Open Journal of Applied Sciences, 2023, 13, 1834-1843
https://www.scirp.org/journal/ojapps
ISSN Online: 2165-3925
ISSN Print: 2165-3917

Determination of the Electrical Parameters of a Solar Cell in Steady State

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How to cite this paper: Sadio, O.D., Kouyaté, M., Traoré, P.T., Barro, F.I. (2023) Determination of the Electrical Parameters of a Solar Cell in Steady State. *Open Journal of Applied Sciences*, **13**, 1834-1843.
https://doi.org/10.4236/ojapps.2023.1310144

Received: September 3, 2023
Accepted: October 27, 2023
Published: October 30, 2023

Abstract

Photovoltaic solar energy can be obtained by using several types of technologies, including silicon solar cells. The characterization of its solar cells makes it possible to know them better. This article presents, on the one hand, the work that has been carried out on these cells. On the other hand, a theoretical study of the cell under illumination using Lambert's W function. On the basis of the electrical parameters provided by the manufacturer, the parameters such as the series and shunt resistances and the electrical quantities such as the photocurrent and the photovoltage, are determined and studied according to the ideality factor of the diode. From the results obtained the shunt resistance increases when the ideality factor increases, the series resistance decreases very weakly.

Keywords

Solar Cell, Series Resistance, Shunt Resistance, Ideality Factor, Lambert Function

1. Introduction

Solar photovoltaic has seen many developments and several technologies have emerged to date. The mastery of its technologies therefore becomes a necessity to consider their improvement. Research on different materials is being carried out in this direction. In this research, we distinguish the characterization of these materials in their morphological, optical and electrical aspect. Electrical characterization makes it possible to determine the electrical parameters of solar cells and to better understand their evolution. This characterization can be done in steady state (quasi-steady state), transient state or electrical or optical frequencymodulation. This present study was carried out in steady state. Theoretical studies are characterized by the presentation of a mathematical model which translates the physical behavior of the solar cell. These models are mathematical equations that are most often implicit. These equations are relations between the electrical physical quantities and their related parameters; The resolution of these equations can be done analytically or numerically.

In the literature, many authors have made the electrical characterization of solar cells by application of the analytical method. Among these methods we can cite the work of: Chan *et al.* [1] who used the single diode method to calculate the five electrical parameters of a solar cell. They first plotted the I-V curve of the cell. Then, from the I-V curve, they determined the short-circuit current, the open-circuit voltage, the current and voltage at the maximum power point, the slope at the open-circuit point R_{so} and that at the short-circuit R_{sho} [1].

Chegaar *et al.* [2] proposed a simple conductance technique. They have, in two steps, determined the five parameters of a solar cell. First, they determined the shunt conductance G_{sh}. Then, they calculate the conductance G and determined the ideality factor n of the diode [2].

Jia and Anderson [3], considering the one-diode model of the solar cell under illumination, proposed a method for determining the series resistance and ideality factor of the diode. They considered the ideality factor as a variable. From the graph of the I-V characteristic, they fixed two values of n: the first $n = 1$ corresponding to the operation in open circuit and the second $n = 2$ corresponding to the operation in short circuit. They calculated the series resistance by making somme approximations. They then calculated the ideality factor of the diode.

Agarwal *et al.* [4] developed a method to determine the series resistance R_s by tuning the one-diode model of the solar cell, they considered the series resistance to be equal to infinity and the resulting short-circuit current equal to the photogenerated current under an illumination of 700 W/m^2. For a low illuminance level, they found a linear dependence on the illuminance level. For an illumination level higher than 700 W/m^2, they found a sublinear dependence.

Cowley and Sze [5] proposed a method for determining series resistance from semi-logarithmic I-V characteristics. They considered the one-diode model under darkness. To calculate the series resistance, they took the difference between the semi-logarithmic value and the diffusion line, on the V axis.

The numerical method is also the subject of much work. Among these works, we can mention: Mohammad Rasheed *et al.* [6] proposed an algorithm allowing the resolution of the Equation (1) of the solar cells. They used the one-diode model by making several iterations with an initial value of 0. The electrical parameters were determined by considering the ambient temperature. Volker Quaschning and Rolf Hanitsh [7], proposed a general model for the description of solar generators, giving the values of voltages and currents. They used the Newton-Raphson method to characterize a partially shaded solar generator and determine the electrical parameters. LianLian Jiang *et al.* [8] proposed an optimization technique based on improved adaptive differential evolution (IADE) to determine the electrical parameters of solar cells. For this, they proposed new formulas for the "scaling factor" and the "crossover rate". N Belhaouas *et al.* [9] proposed a numerical method based on Matlab-Simulink for the characterization of solar cells/modules under the influence of environmental parameters such as irradiance level, temperature and surface conditions. They used the electric diode model.

The equations that govern the evolution of the electrical quantities of solar cells are most often implicit. Their resolution most often requires the application of a numerical method. Numerical methods give an approximation of the calculated quantity. They require the knowledge of several variables, and they use algorithms to determine the electrical parameters. With analytical methods, the unique knowledge of the parameters given by the manufacturer makes it possible to determine the other parameters and electrical quantities of the solar cells.

In the present study, an analytical method is used for the determination of the electrical parameters of solar cells.

Unlike numerical methods, the approach consists, from the unique knowledge of the parameters given by the manufacturer, in determining the other parameters and electrical quantities of the solar cells such as the photocurrent, the short-circuit current, the series resistance and the shunt resistor. The mathematical formulation that has been proposed has been obtained by considering the one-diode model of the solar cell under illumination. Unlike the analytical methods presented above, this mathematical formulation was solved by using Lambert's W function. The expressions of the different parameters and quantities were expressed as a function of the ideality factor α of the diode and simulations were made. These simulations made it possible to determine the typical value of the diode factor for the studied solar cells. The results obtained are then compared to those available in the literature.

2. Mathematical Formulation

The structure of a solar cell is formed by the superposition of four layers which are in contact [10]. Contacts between the four zones result in an ohmic resistance R_s. The series resistance R_s characterizes the resistive effects of the solar cell [11].The current generatedinside a solar cell is not completely collected, there are leakage currents in the solar cell. The effects of these leakage paths are characterized by the shunt resistance R_{sh} [12]. In steady state, the electrical equivalent circuit of solar cell is then given by the well-known one-diode model presented in **Figure 1**.

The current I is given by:

$$I = I_{ph} - I_0\left[\exp\left(\frac{V + IR_s}{\alpha V_T}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \tag{1}$$

In the Equation (1), I_{ph} is the photocurrent, I_0 is the reverse saturation current, V_T the thermal and$\alpha$the ideality factor or quality factor of the diode.

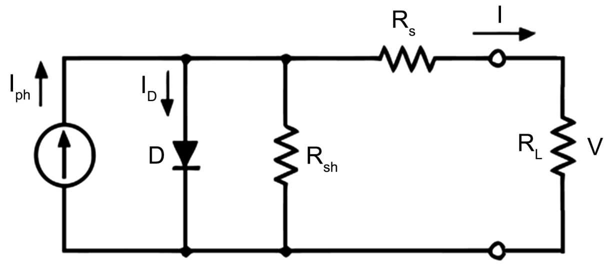

Figure 1. One diode model of the solar cell.

Since the objective of this work is to determine the electrical parameters of solar cells, thereafter only the following parameters will be examined: the series resistance R_s, the shunt resistance R_{sh}, the reverse saturation current I_0 and the photocurrent I_{ph}.

When operating in short-circuit condition, the voltage V is removed from Equation (1) and the current I is replaced by the short-circuit current I_{sc}:

$$I_{sc} = I_{ph} - I_0\left[\exp\left(\frac{I_{sc}R_s}{\alpha V_T}\right) - 1\right] - \frac{I_{sc}R_s}{R_{sh}} \tag{2}$$

The second term of the right-hand side (diode current) is negligible. Equation (2) becomes:

$$I_{sc} = I_{ph} - \frac{I_{sc}R_s}{R_{sh}} \tag{3}$$

From Equation (3), we get the expression for the photocurrent:

$$I_{ph} = I_{sc}\left(\frac{R_{sh} + R_s}{R_{sh}}\right) \tag{4}$$

At open circuit the current becomes zero and the voltage V becomes equal to the open circuit voltage V_{oc}:

$$0 = I_{ph} - I_0\left[\exp\left(\frac{V_{oc}}{\alpha V_T}\right) - 1\right] - \frac{V_{oc}}{R_{sh}} \tag{5}$$

Equation (5) can be reduced if we consider $V_{oc} \gg \alpha V_T$:

$$\exp\left(\frac{V_{oc}}{\alpha V_T}\right) - 1 \cong \exp\left(\frac{V_{oc}}{\alpha V_T}\right) \tag{6}$$

We then have:

$$I_0 = \frac{(R_{sh} + R_s)I_{sc} - V_{oc}}{R_{sh}\exp\left(\frac{V_{oc}}{\alpha V_T}\right)} \tag{7}$$

In addition to the short-circuit current I_{sc} and the open-circuit voltage V_{oc}, the I-V curve is also characterized by the maximum power point. This point corresponds to the maximum power that the cell can deliver. At this point, in Equation (3), we replace I by I_m and V by V_m:

$$I_m = I_{ph} - I_0\left[\exp\left(\frac{V_m + I_m R_s}{\alpha V_T}\right) - 1\right] - \frac{V_m + I_m R_s}{R_{sh}} \tag{8}$$

The power delivered by the solar cell is: $P = IV$

Its derivative with respect to the voltage is then:

$$\frac{\partial P}{\partial V} = V\frac{\partial I}{\partial V} + I \tag{9}$$

At this point, the derivative of the power with respect to the voltage is zero

From Equation (9) setting the maximum power point we have:

$$\left(\frac{\partial I}{\partial V}\right)_{I_m, V_m} = -\frac{I_m}{V_m} \tag{10}$$

Considering Equation (1) and taking the derivative with respect to V, we get

$$\frac{\mathrm{d}I}{\mathrm{d}V} = -I_0\left(\frac{1}{\alpha V_T} + \frac{R_s}{\alpha V_T}\frac{\mathrm{d}I}{\mathrm{d}V}\right)\exp\left(\frac{V + IR_s}{\alpha V_T}\right) - \left(\frac{1}{R_{sh}} + \frac{R_s}{R_{sh}}\frac{\mathrm{d}I}{\mathrm{d}V}\right) \tag{11}$$

At the maximum power point, considering Equation (11) we then have:

$$-\frac{I_m}{V_m} = -\frac{I_0}{\alpha V_T}\left(1 - \frac{I_m}{V_m}R_s\right)\exp\left(\frac{V_m + I_m R_s}{\alpha V_T}\right) - \frac{1}{R_{sh}}\left(1 - \frac{I_m}{V_m}R_s\right) \tag{12}$$

Considering Equations (10) and (11), Equation (12) can be rewritten as:

$$\frac{\alpha V_T V_m\left(2I_m - I_{sc}\right)}{\left[V_m I_{sc} + V_{oc}\left(I_m - I_{sc}\right)\right]\left[V_m - R_s\right] - \alpha V_T\left[V_m I_{sc} - V_{oc} I_m\right]} = \exp\left[\frac{V_m + I_m R_s - V_{oc}}{\alpha V_T}\right] \tag{13}$$

Rearranging Equation leads to:

$$-\frac{V_m\left(2I_m - I_{sc}\right)}{V_m I_{sc} + V_{oc}\left(I_m - I_{sc}\right)}\exp\left(\frac{V_{oc} - 2V_m}{\alpha V_T} + \frac{V_m I_{sc} - V_{oc} I_{sc} + V_{oc}\left(I_m - I_{sc}\right) I_m}{V_m}\right) = \left(\frac{I_m R_s - V_m}{\alpha V_T} + \frac{V_m I_{sc} - V_{oc} I_m}{V_m I_{sc} + V_{oc}\left(I_m - I_{sc}\right)}\right)\exp\left(\frac{I_m R_s - V_m}{\alpha V_T} + \frac{V_m I_{sc} - V_{oc} I_m}{V_m I_{sc} + V_{oc}\left(I_m - I_{sc}\right)}\right) \tag{14}$$

Let $x = \frac{I_m R_s - V_m}{\alpha V_T} + \frac{V_m I_{sc} - V_{oc} I_m}{V_m I_{sc} + V_{oc}\left(I_m - I_{sc}\right)}$ and

$$y = -\frac{V_m\left(2I_m - I_{sc}\right)}{V_m I_{sc} + V_{oc}\left(I_m - I_{sc}\right)}\exp\left(\frac{V_{oc} - 2V_m}{\alpha V_T} + \frac{V_m I_{sc} - V_{oc} I_{sc} + V_{oc}\left(I_m - I_{sc}\right) I_m}{V_m}\right)$$

We then have:

$$y = x\mathrm{e}^{x} \tag{15}$$

Considering the Lambert function defined as $z = W(z)\mathrm{e}^{W(z)}$, z being any complex number, we obtain:

$$x = f^{-1}(y) = W(y) \tag{16}$$

This implies the application of the secondary branch $W_{-1}(x)$.Substituting x and y in Equation (16), we obtain:

$$\frac{I_m R_s - V_m}{\alpha V_T} + \frac{V_m I_{sc} - V_{oc} I_m}{V_m I_{sc} + V_{oc}\left(I_{\max} - I_{sc}\right)}$$
$$= W_{-1}\left(-\frac{V_m\left(2I_m - I_{sc}\right)}{V_m I_{sc} + V_{oc}\left(I_m - I_{sc}\right)}\exp\left(\frac{V_{oc} - 2V_m}{\alpha V_T} + \frac{V_m I_{sc} - V_{oc} I_{sc} + V_{oc}\left(I_m - I_{sc}\right) I_m}{V_m}\right)\right) \quad (17)$$

Let's set: $A = \frac{\alpha V_T}{I_{\max}}$, $B = -\frac{V_m\left(2I_m - I_{sc}\right)}{V_m I_{sc} + V_{oc}\left(I_m - I_{sc}\right)}$, $C = \frac{V_m I_{sc} - V_{oc} I_m}{V_m I_{sc} + V_{oc}\left(I_m - I_{sc}\right)}$, $D = \frac{V_{oc} - 2V_m}{\alpha V_T}$ and $E = \frac{V_{\max}}{\alpha V_T}$. We can then rewrite Equation (17) and deduce the series resistance in the form:

$$R_s = A\left[W\left(B\exp\left(D + C\right)\right) - C + E\right] \quad (18)$$

Shunt resistance is derived as:

$$R_{sh} = \frac{\left(V_m - I_m R_s\right)\left(V_m - R_s\left(I_{sc} - I_m\right) - \alpha V_T\right)}{\left(V_m - I_m R_s\right)\left(I_{sc} - I_m\right) - \alpha V_T I_m} \quad (19)$$

Knowing the series resistance R_s and the shunt resistance R_{sh} will make it possible to calculate the reverse saturation current I_0 from Equation (7) and the photocurrent I_{ph} from Equation (4).

3. Results and Discussion

To perform the simulation, the values of the four parameters I_{sc}, V_{oc}, I_m and V_m from Table 1 were used [13].

The results obtained are presented on Table 2.

The results that have been obtained are based on the single-diode model of the solar cell. In this model, the electrical parameters depend on the ideality factor of

Table 1. Electrical characteristics for blue color and gray color cells.

Cell	T(K)	α	Voc (V)	Isc (A)	Vm (V)	Im (A)
Blue color	300	1.51	0.536	0.1023	0.433	0.0934
Gray color	307	1.72	0.524	0.561	0.387	0.485

Table 2. Values of the four electrical parameters of the blue cell and the gray cell.

Parameter	Blue color			Grey color		
	Method	Method	Presented Method	Method	Method	Presented Method
Rs (Ω)	0.07 ± 0.009	0.0671	0.0655	0.08 ± 0.01	0.0784	0.0782
Rsh (Ω)	1000 ± 50	977	941.6460	26 ± 1	26.09	19.5879
I_0 (A)	$(110 \pm 50) \times 10^{-9}$	111×10^{-9}	110.19×10^{-9}	$(6 \pm 3) \times 10^{-9}$	560×10^{-6}	532.77×10^{-6}
Iph (A)	0.1023 ± 0.0005	0.1023	0.1023	0.5625 ± 0.0005	0.561	0.5632

the diode. In this present study we varied the ideality factor in the range of 1 to 1.5. This choice is explained on the one hand by the fact that for values of $\alpha < 1$, the contact would be non-ohmic. Authors have reported that this means the presence of an additional diode at the rear contact [14]. On the other hand, this choice is explained by the fact that the I-V characteristics of a solar cell must agree with the model of current transport in the solar cell [15]. In the literature, authors have presented methods for determining the ideality factor. Several methods can be found in [16].

Figures 2(a)-(d) and Figures 3(a)-(d) present the variation of the parameters according to the ideality factor of the diode.

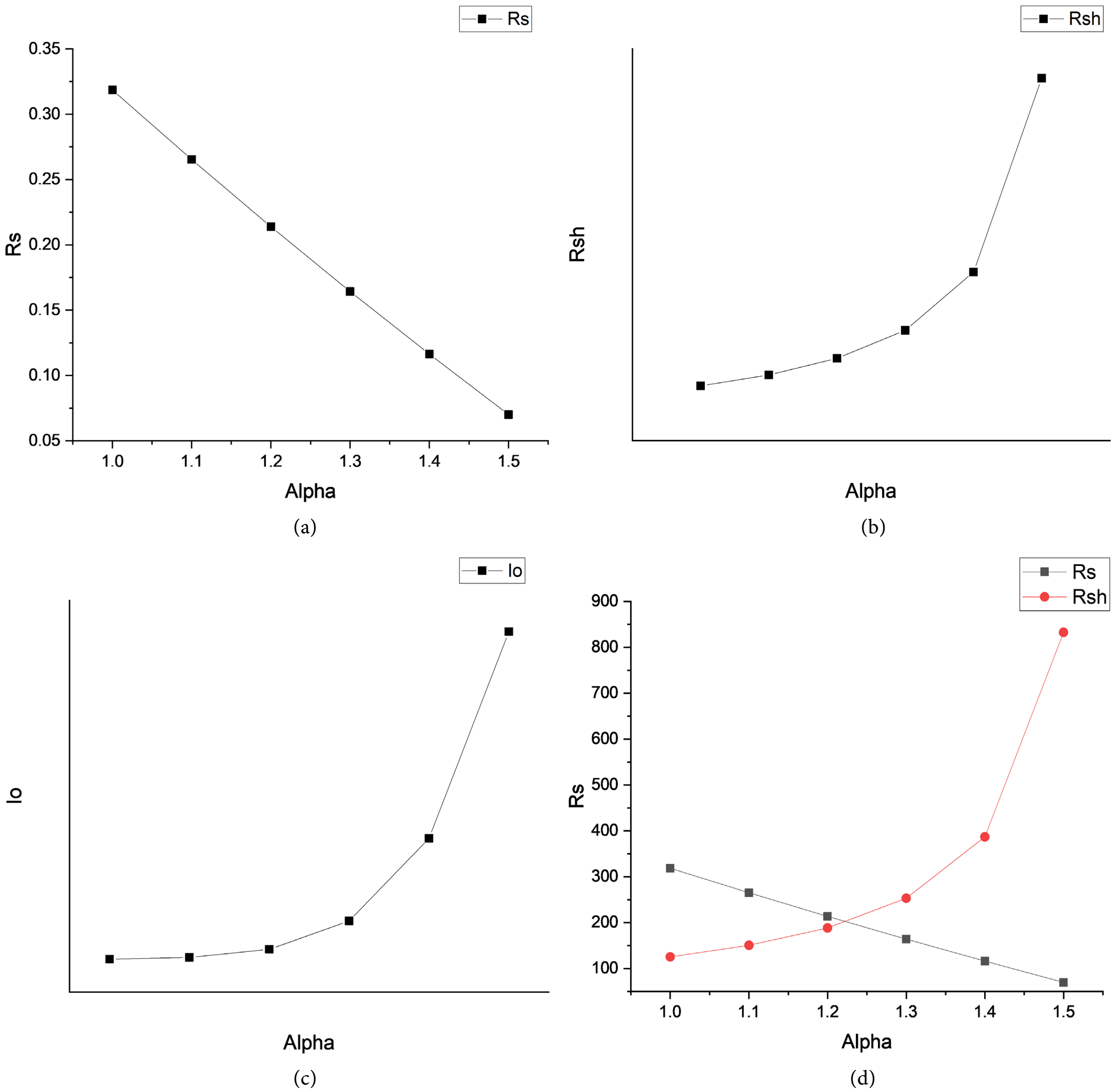

Figure 2. Variation of a) Rs, b) Rsh, c) Io d) Rs and Rsh both, for different values of α of the blue cell.

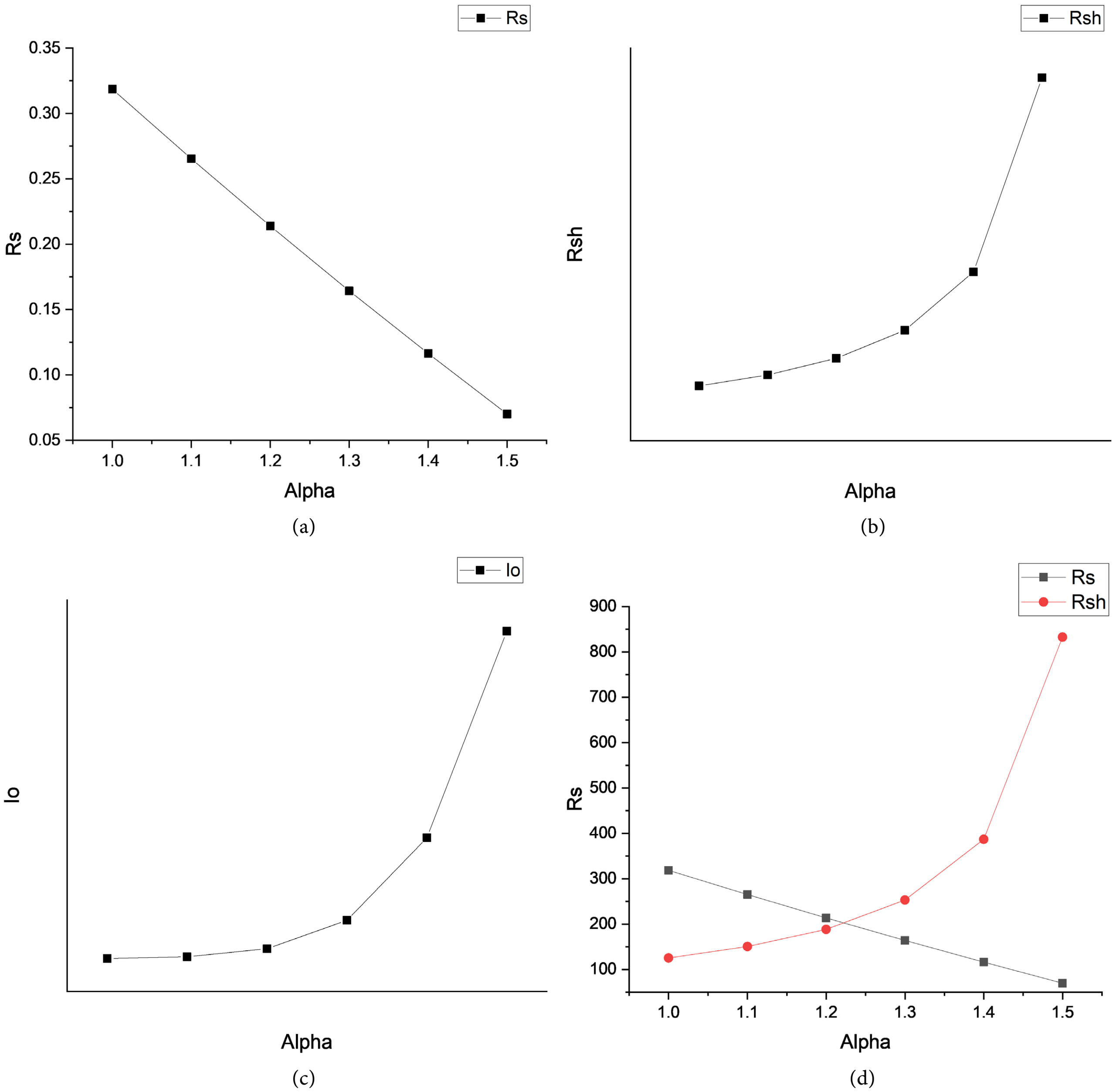

Figure 3. Variation of (a) Rs, (b) Rsh, (c) Io and (d) Rs and both Rsh, for different values of α for the gray cell.

Figure 2(a), Figure 2(b) and Figure 2(c) of the blue cell and Figure 3(a), Figure 3(b) and Figure 3(c) show the respective variations of R_s, R_{sh} and I_0 when the diode factor varies. For α between 1 and 1.4, the shunt resistance varies slightly. The same is true for the reverse saturation current. The shunt resistance and the reverse saturation current vary greatly when α is above 1.4. From the results obtained on R_s and R_{sh}, it appears that the shunt resistance is relatively of the order of 1000 of the series resistance [17].

With Figure 2(a) and Figure 2(b) of the blue cell and Figure 3(a) and Figure 3(b) of the gray cell, it is possible to determine the value of α for which the shunt resistance R_{sh} would be a proportion of the order of 1000 the series resistance R_s

Table 3. Parameters values at the point $a = a_P$.

Parameters	a_P	Rs (Ω)	Rsh (Ω)	Io (A)	Iph (A)
Blue color	1.209	0.2093	193.0468	3.5312×10^{-9}	0.1024
Grey Color	1.320	0.1103	10.8564	156.89×10^{-9}	0.5667

for the blue cell and of the order of 100 for the gray cell. This point is then used to calculate the value of I_0 and I_{ph} corresponding to $R_{sh} = 1000 \times R_s$ for the blue cell and $R_{sh} = 1000 \times R_s$ for the gray cell. Figure 2(c) and Figure 3(d) give the value of a corresponding to this point. Values of 1209 and 1320 were found for the blue cell and the gray cell respectively. Table 3 gives the value of the four parameters at this point.

From the results obtained, it appears that the photocurrent varies very slightly when the ideality factor varies. These variations being of the order of 10^{-3}, it can therefore be said that the photocurrent is equal to the short-circuit current according to the data in Table 2.

4. Conclusion

This article presents an analytical method, based on Lambert's W function, to determine the electrical parameters of solar cells on the basis of information provided by the manufacturer. The series resistance, the shunt resistance, the reverse saturation current of the diode and the photocurrent were determined and compared with those obtained in the literature with good agreements. In order to better understand these parameters, the influence of environmental parameters such as temperature and level of illumination on these parameters can be studied in perspective.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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