Article citation info:
Bouzidi M, Ben Rahmoune M, Nasri A, Mansouri S, Hamouda M. Extracting electrical parameters of solar cells using Lambert function. Diagnostyka. 2024;25(2):2024214. https://doi.org/10.29354/diag/188466.

DIAGNOSTYKA, 2024, Vol. 25, No. 2

e-ISSN 2449-5220
DOI: 10.29354/diag/188466

EXTRACTING ELECTRICAL PARAMETERS OF SOLAR CELLS USING LAMBERT FUNCTION

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Abstract

Photovoltaic cells are intricate systems that transform solar energy into electrical power. Certain internal parameters, such as diode saturation current, conversion resistance, and series resistance, significantly influence the performance of electrical components. Frequently, manufacturers do not provide these parameters. At the moment, researchers need new and clear ways to measure these factors so they can get a better idea of how solar cells work and improve efficiency through simulations. We present a novel approach to accurately determining the five parameters (series resistance, shunt resistance, photovoltaic cell current, and diode saturation current) for multi-crystalline silicon solar cell models. This approach employs the Lambert function and the curve of parasitic resistance. By utilizing the extracted internal electrical parameters, this method will enhance the efficiency of solar cells through the facilitation of more accurate simulations.

Keywords: extraction of parameters, photovoltaic cells, function Lambert W, factor of ideality, single diode

1. INTRODUCTION

The utilization of solar energy technology has significant potential as an ecologically sound solution for attaining sustainability. Photovoltaic solar power is a widely used type of sustainable energy. The process entails the transformation of sunlight into electricity through the utilization of the photovoltaic effect. The current-voltage (I-V) curve illustrates the unique characteristics and effectiveness of a solar cell. Photovoltaic utilize the vast energy of the sun to produce environmentally friendly electricity [1-4].

The current-voltage (I-V) characteristic provides valuable insights into how a solar cell responds to variations in applied voltage and current. Analyzing the I-V curve is essential for evaluating the electrical efficiency of the cell and determining its capacity to convert sunlight into electrical energy [3–4].

The (I-V) curve illustrates the correlation between the current (I) and voltage (V) of the cell, given specific test conditions. The process enables the retrieval of crucial parameters such as open-circuit voltage (Voc), short-circuit current (Isc), maximum power point, fill factor, and efficiency. An analysis of the curve's shape and characteristics can yield insights into shunt and series resistances, ideality factors, and other phenomena. In general, the I-V characteristic is a fundamental component used to analyze and enhance the performance of photovoltaic devices. The data obtained from the curve assists researchers in identifying constraints on performance and potential areas for enhancing the power output and conversion efficiency of the solar cell through design improvements [2-3].

This graph makes it easier to find out important things about cells, like their maximum power point, best operating points, conversion efficiency, open-circuit voltage (Voc), and short-circuit current (Isc) [5–6]. Possible constraints of the technology employed in the fabrication of solar cells may encompass deficiencies in the cell structure or the manufacturing processes.These imperfections may consist of material impurities, unregulated production processes, and other factors that can hinder the performance of solar cells. To evaluate

Received 2024-01-25; Accepted 2024-05-09; Available online 2024-05-28

these imperfections and enhance the quality of solar cells, a thorough analysis of their electrical attributes using the I-V characteristic is essential.

The research emphasis has shifted towards solar cell modelling due to the growing utilization of solar systems. A significant number of studies employ the single-diode model, which relies on variables such as short-circuit current and diode saturation current. Precise models are essential for the design and optimization of photovoltaic systems [6–8].

Precisely determining the parameters of solar cell models continues to be difficult, yet it is crucial for simulation, quality assurance, and manufacturing purposes. The Shockley equation's implicit current function necessitates the simultaneous consideration of multiple variables. The Lambert W function facilitates the derivation of analytical solutions for obtaining these parameters [9–12].

This paper introduces a novel method for precisely determining the crucial electrical characteristics of solar panels. The method employs graphical representation and the Lambert function to approximate parameter values. The analysis enhances comprehension of solar panel performance and optimizes the utilization of solar energy.

2. THE PROPOSED METHODOLOGY

This study presents a newly devised technique to overcome the barriers that impede the successful extraction of electrical information from solar cells. The study is structured into two main phases to comprehensively examine the electrical performance of these cells from all angles.

The initial stage of the study involved utilizing the Lambert function to compute electrical parameters. This was done by employing various estimated values for the diode ideality factor (n), which encompassed a spectrum of values ranging from 1 to 1.6. The objective of this section is to examine the impact of altering the value of n on the efficiency of the photovoltaic cell.

In the second step of the process, the model's series resistance (Rs) and shunt resistance (Rsh) were looked at to get the most accurate estimate of the diode ideality factor.

The objective of this section is to improve the precision of estimating the ideality factor by utilizing existing data instead of depending on prior estimations.

The experimentation was conducted on an MSX-77 polycrystalline silicon solar panel, comprising 36 photovoltaic cells. Table 1 presents the electrical data of a solar panel when subjected to Standard Test Conditions (STC), with a temperature of 25° and an irradiance of 1000 W/m2. This confirms the validity of the suggested method for enhancing the estimation of electrical parameters in a panel.

Table 1. The data sheet from the manufacturer (Typical Electrical Parameters)

Maximum power	77W (0/+5 W)
MPP voltage (V_{mp})	16.9V
MPP Current (I_{mp})	4.56A
Open circuit voltage (Voc)	21V
Short circuit current (Isc)	5A
Number of photocells	36

3. MODELLING OF PHOTOVOLTAIC SYSTEMS

The solar cell's mathematical model is derived from the PN junction model. Furthermore, we include the photocurrent, represented as Iph, which is directly proportional to the intensity of irradiation.

Additionally, we propose the introduction of a term to govern internal electrical processes. Figure 1 displays the electrical circuit that corresponds to a solar cell containing a single diode. While VT refers to the thermal voltage of the diode, Iph stands for the current that the photovoltaic cell produces. Equations (1) and (2) demonstrate the correlation between these two numerical values.

Several scholars have extensively examined this topic in their publications [7–8] and [13–18].

$$I = I_{ph} - I_0\left[\exp\left(\frac{V+IRs}{nV_T}\right) - 1\right] - \frac{V+R_SI}{R_{sh}} \quad (1)$$

$$V_{T=}N_s\frac{KT}{q} \quad (2)$$

Where n represents the ideality factor of the diode, Rs represents the series resistance, and Rsh represents the shunt resistance, in addition to: K represents Boltzmann's constant, which has a value of 1.38006 x 10-23J/K. T denotes the temperature of the cell, measured in degrees Kelvin (°K). q Symbolizes the electric charge, with a value of 1.60218 × 10−19C.

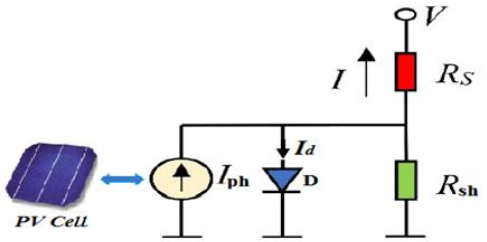

Fig.1. Solar cell model with a single diode

It can be seen in the figures (2), (3), and (4) how the ideality factor (n), series resistance (R_s), and shunt resistance (R_{sh}) change the current-voltage (I-V) relationship. An analysis of the presented curves reveals that series resistance (R_s) causes a decrease in the current in a solar cell, while parallel resistance (R_{sh}) leads to an increase in shunt current and a decrease in cell current. The ideality factor has an impact on cell current, depending on the extent to which it deviates from ideal behavior.

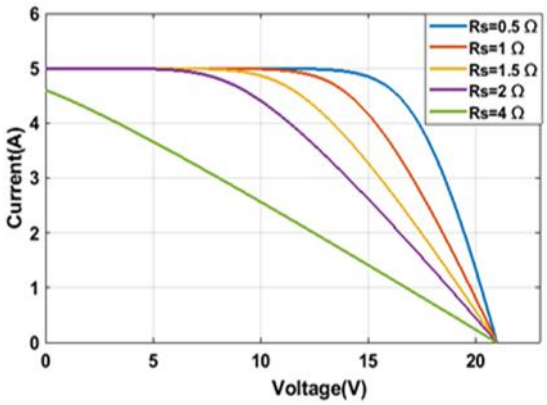

Fig. 2. The effect of series resistance on (I-V) characteristics.

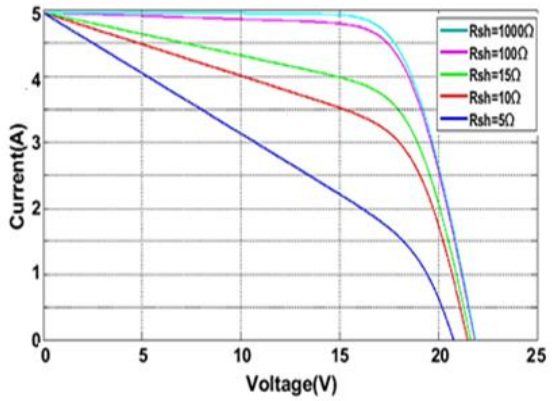

Fig. 3. The effect of parallel resistance on (I-V) Characteristics

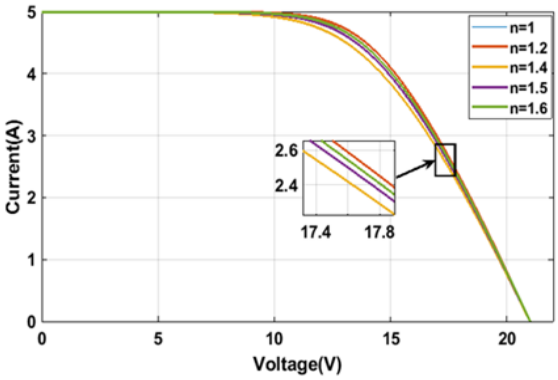

Fig. 4.The impact of the diode ideality factor on the photovoltaic cell's characteristic (I-V)

4. DETERMINE PV PANEL MODEL PARAMETERS

To determine the five fundamental parameters of the photovoltaic panel, we will examine the I (V) characteristic curve at three distinct operating points. The short-circuit point; the maximum power point, and the open-circuit point are the three key points. As shown in Figure 5.

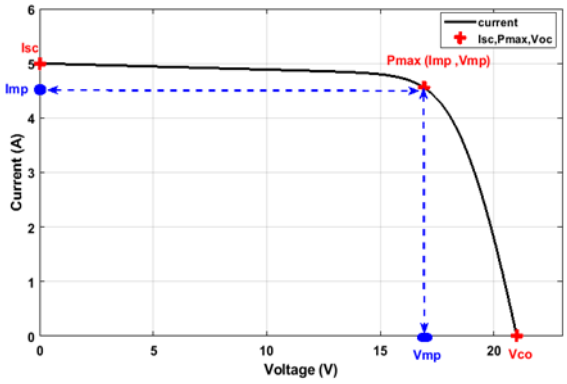

Fig. 5. (IV) characteristics of photovoltaic modules

Equations (1) [7], [19–21] represent the three key points of I(V) characteristics:

$$I_{sc} = I_{ph} - I_0\left[\exp\left(\frac{I_{sc}R_s}{nV_T}\right) - 1\right] - \frac{I_{sc}R_S}{R_{sh}} \tag{3}$$

$$I_{oc} = 0 = I_{ph} - I_0\left[\exp\left(\frac{I_{sc}R_s}{nV_T}\right) - 1\right] - \frac{V_{oc}}{R_{sh}} \tag{4}$$

$$I_{mp} = I_{ph} - I_0\left[\exp\left(\frac{V_{mp}+I_{mp}R_s}{nV_T}\right) - 1\right] - \frac{V_{mp}+I_{mp}R_s}{R_{sh}} \tag{5}$$

At the inflection point, the maximum power produced by a panel is zero when the derivative of power with respect to voltage is zero, which is the product of the maximum current (Imp) and the maximum voltage (Vmp) [7], [19–20].

$$\frac{\partial P}{\partial V} = 0 = \frac{\partial(V.I)}{\partial V} = V\frac{\partial I}{\partial V} + I = 0 \tag{6}$$

$$\left.\frac{\partial I}{\partial V}\right|_{I_{mp},V_{mp}} = -\frac{I_{mp}}{V_{mp}} \tag{7}$$

The value of the limit between the brackets in equation (3) on the right-hand side is negligible compared to the other side [7-9], [20-21]:

$$I_{ph} = \left(\frac{R_s+R_{sh}}{R_{sh}}\right)I_{sc} \tag{8}$$

References [21–22] describe how to deduce the relationship for the current I0 using Equation (4):

$$I_0 = \left(I_{sc} - \frac{V_{oc}-I_{sc}.R_s}{R_{sh}}\right)e^{-\frac{V_{oc}}{nV_T}} \tag{9}$$

Mr. A and others in [7], [21–24], and Dezso S and others in [25] examined Equations (10), (11), and (12).

$$I_{mp} = I_{sc} - \left(I_{sc} - \frac{V_{oc}-R_sI_{sc}}{R_{sh}}\right)e^{\left(\frac{V_{mp}+I_{mp}R_s-V_{oc}}{nV_T}\right)} - \left(\frac{V_{mp}+I_{mp}-R_sI_{sc}}{R_{sh}}\right) \tag{10}$$

$$e^{\left(\frac{V_{mp}+I_{mp}R_s-V_{oc}}{nV_T}\right)} = \frac{nV_TV_{mp}(2I_{mp}-I_{sc})}{\left(V_{mp}I_{sc}+V_{oc}(I_{mp}-I_{sc})\right)(V_{mp}-I_{mp}R_s) - nV_T(V_{mp}I_{sc}-V_{oc}I_{mp})} \tag{11}$$

$$\left.\frac{1}{R_{sh}}\right|_{I=I_{sc}} = \frac{\frac{(I_{sc}R_{sh}-V_{oc}+I_{sc}R_s)\exp\left[\frac{I_{sc}R_s-V_{oc}}{nV_T}\right]}{nV_TR_{sh}}}{1+\frac{(I_{sc}R_{sh}-V_{oc}+I_{sc}R_s)\exp\left[\frac{I_{sc}R_s-V_{oc}}{nV_T}\right]}{nV_TR_{sh}}+\frac{R_s}{R_{sh}}} \quad (12)$$

To determine the series resistance (Rs) of the equivalent circuit [7], [20–25], transform equation (11) into an explicit equation using the Lambert (w) function.

W(y) represents the Lambert W function, which is the mathematical inverse of itself. It solves equations of the form [22–28].

$$Y = Xe^X \quad (13)$$

Then the Lambert W function, W(y), is the function that allows you to find x in terms of y:

$$x = W(y) \quad (14)$$

Various disciplines, such as mathematics, science, and engineering, extensively utilize the Lambert W function. The Lambert W function is highly valuable for resolving transcendental equations and addressing exponential growth and decay problems that are not readily solvable using conventional functions. The Lambert W function enables the expression of equations containing exponential terms into more straightforward forms with analytical solutions. One frequently employed method involves utilizing an equivalence relationship to convert exponential equations into solvable forms by employing the Lambert W function. This allows for the discovery of manageable solutions to numerous intricate exponential equations that would otherwise lack a straightforward algebraic solution. [21-25]:

$$X = Ye^Y \Leftrightarrow Y = W(X) \quad (15)$$

By linking the expressions of the parameters to be extracted, substituting them in Equation (11), and applying Equation (15), the following equation can be derived:

$$\frac{I_{mp}R_s - V_{mp}}{nV_T} + \frac{V_{mp}I_{sc} - V_{oc}I_{mp}}{V_{mp}I_{sc} + V_{oc}(I_{mp} - I_{sc})} = W_{-1}\left(\begin{matrix} -\frac{Vmp(2Imp - Isc)}{(VmpIsc + Voc(Imp - Isc))} \\ \exp\left(\begin{matrix} -\frac{2Vmp - Voc}{nV_T} \\ +\frac{VmpIsc - VocImp}{VmpIsc + Voc(Imp - Isc)} \end{matrix}\right) \end{matrix}\right) \quad (16)$$

By using Equation (16), we can derive the explicit expression for the series resistance in the equivalent circuit [7], [25].

$$R_s = \frac{nV_T}{Imp} W_{-1}\left(\begin{matrix} -\frac{Vmp(2Imp - Isc)}{(VmpIsc + Voc(Imp - Isc))} \cdot \\ \exp\left(-\frac{Vmp - Voc}{nV_T}\right) \end{matrix}\right) \quad (17)$$

Equations (17), (12), (9), and (8) allow for the calculation of the four parameters (Rs, Rsh, I0, and Iph), respectively. This procedure determines the saturation current by calculating the ideality factor (n), which is a dimensionless number ranging from 1 to 1.6.

The ideality factor quantifies the degree to which the diode conforms to the ideal diode equation. The presence of the ideality factor enables the computation of the saturation current. A diode that has an ideality factor closer to 1 exhibits a higher degree of adherence to the ideal equation. The knowledge of the ideality factor allows for the determination of the saturation current.

5. ANALYSIS AND DISCUSSION OF THE RESULTS

Table 2 clearly displays that the photocurrent (Iph) is always equal to the short-circuit current (Isc), even when the ideality factor (n) changes.

This phenomenon arises due to the fact that the series resistance (Rs) exhibits a significantly lower value compared to the shunt resistance (Rsh) in these experimental scenarios. The results of this study show that the ideality factor doesn't change the fact that photocurrent and short-circuit current are the same, as long as the series resistance is much lower than the shunt resistance.

Because of the low value of Rs compared to Rsh, Iph equals Isc for all estimated values of n.

This study emphasizes significant discrepancies in the values of series resistance (Rs) and shunt resistance (Rsh) that correspond to different ideality factors. The ideality factor demonstrates a clear contrast between its lowest value (n = 1) and its highest value (n = 1.6). The data highlights the significant impact of the ideality factor on the electrical properties of the system. When the ideality factor decreases to 1, both the series resistance (Rs) and the shunt resistance (Rsh) display noticeable variations, highlighting the system's susceptibility to changes in the ideality factor. On the other hand, an ideality factor of 1.6 results in different electrical characteristics, highlighting the significant influence of this factor on the performance of the system.

Table 2. Extracted parameters for estimated ideal factors (I_{ph}=I_{sc})

n	R_s(Ω)	R_{sh}(Ω)	I_0(A)
1	0,3095	95,93	1,75E-08
1,1	0,2673	110,84	1,03E-07
1,2	0,2327	131,74	4,51E-07
1,3	0,1903	160,8	1,57E-06
1,4	0,1559	207,94	4,61E-06
1,5	0,1198	292,44	1,17E-05
1,6	0,0869	496,14	2,64E-05

As the ideality factor (n) changes, Figures 6, 7, and 8 show how the series resistance (Rs), shunt resistance (Rsh), and saturation current (I0) change

Table 3. Parameter values of one PV cell

n	R_{scell} *1000(Ω)	R_{shcell}(Ω)
1	8,59	2,66
1.1	7,42	3,07
1.2	6,46	3,66
1.3	5,28	4,47
1.4	4,33	5,78
1.5	3,32	8,12
1.6	2,41	13,78

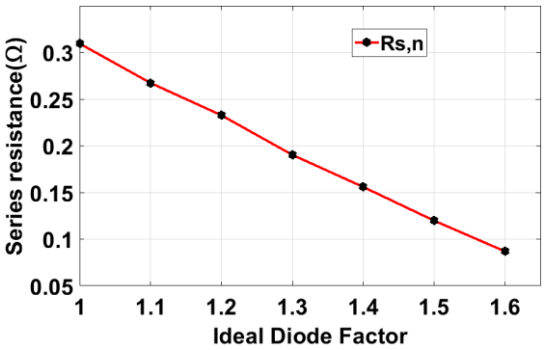

Fig. 6. Variations in the series resistance (Rs)

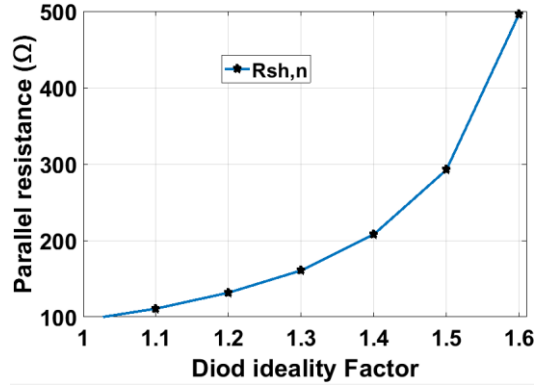

Fig. 7. Differences in branch resistance (Rsh)

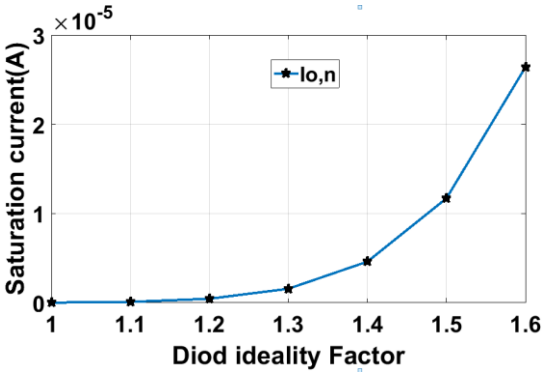

Fig. 8. The variation in the saturation current I0

The next step is to pick the best value for the diode ideality factor from the seven previous estimates. To do this, we use the serial and shunt resistance variation curves (Figures 6 and 8) to find the coordinates of this point on the graph. Here are the steps we take: To find the resistance values per cell, we divide the serial and shunt resistance values by the number of cells in the panel being studied (N = 36). It's important to note that the serial resistance values are very small compared to the shunt resistance values, so we multiply Rs by 1000 as shown in Table 3 to make them the same order of magnitude.

Lastly, we graph the resistance curves for a solitary cell on a shared plot. We plot the curve of the series resistance (Rshcell multiplied by 1000) against the ideality factor (n), and we also plot the curve of the parallel resistance (Rscell) against the ideality factor. It is crucial to acknowledge that every curve possesses its own unique form. The Rscell curve exhibits a negative correlation with the ideality factor, whereas the Rshcell*1000 curve demonstrates a positive correlation with an increase in the ideality factor.

The objective is to ascertain the coordinates of the points where these curves intersect. The points correspond to the state of equilibrium of the cell at a particular ideality factor. Put simply, the series and parallel resistances of the cell are equal at the intersection points. Analyzing the graph presented in Figure 9 accurately determines the precise value of the ideality factor.

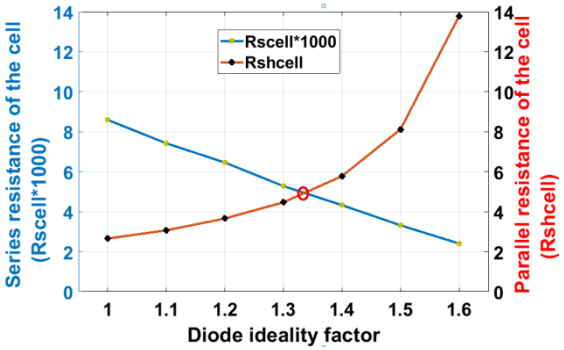

Fig. 9. Intersection of curves (1000*Rscell and Rshcell) and determine the exact value of the ideal factor n graphically

Figure 9 determines the optimal zone as the area where the two curves intersect, indicating an ideality factor of n = 1.3. The precise point of intersection represents the optimal point, which produces the optimal value for n based on its x-coordinate. In order to accurately estimate the parameter values, we need to determine the exact value of the ideality factor. To achieve this, we narrow down the range of n to 1.3–1.35. Subsequently, we ascertain the resistor values for both series and parallel configurations that correspond to each specific ideality factor value. Using the Matlab software, Figure 10 displays the coordinates at which the curves Rscell *1000 and Rshcell intersect.

It is crucial to emphasize that when we graphically determine the resistance value for the series configuration, we must divide the outcome by 1000 to obtain its accurate, initial value. By referring to Figure 10, we can use the available data to determine the exact coordinates of the intersection point.

$$X = n = 1{,}336 \text{ and } Y = RR_{shcell} = R_{scell} * 100 = 4{,}941\Omega$$

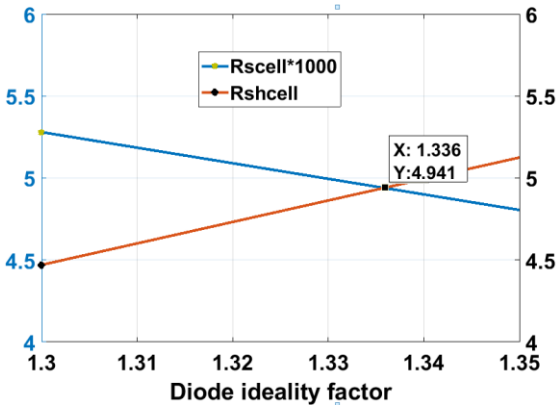

Fig.10. Spot where the Curve Rscell *1000 and the Curve Rshcell cross

Graphically inserting the parameter values of n, Rscell, and Rshcell into equations (8) and (9) computes the values of I0 and Iph. The resulting values are: I0 = 3.158E-8 A, and Iph = 5.005A.

6. CONCLUSION

The main aim of this research paper is to streamline the process of retrieving internal data from solar cells. The process showcases the extraction of the five parameters (Rs, Rsh, I0, and Iph) for the chosen equivalent circuit model by utilizing the manufacturer's datasheet. The Lambert-W function surpasses the inherent constraints of complex equations. In the [1–1.6] domain, we have identified the ideal value of the ideality factor, which is contingent upon the presence of parasitic resistances. Ultimately, it stabilized within the interval of [1.3–1.35]. We have determined the precise estimated value of the ideality factor to be 1.33. The novel approach demonstrates favorable performance in terms of accuracy. Scientists and technicians can utilize these principles to improve the effectiveness of solar cells and evaluate their ability to convert energy. The correct application of these principles promotes the development of environmentally friendly technology and the preservation of resources, resulting in enhanced efficiency of solar cells and broader utilization.

Source of funding: *This research received no external funding.*

Author contributions: *research concept and design, M.B.; Collection and/or assembly of data, M.B., M.B.R., S.M.; Data analysis and interpretation, M.B.R. A.N.; Writing the article, M.B., S.M.; Critical revision of the article, M.B.R., A.N., M.M.; Final approval of the article, M.M.*

Declaration of competing interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

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