

Results on series and shunt resistances in a c-Si PV cell. Comparison using existing methods and a new one

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The article includes a review of some methods to determine series and shunt resistances. It also presents a new method to determine series and shunt resistances and a comparison of results to previous literature methods. The new method is based on the one diode model for solar cells and is applied on a c-Si cell. The dependence of the series resistance on the irradiance levels is also presented. The complex programme developed to determine the cell characterization and implicitly for the determination of series resistance is included. The programme was created in the graphical programming language LabVIEW.

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1. Introduction

The series resistance is one of the most important factors influencing the solar cells performance. The series resistance in a solar cell is determined by the series resistance of the base, the resistance of the metal-semiconductor contacts at electrodes and by the resistance of the diffused layer from the illuminated surface of the cell. While the series resistance of the base is generally very low, negligible in some cases, the contacts resistance thus being possibly lowered by construction, the major contribution to the series resistance of the solar cell is that of the distributed resistance of the diffused layer (generally the n layer) from the surface [1]. It depends on the physical parameters of the material, but also on the dimensions and the shape of the contact at this layer, contact which can be realized under different shapes.

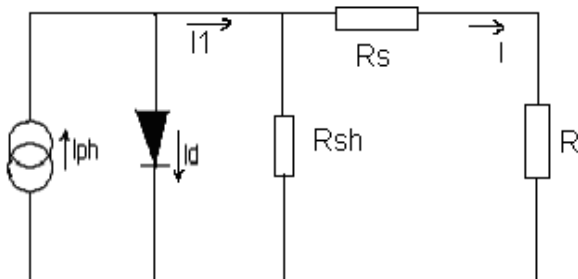


Fig. 1. The equivalent circuit with parasite resistance.

All parallel high-conductivity paths (shunts) across the solar cell p-n junction or on the cell edges are represented by R_{sh} , the shunt resistance, [2]. These shunt paths lead currents away from the intended load and their effects have a negative influence upon the module performance especially at low intensity levels [3], [4].

Also, a decrease in R_{sh} entails the decrease of V_{oc} [5]. Decreasing R_{sh} reduces both P_{max} and FF of the cell.

The internal losses in the equivalent circuit must be taken into consideration, so the parasite resistances must also be included.

The equivalent circuit completed by these resistances becomes, see in Fig. 1 and the Equation (1):

$$I = I_{ph} - I_0 \left(\exp \left(\frac{q(V + IR_s)}{mkT} \right) - 1 \right) - \frac{V + IR_s}{R_{sh}} \quad (1)$$

2. Theory

As it can be observed from the information presented above it is important that we are able to determine the possibilities to minimize the series resistance and to maximize the shunt resistance. This implies knowledge of the series and shunt resistance determination. The comprehension of mechanisms that take place inside of the solar cell leads to determine the ideality factor of the diode.

There are plenty of methods [6], described in the literature, to determine these three parameters, methods that will be succinctly presented in this article. Some of these refer to only one parameter; others offer results for two or all of the three parameters under discussion.

2.1. Methods to determine the series resistance

The methods described below lead to determine the series resistance, the shunt resistance being considered as infinite.

1. A static method - using the one diode model and raising the I-V characteristic in the dark. R_s can be

deduced as the value from the gap on the V axis, between the actual curve and the diffusion line [7].

2. A dynamic method - using the one diode model, superposing a very low amplitude a.c. signal to a forward electric injection, the following expression is obtained for the dynamic resistance [7]:

$$r_d = \frac{dV}{dI}_{I=ct.} = \frac{mkT}{q} \frac{1}{I} - R_s \quad (2)$$

The series resistance is determined at the intersection of the curve $r_d = f(1/I)$ with the r_d axis.

3. Method of slope at the $(V_{oc}, 0)$ point [6] - at constant illumination and using the one diode model. R_s is determined from the relation:

$$R_s = \frac{dV}{dI}_{I=0.} = \frac{mkT}{q} \frac{1}{I_{ph} + I_o} \quad (3)$$

4. The two characteristics method [7] - is a method that uses two I-V characteristics raised at the same temperature for two illumination levels, see Fig. 2.

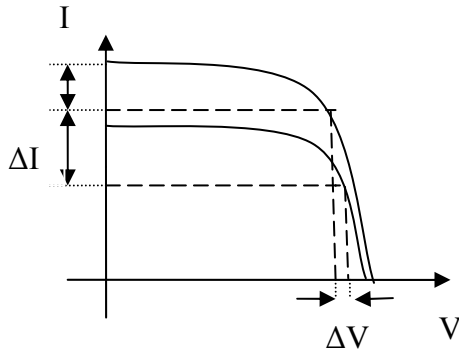


Fig. 2. I-V curves used to determine the series resistance.

The series resistance will be thus determined from the ratio:

$$R_s = \frac{\Delta V_1}{\Delta I_{sc}} \quad (4)$$

5. Maximum power point method [6] - the method uses the one diode model and the I-V characteristic is raised for a single illumination level. R_{sh} is considered infinite and n has a constant value over the entire curve. The series resistance can be determined using the relations (5-6):

$$R_s = \frac{V_m}{I_m} - \frac{1}{B(I_{ph} - I_m)} \quad (5)$$

$$B = \frac{[I_m / (I_{ph} - I_m)] + \ln[(I_{ph} - I_m) / I_{ph}]}{2V_m - V_{oc}} \quad (6)$$

where: $I_{ph} \approx I_{sc}$.

6. A flash lamp method [8] - uses the one diode model, with the shunt resistance neglected. R_s can be calculated using relation (7):

$$R_s = R_L \left(\frac{V_{oc}}{V_L} - 1 \right) \quad (7)$$

where: V_L is the voltage measured on a resistance of charge R_L when the cell is illuminated by a high intensity flash lamp.

7. The area method [6] - using equation (8) R_s is calculated:

$$R_s = 2 \left(\frac{V_{oc}}{I_{sc}} - \frac{A}{I_{sc}^2} - \frac{mkT}{qI_{sc}} \right) \quad (8)$$

where: A is the area between the I-V characteristic, the V axe and the I axe.

8. Method of the difference between the photogenerated and the short circuit currents [9] - the series resistance can be determined from the slope of the line $\ln(I_{ph} - I_{sc})$ vs. I_{sc} , see equation 9. For high illumination levels the curve I_{ph} vs. E is no longer a straight line. The curve has a saturation tendency.

$$\ln \frac{I_{ph} - I_{sc}}{I_0} = \frac{qI_{sc}R_s}{mkT} \quad (9)$$

9. The simplified maximum point method [6] - using the one diode model with the parasite resistances R_s and R_{sh} taken into consideration. For the series resistance the following formula is found:

$$R_s = \frac{V_{oc}}{I_{sc}} - \frac{V_m}{I_m} \quad (10)$$

Thus an R_s value can be obtained by this approach from a single I-V curve, though obviously if R_s is small, very large I_{sc} values and hence high concentrations will have to be used to obtain sufficient accuracy.

9. A new method of determination of series and shunt resistances of silicon solar cells[10] - the method uses the one diode model and I-V characteristics in III and IV quadrants and the V_{oc} - I_{sc} characteristics of the cell. Eq. (11) can be used for the determination of R_s by iteration or by the approximate eq. (12) used without iteration.

$$R_s = \frac{mkT}{qI_f} \ln \left\{ \frac{I_r P - (V_r + V_f + I_f P)}{I_0 (P - R_s)} \right\} - \frac{V_f}{I_f} \quad (11)$$

$$\text{As } P = R_s + R_{sh} \gg R_s \quad (12)$$

Eq.(11) can be rewritten

$$R_s = \frac{mkT}{qI_f} \ln \left\{ \frac{I_r P - (V_r + V_f + I_f P)}{I_0 P} \right\} - \frac{V_f}{I_f} \quad (13)$$

11. The two diode solar cell method[11] – using formula (18) deriving from the equation describing the equivalent model with two diodes for the solar cell the series resistance can be found:

$$R_s = - \left(\left(\frac{\partial I}{\partial V} \right)_{V=V_{oc}} \right)^{-1} - \left(\frac{q}{mkT} I_{ph} \right)^{-1} \quad (14)$$

For m two values theoretically accepted are considered 1 and 2, determining in this way a underestimated value of R_s , respectively a overestimated one. R_s is obtained as a mean between the two values.

12. The two points method [12] - uses a single characteristic and the one diode model. Two points are considered (V_1, I_1) and (V_2, I_2) belonging to the I-V characteristic of the cell and after some transformations the bound (15) is obtained, allowing the determination of the series resistance:

$$R_s = \frac{1}{\lambda} \frac{1}{I_2 - I_1} \ln \frac{I_{ph} - I_2}{I_{ph} - I_1} - \frac{V_2 - V_1}{I_2 - I_1}, \quad \lambda = \frac{q}{mkT} \quad (15)$$

There are many other methods of determining the series resistance, such as:

- theoretical methods accurately computing the series resistance, see [13];
- another dynamic method in which low intensity flashes with a constant frequency are overlapped on a constant intensity, see [8] where a third dynamic method is also described;
- the method of Signal, see [14];
- the method described in [8]-uses two charge resistances and two flashes from a flash lamp;
- the method using OVCD-open circuit voltage decay after a flash illumination, see [15].

2.2. Methods for determination of parameters

13. Method of Quanxi Jia and Anderson[16] - the method uses the one diode model using the I-V characteristic raised for a single illumination level. R_{sh} is considered infinite and n variable in value on the curve.

The series resistance can be determines using the relation (16):

$$R_s = \frac{V_m}{I_m} \cdot \frac{\frac{1}{V_t} \cdot (I_{sc} - I_m) \left[V_{oc} + V_t \left(1 - \frac{I_m}{I_{sc}} \right) \right] - I_m}{\frac{1}{V_t} \cdot (I_{sc} - I_m) \left[V_{oc} + V_t \left(1 - \frac{I_m}{I_{sc}} \right) \right] + I_m} \quad (16)$$

The mean value of n can be written and calculated using relation (17):

$$nV_t = (V_m + I_m R_s) \ln \left[\left(1 - \frac{I_m}{I_{sc}} \right) \exp \left(\frac{V_{oc}}{I_{sc}} \right) + \frac{I_m R_s}{2V_t} + \frac{I_m}{I_{sc}} \right] \quad (17)$$

14. The generalized area method [17] - for this method it is necessary to raise the I-V characteristic for three illumination levels of the solar cell and to calculate the area A (the area between the I-V characteristic, the V axe and the I axe) for each curve. In this method the shunt resistance effect is not neglected. The two resistances, series and shunt, can be found by solving the system:

$$\rho_i = \left(\frac{I_{sc}}{2V_{oc_i}} \right) r + \left(\frac{1}{V_{oc_i}} \right) m + \left(\frac{V_{oc}}{2I_{sc_i}} \right) g - \left(\frac{1}{I_{sc_i}} \right) \gamma g m \quad (18)$$

where

$$\rho_i = \left(\frac{I_{sc} V_{oc} - A}{I_{sc} V_{oc}} \right)_i; \quad r = R_s; \quad \gamma = \frac{kT}{q} \quad \text{and} \quad g = \frac{1}{R_{sh}} \quad (19)$$

15. An approximation equation and fitting procedure [18] - As the fitting of the I-V characteristic is more accurate and easier the less parameters must be determined, an approximate equation can be found, and it gives good results. Thus, the reverse saturation current is eliminated. The one diode model is used. Approximated equation (20) contains three parameters: V_{oc} , I_{sc} ,

$\Lambda = \frac{q}{mkT}$. From a solar cell (I-V) curve, all parameters contained in equation (20) can be found from experimental data. R_s can be found from the approximated equation by using the iteration method.

$$V = V_{oc} - IR_s + \frac{1}{\Lambda} \ln \left\{ \frac{I_{sc} - I}{I_{sc}} + \exp \left[\Lambda (I_{sc} R_s - V_{oc}) \right] \right\} \quad (20)$$

16. The Analytical Five Point Method- The method consists of determining the cell parameters by using: V_{oc} -the open circuit voltage, I_{sc} -the short circuit current, I_m -the

current at maximum power point, V_m -the voltage at the maximum power point, R_{so} -the slope at the open circuit point and R_{sho} -the slope at the short circuit point measured from the I-V characteristic. The relations for the solar cells parameters are given below [19].

Other methods:

-a practical method-the parameters R_s , R_{sh} , I_o and I_{ph} are computed from the experimental data of the fourth-quadrant characteristic using a programmable calculator, see [20];

-raising in dark conditions and fitting the I-V characteristic using the two diodes model, see [21];

- the vertical optimization method- leads to the determination of the parameters: I_{ph} , I_o , m , R_s , $G_{sh} = 1/R_{sh}$, using a non linear least-square optimization algorithm based on the Newton method modified by introducing the so-called Levenberg parameter [22];

- the conductance optimization method, see [23]

- the simple conductance technique- based on Werner's method [24] for determining the cell parameters using current as well as conductance of both Schottky diodes and pn junctions.

- the ideality factor, n , is calculated between adjacent pairs of I-V curves by using V_{oc} , I_{sc} pairs (21). The equivalent of this method is raising the characteristic $V_{oc} = V_{oc}(\ln I_{sc})$

$$m = \frac{V_{oc1} - V_{oc2}}{\frac{KT}{q} \ln \left(\frac{I_{sc1}}{I_{sc2}} \right)} \quad (21)$$

-using the Lambert W functions to determine the solar cell parameters [25].

2.3. The new method

To determine the series and shunt resistances the one diode model was applied and only one I-V characteristic needs to be raised.

The series resistance has as an effect the translation towards the left of the I-V characteristic, and the shunt resistance has as an effect the lowering of the characteristic, (the increase of the slope in the plateau). The translation on the vertical area is given by $I \cdot R_s$, and on the plateau slope by V/R_{sh} .

Using the points pairs (V_i, I_i) obtained through measurements in the real case, we raise the ideal characteristic of the cell, in which the series and shunt resistances are not taken into consideration. The characteristic is raised using the equation:

$$I = I_{sc} - I_o \left(e^{\frac{qV}{mkT}} - 1 \right) \quad (22)$$

where I_{sc} is determined, m is obtained from the slope of the line $V_{oc} = V_{oc}(\ln I_{sc})$ and I_o is calculated from the intercept.

As the important working point for the solar cell is the maxim power point, the series and shunt resistances for this point will be determined.

The R_s is given by the following:

$$R_s = \frac{\Delta V}{I_{max}} = \frac{V_{ideal} - V_{max}}{I_{max}} \quad (23)$$

where V_{ideal} is obtained as the intersection between the line $y = I_{max}$ and the ideal characteristic I-V.

The shunt resistance is obtained using the relation:

$$R_{sh} = \frac{\Delta I}{V_{max}} = \frac{I_{ideal} - I_{max}}{V_{max}} \quad (24)$$

where I_{ideal} is obtained as the intersection between the line $x = V_{max}$ and the ideal characteristic I-V.

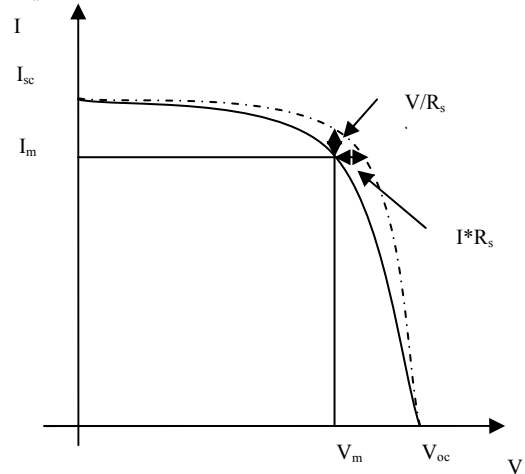


Fig. 3. The I-V characteristics for solar cell (full line – real, interrupted line – ideal)

3. The experiment

The measurement chain consists of:

- the light source-halogen lamp, mobile in order to vary the light intensity;
- a massive copper thermostat in which a LM355 is placed in contact to the back of the cell for measuring the temperature and for maintaining the temperature constant during the measurements;
- the automatic system for raising the characteristic.

The measurements were performed at room temperature.

The raising of the I-V characteristic is automatically realized in less than one second. It is performed using a capacitor during the charge. So that the system could be used for a high variety of cells, the capacitor used can be easily changed or a supplementary relay can be used to make an automatic changing-over if needed.

The acquisition system is formed by a NI 6036E board and a PC. The data acquisition card used is a 16 analogue inputs at up to 1.25 MS/s, 16-bit resolution, this giving it a high accuracy. The measurement channels can be used in the differential mode, for a measurement with a high resolution.

The measurements are made for a c-Si solar cell, of 3 x 1 cm, with an area of 3 cm². The temperature measured on the back of the solar cell was maintained constant during the measurements, at 25°C.

To determine the irradiance a silicon pyranometer was used. The measurements were realised for different illumination levels, varying from 500 to 1000 W/m².

4. Results and discussion

Ten methods were tested for determining the series resistances from the methods presented above.

To determine m and I_0 the characteristic $V_{oc} = V_{oc}(\ln I_{sc})$ was raised, see Fig. 4.

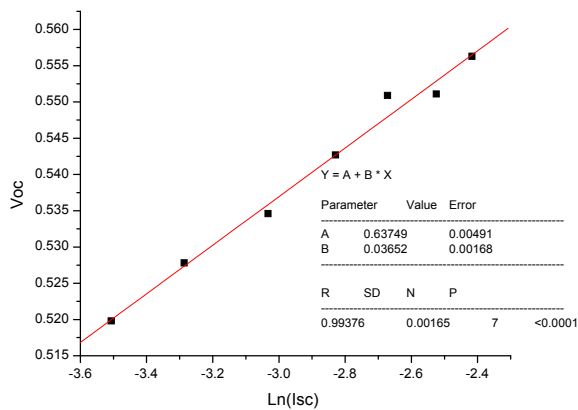


Fig. 4. The characteristic $V_{oc} = V_{oc}(\ln I_{sc})$.

Table 1 The values obtained for the three parameters.

Method Param.	3	4	5	7	9	12	13	14	16	Our method
R_s [Ω/cm ²]	0.131	0.118	0.148	0.099	0.132	0.453	0.713	0.1091	0.133	0.135
R_{sh} [Ω]	-	-	-	-	-	105	-	129	154	70.5
m	-	-	-	-	-	-	2.4	1.67	1.55	-

The area method, 7, sometimes gave negative results and extremely different from the other methods, fact signalled by other researchers as well, [6],[26].

The results obtained for series resistance by the method of Quanxi Jia and Anderson (method 13) are high for both the series resistance and the ideality factor of diode, but this matches the results obtained by other authors as well.(see paper [9]). With the two points method a high value is also obtained for the series

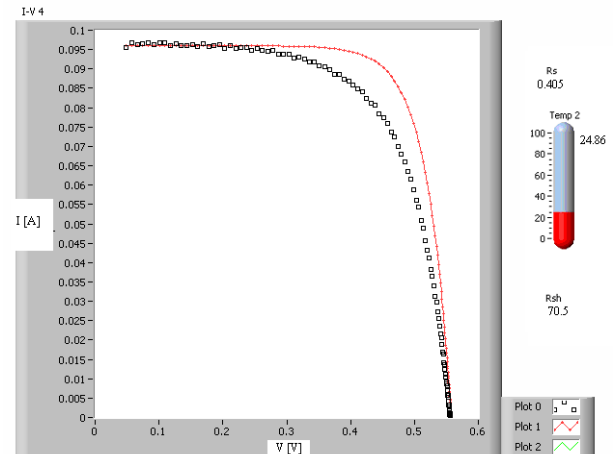


Fig. 5. The real and ideal characteristics raised for the determination of the parasite resistances.

The ideal characteristic is raised with the values obtained for m and I_0 and the series and shunt resistances are calculated using the programme created in LabVIEW, with the equations 22-24, see Fig. 5.

Table 1 comparatively presents the results obtained by nine methods presented above and also by the method proposed by the authors for the series resistance of the c-Si solar cell with an area of 3 cm². The table also contains results for the shunt resistance and ideality factor of the diode.

As it can be seen from table 1, the methods 3, 4, 5, 9, 14, 16 give for the series resistance values within the interval (0.109, 0.148).

resistance, possibly because of the choice of points. The points needed for the method were chosen around the point that gives P_{max} . The series resistance obtained by this new method described in this article gives a result within the interval (0.109, 0.148), approximately the same with values offered by other three methods. For the shunt resistance the result obtained is smaller, but this is due to the point of calculations. The choice of this point was

made taking into account its importance in solar cells characterization.

Repeating the experiment leads to a $\pm 1\%$ variation of the series resistance. The change of the point in which the series resistance is calculated determines a 5 % variation of the series resistance.

In Fig. 6 the dependence of the series resistance on the illumination level is presented.

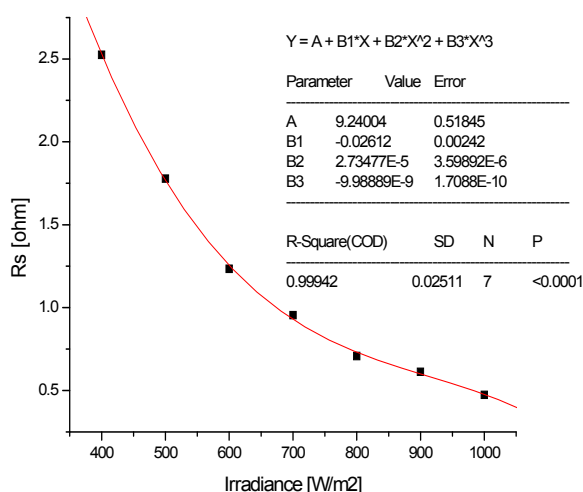


Fig. 6. The dependence of the series resistance on irradiance

This dependence is fitted with a third degree polynomial. The raise of the series resistance is rapid for small illumination levels, thus explaining the non-linear dependence of the open circuit voltage on the illumination levels. Similar results were obtained by Priyanka, [27].

5. Conclusions

This paper reviews the main methods to determine some solar cell parameters, such as the series resistance, the shunt resistance and the ideality factor of the diode. For some of the methods presented, (3, 4, 5, 7, 9, 12, 13, 14, 16 and the new method) measurements were performed. The values obtained are compared with the values determined by the method proposed by the authors, method using the one diode model. The values obtained with our method are comparable with the results obtained by other methods, fact which validates its use for determining the series resistance.

The value of the series resistance obtained for the c-Si solar cell, with an area of 3cm^2 , per area unit is in the order of hundreds of milliohms. This result matches Lindmayer and Allison relationship [6], asserting that the value of R_s is reversely proportional to the solar cell area.

The determination of the series and shunt resistances is automatically performed by the programme created in the graphical programming language LabVIEW. This

programme integrates the methods to determine the series resistance in more complex software [28].

The method will be in future applied on a series of solar cells of different areas, different materials and encapsulation methods.

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