar cells. An accurate knowledge of the value of R_S is necessary for predicting the output power at various light intensity levels in computer modelling.

In this paper we discuss all published works related to the experimental methods of R_S determination; a literature study of theoretical, approximate methods is briefly indicated; experiments with commercial solar cells are described and lead to a confrontation of the methods that enable one to determine the limitation of each approximate method.

2. Literature Review

Fig. 1 reproduces I–U characteristics of a solar cell generator under different solar irradiations; a good description of the characteristics may be achieved with the (I, U) relationship [1]

$$I = I_{\mathrm{ph}} - \frac{U + R_S I}{R_{\mathrm{Sh}}} - I_S \left[\exp\left(e\,\frac{(U + R_S I)}{(AkT)}\right) - 1\right], \tag{1}$$

[1]) B.P. 5036, Dakar-Fann, Senegal.
[2]) B.P. 72, Mansourieh, Lebanon.
[3]) Place E. Bataillon, 34060 Montpellier, France.

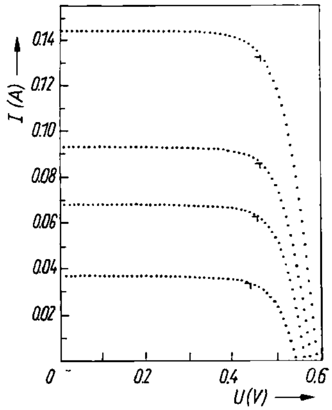

Fig. 1. Measured I–U curves. $T = 303.0$ K. ⌐ indication of the maximum power point

where I_{ph} is the light-generated current, I_S the diode dark saturation current, R_S and R_{Sh} are the series and shunt resistances, A is the diode quality factor. The macroscopic parameters I_{ph}, I_S, A, R_{Sh}, R_S are interesting because they are related to internal properties of the components of solar cells [2 to 4]. They are determined so that (1) gives a good fit of the characteristic in Fig. 1. Both experimental and theoretical methods for determining the series resistance are based upon the relationship described by (1).

These methods may be separated into two kinds depending on whether they need experiments with different illumination levels or whether they consider the cell under the condition of constant light intensity.

2.1 *Different illumination level methods*

Wolf and Rauschenbach [5] have proposed a determination of R_S from the characteristics obtained at two different illumination levels that give I_{sc1} and I_{sc2}, respectively, as short-circuit current; the graphical determination, on each curve, of the abscissa U_1 and U_2 of points such that ordinates are

$$I_i = I_{sci} - \delta \qquad (i = 1, 2) \tag{2}$$

with an arbitrary constant intensity δ, leads to

$$R_S = \frac{(U_1 - U_2)}{(I_{sc1} - I_{sc2})} \tag{3}$$

(it is referred to in this paper as the constant diode voltage (C.D.V.) method). It as been discussed later by some authors [6, 7, 8]; the determination may be done along the characteristics for different δ values: a large increase of R_S with increasing terminal current has been obtained. Cape and Zehr [9] pointed out a large "error" in the inferred value of R_S, introduced by a difference in temperature of the cells between the two measured points.

Another method [6, 5] consists in comparing the dark forward characteristic with the photovoltaic characteristic (referred to as the dark illumination curves (D.I.C.) method); after a translation $I' = I + I_{sc}$ applied to the dark curve, the difference ΔU between the two curves at ordinate I gives $R_S I_{sc}$. The authors got variations of R_S with terminal current or with temperature in good agreement with determinations using the C.D.V. method, and indeed, closer values when large δ values are utilized with the C.D.V. method. An alternate way of this method is the comparison of the plots of ln (I) versus U for the two characteristics; it has been discussed [10]. D.I.C. supposes that the modification of (I, U) characteristics caused by series resistances can be described by a simple translation, that is not exact [11, 12] and may explain the variations of R_S versus terminal current close to 5 ΩA^{-1}.

An equivalent method has been used by some authors [13, 14] who compared the forward (I, U) characteristic with (I_{sc}, U_{oc}) measurements.

Smirnov and Mahan [15] proposed a comparison of the experimental characteristic with an ideal curve (computed using (1) with $R_S = 0$); the measurement of the ΔU shift at the power maximum point gives $R_S = \Delta U/I_m$; it is not a pure graphic method, because it supposes to solve (1), and further it needs the previous determination of the other parameters.

From the graph of $\ln\big((I_{ph} - I_{sc})/I_S\big)$ versus I_{sc} (by increasing the illumination) Agarwal et al. [16] have shown that R_S can be calculated from the slope of the graph; it needs also the previous determination of the light-generated current I_{ph} and of the diode quality factor A.

2.2 Constant illumination level methods

In the case $R_S I_{sc} \ll U_{oc}$ Warashina and Ushirokawa [17] have developed an elegant graphic method to obtain R_S and A (referred to as G.M.S.): these authors showed, from (1), that the curve $-\mathrm{d}U/\mathrm{d}I$ versus $(I_{sc} - I)^{-1}$ is a straight line and that R_S may be extrapolated as the value of $-\mathrm{d}U/\mathrm{d}I$ for $(I_{sc} - I)^{-1}$ going to zero.

A particular case is the determination of R_S by the slope of the characteristic at $U = U_{oc}$ (referred to as V.O.C.S. method); from (1) we get

$$\left(\frac{\mathrm{d}I}{\mathrm{d}U}\right)_{U=U_{oc}} = -\frac{\beta I_{ph}}{(1 + R_S\beta I_{ph})} \tag{4}$$

with $\beta = e/(AkT)$; with the assumption that $R_S\beta I_{ph} \gg 1$ (4) leads to

$$R_S = -\left(\frac{\mathrm{d}U}{\mathrm{d}I}\right)_{U=U_{oc}}. \tag{5}$$

Cape and Zehr [9] found an approximated value of R_S from the determination of the maximum power point coordinates (I_m, U_m),

$$R_S = \frac{U_{oc}}{I_{sc}} - \frac{U_m}{I_m} \tag{6}$$

(referred to as M.P.M.). The authors claimed that very large I_{sc} values will have to be used to obtain sufficient accuracy; this comes from the approximation needed to derive (6).

A pure experimental method [18] has been derived from the measurements of I_{sc}, with the same illumination level, for different values of a resistor R put in series with the cell. The limit I_{ph} of I_{sc} versus R, when R reaches zero, enables to determine R_S (referred to as variable resistor series (V.R.S.) method).

Particular methods with pulsed light [9] or flash testing [19] have been published; they consider the cell out of thermal equilibrium and may be of interest for concentrator cooled solar cells.

At last, Araujo et al. [20] have considered a two-exponential model and an approach based on a least-squares technique for linear functions to determine the solar cell parameters.

A test of validity of each approximate method may be the degree of accuracy which is achieved with the measured parameter to describe the experimental characteristics. A practical method of analysis of the current-voltage characteristic of solar cells has been published by Charles et al. [21] (referred to as P.M.A. method); the macroscopic parameters R_S, R_{Sh}, I_S, A, and I_{ph} are computed, from experimental data for three points of the characteristic, to give the best fit of the experimental characteristic. The agreement between the calculated current and the experimentally observed current is within $\pm 0.5\%$ on average for the solar cells tested.

3. Results and Discussion

The value of R_S obtained with P.M.A. will be considered in the discussion as the best value and used as a reference (noted R_0) to enable a comparison with all the methods.

3.1 C.D.V. and D.I.C. methods

With C.D.V. and D.I.C. two points are of importance: as R_S may be calculated at various points along the I–U characteristic, one has to determine the point leading to a R_S value closer to the best one; the second point considers the application of the methods for different illumination levels to consider if the accuracy of the method is better at high or at low light intensity levels. In this way it seems better to speak of the multiple R_S values obtained along a characteristic than of a current dependence of R_S, since the value is single because it is introduced with the model considered in (1) to get a good fit of the (I, U) curve under study.

Results in Fig. 2a and 2b have been obtained with a commercial cell[4]), whose characteristics are shown in Fig. 1. (The cell was mounted on a copper block using water as coolant; the temperature was measured through a digital thermometer and a small 1 mm² platinum resistance surface transducer; the illuminated I–U characteristics were measured under 2 NORMA 100 W tungsten iodine quartz bulbs and

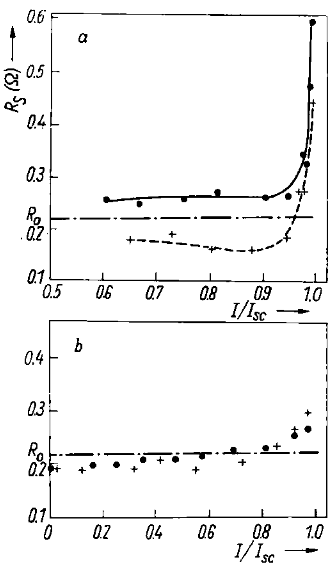

Fig. 2. Experimentally determined series resistances versus terminal current I relative to short-circuit current I_{sc} at two illumination levels: ● at 1.2 suns, + at 0.8 sun (R_0 is the best value); a) with constant diode voltage method (C.D.V.), b) with dark illumination curve method (D.I.C.)

4) Made by SAT, 41 rue Cantagrel, 75624 Paris Cédex 13, France.

a 1 cm water filter; the light intensity of the source was monitored through an electronic circuit with reference to the short-circuit current of a photovoltaic cell fixed near the bulbs.) The graphic determinations of R_S along the characteristics for two light levels (1.2 and 0.8 suns) are comparable for the two methods and yield the variation observed by Imamura and Portscheller [6]. The results compared to the R_0 value show a difference of about 12%. The graphic precision with C.D.V. is larger than 25% for I/I_{sc} values greater than 0.95 or lower than 0.75, and around 7% between these values when $\delta \gg I_{sc}/4$; it is 7% with D.I.C. when $I/I_{sc} \leqq 0.9$. This comes from the shape of the characteristics. An important point to be considered is the shift of the curve due to a temperature variation; with R_S in the form $R_S = \Delta U/\Delta I$ the error is

$$\Delta R_S \leqq \left(\frac{|\partial U/\partial T|}{\Delta I} + \frac{R_S\,|\partial I/\partial T|}{\Delta I}\right) \Delta T\,, \tag{7}$$

where the first contribution is of importance; since the temperature coefficient of U is $|\partial U/\partial T| \sim 2$ mV/K, with $\Delta I \approx 50$ mA equation (7) implies $\Delta R_S \leqq 0.04\,\Delta T$; we get ΔR_S values such as 0.2 Ω with $\Delta T = 5$ K, that is greater than a simple correction.

A study in modelling has been made with D.I.C. applied at $U = U_{oc}$ [13, 14]; we have compared the theoretical curves obtained with (1) when $I_{ph} = 0$ A: the results show for all I_{ph} values that the theoretical value of R_S equals $(\Delta U/I_{sc})_{U=U_{oc}}$ within 0.5%; we have obtained experimentally (see Fig. 2b at $I = 0$ A) the value $R_S = (0.19 \pm 0.015)$ Ω that is far from $R_0 = (0.22 \pm 0.01)$ Ω; these results signify that the one-diode model (1) is not able to describe with comparable accuracy the illuminated and the dark curves using the same set of values of parameters: it is confirmed by P.M.A. that leads at $T = 307$ K to: $R_S = 0.21$ Ω, $R_{Sh} = 5253$ Ω, $I_S = 0.41 \times 10^{-8}$ A, $A = 1.3$ when $I_{ph} = 0$ A, and $R_S = 0.22$ Ω, $R_{Sh} = 5827$ Ω, $I_S = 0.25 \times 10^{-8}$ A, $A = 1.4$ when $I_{ph} = 0.118$ A, under AM1 conditions; this is the cause of the discrepancy observed in Fig. 2b.

3.2 G.M.S. method

With G.M.S. we obtained very bad results reproduced in Fig. 3 for the two illumination levels indicated (1.2 and 0.6 suns); a straight line is found, as predicted, only at low illumination but it leads to a negative R_S value (the graphic precision is around 15%); but consider the calculations in [17]: the derivation of (3) of [17] needs the approximation

$$\exp\left(\frac{R_S I_{sc} e}{AkT}\right) \ll 1 \tag{8}$$

that is never achieved; further, if this exponential term is close to unity, then (3) of [17] reads

$$I_{sc} = I_L \tag{9}$$

and the following relations are right with the assumption

$$\exp\left(\frac{Ue}{AkT}\right) \gg 1\,. \tag{10}$$

So the application of G.M.S. needs very low R_S values (about 0.01 Ω) and (or) low shunt circuit current: this is the case the authors considered. (This approximation (8) has also be done in the paper from Agarwal et al. [16].)

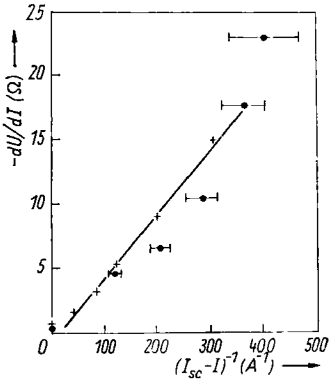

Fig. 3

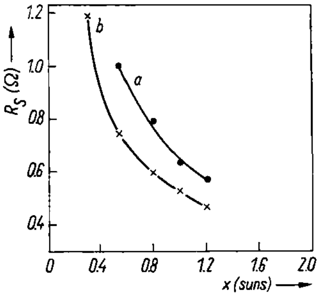

Fig. 4

Fig. 3. Experimentally determined slope along the I–U characteristics vs. $(I_{sc} - I)^{-1}$ at two illumination levels: ● at 1.2 suns, + at 0.6 sun

Fig. 4. Experimentally determined series resistances at different illumination levels (AM1 is $x = 1$): (a) with $R_S = U_{oc}/I_{sc} - U_m/I_m$, (b) with $R_S = -(\mathrm{d}U/\mathrm{d}I)_{U=U_{oc}}$

Table 1

Experimental values of R_S obtained with the indicated methods (the precision is a graphical estimation)

method	V.O.C.S.	M.P.M.	V.R.S.
R_S (Ω)	0.53 ± 0.02	0.64 ± 0.02	0.20 ± 0.03

The three other methods V.O.C.S., M.P.M., and V.R.S. give at one sun (AM1) the results cited in Table 1. The last method gives the best value but needs longer experiments. V.O.C.S. and M.P.M. are also compared in Fig. 4 that displays measurements (from Fig. 1) at different light intensity levels; such results come from the approximations made needing large values of the product $R_S I_{ph}$ (>0.3 ΩA); this condition is difficult to be satisfied: for example with $R_S = 0.2$ Ω, I_{ph} must be at least 1.5 A that requires concentrators and then cells with lower R_S values to avoid thermal effects, and then the efficiency decreases.

4. Conclusion

We have considered the lumped series resistance of solar cells as a parameter introduced with the one-diode model; all approximate graphic techniques in the determination of R_S values have been discussed; a single value has been searched for each operational condition (temperature and light intensity level) that enables a good description of the characteristic by (1). It is shown that all the methods derived after mathematical "manipulations" and approximations of (1) lead to results far from the optimum value. The necessity of a precise control of temperature has been pointed out as soon as a comparison is made between characteristics obtained under different operational conditions.

References

[1] S. M. Sze, Physics of Semiconductor Devices, Wiley, New York, 1969 (p. 640).
[2] H. J. Hovel, Semiconductors and Semimetals, Vol. 11, Academic Press, New York, 1975.
[3] A. Rothwarf, Proc. XIII. IEEE Photovoltaic Spec. Conf., Washington 1978 (p. 1312).
[4] A. Rothwarf and K. W. Böer, Solid State Chem. **10**, 71 (1975).
[5] M. Wolf and H. Rauschenbach, Adv. Energy Conv. **3**, 455 (1963).
[6] M. S. Imamura and J. I. Portscheller, Proc. VIII. IEEE Photovoltaic Spec. Conf., Seattle 1970 (p. 102).
[7] D. W. Kammer and M. A. Ludington, Amer. J. Phys. **45**, 602 (1977).
[8] R. J. Handy, Solid State Electronics **10**, 765 (1967).
[9] J. A. Cape and S. W. Zehr, Proc. XXIV. IEEE Photovoltaic Spec. Conf., San Diego 1980 (p. 449).
[10] D. Bonnet, Proc. II. EC Photovoltaic Solar Energy Conf., Berlin 1979 (p. 387).
[11] F. A. Lindholm, J. G. Fossum, and E. L. Burgess, IEEE Trans. Electron. Devices **26**, 165 (1979).
[12] N. G. Tarr and D. L. Pulfrey, IEEE Trans. Electron. Devices **27**, 771 (1980).
[13] K. Rajkanan and J. Shewchun, Solid State Electronics **22**, 193 (1979).
[14] A. Rohatgi, J. R. Davis, R. H. Hopkins, P. Rai-Choudhury, P. G. McMullin, and J. R. Cormick, Solid State Electronics **23**, 415 (1980).
[15] G. M. Smirnov and J. E. Mahan, Solid State Electronics **23**, 1055 (1980).
[16] S. K. Agarwal, R. Muralidharan, A. Agarwala, V. K. Tewary, and S. C. Jain, J. Phys. D **14**, 1643 (1981).
[17] M. Warashina and A. Ushirokawa, Japan. J. appl. Phys. **19**, 179 (1980).
[18] P. Mialhe and J. Charette, Amer. J. Phys. **51**, 68 (1983).
[19] R. J. Chaffin and G. C. Osbourn, Appl. Phys. Letters **37**, 637 (1980).
[20] G. L. Araujo, E. Sanchez, and M. Marti, Solar Cells **5**, 199 (1982).
[21] J. P. Charles, M. Adbelkrim, Y. M. Muoy, and P. Mialhe, Solar Cells **4**, 169 (1981).

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