A simple approach to extract the unknown parameters of PV modules

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Abstract: A simple and accurate technique to compute essential parameters needed for electrical characterization of photovoltaic (PV) modules is proposed. A single-diode model of PV modules, including those with series and shunt resistances, is considered accurate and simple. However, PV module datasheets provided by manufacturers provide current–voltage (I-V) characteristics as well as the values of selected parameters at standard test conditions (STC), i.e. solar radiation of 1000 W/m^2, air temperature of 25 $^\circ$C, and air mass AM = 1.5. Consequently, important parameters such as series resistance (R_s), shunt resistance (R_{sh}), photocurrent (I_{ph}), and diode reverse-saturation current (I_o) are not provided by most manufacturers. Since these parameters are crucial for PV module characterization, our study presents an exact, closed-form expression for R_s that is solvable numerically while increasing the value of the ideality factor (a) in small increments, so that four equations are formulated to compute the unknown parameters. To validate the proposed approach, a set of $I - V$ curves were computed for different values of a, and these results were compared alongside corresponding reference data for the BP SX150 and MSX60 PV modules. Average RMS errors of 0.035 for BP SX150 and 0.014 for MSX60 between the reference data and the computed data suggest that proposed approach could be used as an alternative method to quantify important missing parameters required for characterization of PV modules.

Key words: PV module, Newton Raphson, parameter estimation, MATLAB

1. Introduction

Demand for energy is increasing and the supply of fossil fuels is limited and harmful to environment. Therefore, the need to seek for alternative sources of power is imperative. Among these alternative sources, solar power is considered the best due to its abundance, especially in the Gulf area and even more so in KSA. In this concern, photovoltaic solar energy is a clean and renewable source with a long life and high reliability. Usually, solar cells convert sunlight to electrical energy with limited low voltage. These cells are integrated and connected together to give the commercially available solar modules, which are further connected in series and parallel to form a PV array based on the system requirement of voltage and current.

Since the solar modules are expensive, it is necessary to study their behavior through simulation before practical implementation of the solar system. For simulation purposes, the solar module is described by an equivalent circuit comprising a current source, one or more diodes, and one or more resistors. The single-diode model is known as a five-parameter model as it may be completely characterized by five parameters. Similarly, the double-diode model is known as a seven-parameter model. Furthermore, there is a three-diode model also. Although the double-diode and three-diode models have certain advantages, the extra diodes increase the

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computational complexity. Among these circuit models, the single-diode model, shown in Figure 1, has become the most widely used model as it offers a good compromise between simplicity and accuracy [1,2].
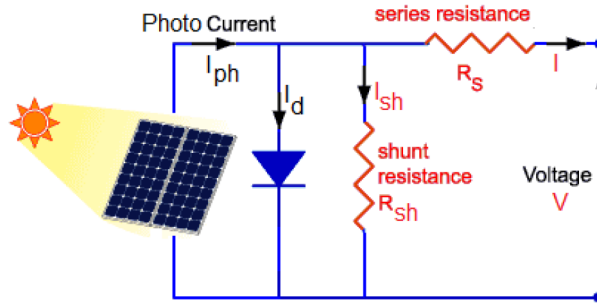

Figure 1. Single-diode equivalent circuit for PV module.

The current (I) and voltage (V) in the single-diode model are related as defined by (1).

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

where I_{ph} and I_o are the photogenerated current and diode reverse-saturation current, respectively; R_s and R_{sh} are the series and shunt resistances; and V_T is the thermal voltage, which is defined in (2).

$$V_T = \frac{a\,N_s\,k\,T}{q} \tag{2}$$

Here a is the diode ideality factor, N_s is the series-connected solar cells per module, q is the electron charge $= 1.60217646 \times 10^{-19}$ C, k is Boltzmann constant $= 1.3806503 \times 10^{-23}$ J/K, and T is the working temperature in Kelvins.

The graphical representation in Figure 2 depicts the $I - V$ relationship in (1), and, as seen therein, the PV cells act as a current source near the short circuit and as a voltage source near the open circuit.
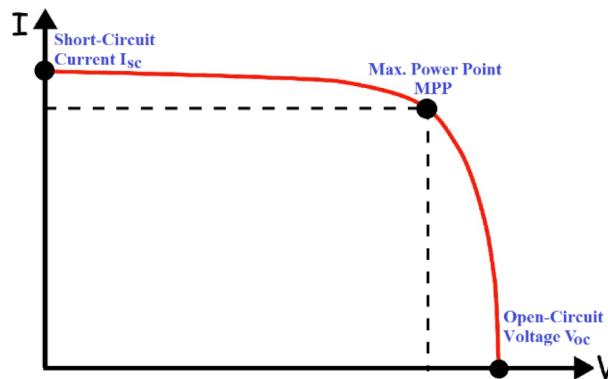

Figure 2. Graphical representation of Eq. (1).

The series resistance has a strong effect in the voltage-source region, whereas the shunt resistance has a great effect in the current-source region. Both resistances are parasitic parameters that significantly affect the electrical characteristics of a PV module.

Eq. (1) constitutes an implicit function with five unknown parameters, which are I_{ph}, I_o, a, R_s, and R_{sh}. These parameters are not provided in the manufacturer datasheet. In mathematics, an implicit function associates one of the variables (the value) with the others (the arguments). This implicit nature complicates the solution of (1) to extract the five parameters.

Researchers of PV modules strive to achieve the most accurate model. This is the reason why the mathematical modeling of PV modules is being continuously updated. Therefore, evaluation of the PV parameters has been the subject of several investigations by many researchers. While some studies used analytical methods with simplifications and approximations, others used numerical analysis methods to solve the implicit nonlinear equations. On the other hand, some studies considered these parameters are fixed, while others considered them to be continuously changing with the environmental conditions.

Ulapane et al. proposed an approach to identify the ideality factor (a) along with the series resistance using a single-diode model neglecting the shunt resistance [3]. In this study, our unknown parameters are compared with those from Ulapane's approach.

Villalva et al. and Bellia et al. separately proposed iterative methods to determine the values of R_s and R_{sh} that warranty an estimated maximum power expression that matches the maximum power given in the manufacturer datasheet [4–6]. However, as a drawback, their approach assumed so many approximations.

El-Tayyan, Conde et al., Zhang et al., and Ghani et al. separately proposed approaches to extract the parameters of a solar cell/module using the Lambert function [7–10]. In later parts of this study, the unknown parameters obtained from [7] are compared with those obtained in our work.

Bonkoungou et al. proposed methods to solve the five equations simultaneously using some simplifications [11]. We will compare the unknown parameters obtained from [11] with those in our work.

Abdel-Halim did not consider the shunt resistance and for simplicity he considered the ideality factor (a) equal to 1, and built his model on a simple equivalent circuit to extract only three parameters [12].

Chatterjee et al. approximated the PV module characteristics given in (1) by neglecting the minus one (-1) term producing five equations that could be solved simultaneously, albeit a tedious undertaking [13].

Balzani and Reatti [14] used the feed forward neural networks that comprise two hidden layers to model the PV module. The back propagation is based on the Levenberg–Marquardt function.

In addition, the least squares approach, which is a common method used in curve fitting, is employed to extract the parameters of a solar cell by minimizing the squared error between the calculated and the experimental data [15–18].

Nguyen and Nguyen [19] proposed a robust PV model built with tag tools in Simulink environment. They assumed a very small value for R_s, that is $0.0001\,\Omega$, and a large value for R_{sh}, that is $1000\,\Omega$. Moreover, they assumed a unity value for the ideality factor (a). They focus in their study on a unique step-by-step modeling procedure in Simulink.

Silvano [20] proposed two mathematical models based on a single-diode model when R_{sh} is neglected (simplified model) and when R_{sh} is considered (complete model). He considered the environmental conditions represented by temperature coefficients for V_{oc} and I_{sc} that are given in the PV datasheet.

Al-Tarabsheh et al. [21] proposed a modified PV equivalent circuit by simplifying the standard one-diode model by removing the shunt resistance and including its effect on the diode part of the circuit. This reduced the number of unknown parameters by one.

All the above-mentioned research used approximation in formulating the mathematical model. In this

work, our goal is to achieve the highest possible electric efficiency by obtaining the exact current–voltage characteristic, which is the key in deriving the parameters of a PV module. Therefore, a new closed-form expression for R_s is obtained based on four equations that are formed as functions of I_{ph}, I_o, R_{sh}, and R_s parameters. The main advantage of this closed-form expression is it is valid for all PV modules and can be solved easily using any numerical technique, while the fifth parameter a is tuned gradually until the calculated $I - V$ characteristic coincides with the experimental one provided by the manufacturer at STC. Moreover, the proposed algorithm shortens the calculation time by solving one closed-form expression rather than solving four equations simultaneously. Additionally, this algorithm can be extended to extract the unknown parameters of any solar cell or array.

2. Proposed approach

Manufacturers of PV modules provide limited information at remarkable points on the PV characteristic at STC, such as the short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and the maximum power point current (I_{mp}) and voltage (V_{mp}), which are called remarkable points. The main idea of the proposed method is to form four equations based on the remarkable-points data as functions of the unknown parameters. By proper substitution among these four equations, a closed form expression for R_s is obtained and then solved numerically for different values of a, producing a set of $I - V$ curves. These curves are compared to the reference curve given by the manufacturer, and the curve that fits closest is selected.

Rewriting (1), we obtain the PV module voltage as a function of module current as presented in (3):

$$V = V_T \times ln\left(\frac{I_{ph} + I_o - I\left(1 + \frac{R_s}{R_{sh}}\right) - \frac{V}{R_{sh}}}{I_o}\right) - IR_s \tag{3}$$

When the terminals of the PV module are left open, then there is no output current. Then substituting ($I = 0$) in (3), we obtain the open-circuit voltage (V_{oc}) given in the form:

$$\frac{V_{oc}}{R_{sh}} = I_{ph} - I_o\left[\exp\left(\frac{V_{oc}}{V_T}\right) - 1\right] \tag{4}$$

Assuming that $A = \exp\left(\frac{V_{oc}}{V_T}\right) - 1$, then:

$$I_o = \frac{I_{ph}}{A} - \frac{V_{oc}}{A\,R_{sh}} \tag{5}$$

If the terminals of the PV module circuit are shorted, the short-circuit current (I_{sc}) can be obtained by substituting ($V = 0$) in (1) as given by (6).

$$I_{sc} = I_{ph} - I_o\left[\exp\left(\frac{I_{sc}R_s}{V_T}\right) - 1\right] - \frac{I_{sc}R_s}{R_{sh}} \tag{6}$$

Assuming that $B = \exp\left(\frac{I_{sc}R_s}{V_T}\right) - 1$, then:

$$I_{sc}\left(1 + \frac{R_s}{R_{sh}}\right) = I_{ph} - B\,I_o \tag{7}$$

At maximum power, both I and V in (1) are replaced by I_{mp} and V_{mp}, respectively, as given by (8).

$$I_{mp} = I_{ph} - I_o \left[\exp\left(\frac{V_{mp} + I_{mp}R_s}{V_T} \right) - 1 \right] - \frac{V_{mp} + I_{mp}R_s}{R_{sh}} \tag{8}$$

Assuming that $C = \mathbf{exp}\left(\frac{\mathbf{V_{mp}+I_{mp}R_s}}{\mathbf{V_T}} \right) - \mathbf{1}$, (8) can be written as

$$I_{mp}\left(1 + \frac{R_s}{R_{sh}} \right) = I_{ph} - CI_o - \frac{V_{mp}}{R_{sh}} \tag{9}$$

To obtain the maximum power (P_{max}), both sides of (9) are multiplied by V_{mp} such that

$$P_{max}\left(1 + \frac{R_s}{R_{sh}} \right) = V_{mp}\left[I_{ph} - C\,I_o \right] - \frac{V_{mp}^2}{R_{sh}} \tag{10}$$

The derivative of P_{max} with respect to V_{mp} is zero; therefore,

$$I_o\left(\frac{V_{mp}(C+1)}{V_T} + C \right) - I_{ph} + \frac{2\,V_{mp}}{R_{sh}} = 0 \tag{11}$$

Obtaining a closed-form expression as a function of R_s based on the four equations presented in (5), (7), (9) and (11) is considered the backbone of the proposed approach.

Substituting (5) into (7) gives

$$I_{ph} = \frac{I_{sc}\left(1 + \frac{R_s}{R_{sh}} \right)A - \frac{V_{oc}}{R_{sh}}}{A - B} \tag{12}$$

Similarly, by substituting (5) into (9), we obtain

$$I_{mp}\left(\frac{R_{sh} + R_s}{R_{sh}} \right) = I_{ph}\left(\frac{A - C}{A} \right) + \frac{C\,V_{oc} - A\,V_{mp}}{A\,R_{sh}} \tag{13}$$

Meanwhile, substituting (12) into (13) yields

$$R_{sh} = \frac{V_{oc}\,(C - B) - V_{mp}(A - B)}{I_{mp}\,(A - B) - I_{sc}(A - C)} - R_s \tag{14}$$

By substituting (5) into (11), we obtain

$$I_{ph}\left(\frac{V_{mp}(C+1)}{A\,V_T} + \frac{C}{A} - 1 \right) - \frac{V_{oc}V_{mp}\,(C+1)}{A\,V_T\,R_{sh}} - \frac{C\,V_{oc}}{A\,R_{sh}} + \frac{2\,V_{mp}}{R_{sh}} = 0 \tag{15}$$

When (12) is substituted into (15), we obtain

$$I_{sc}\left[R_{sh} + R_s \right]\left(V_{mp}\,(C+1) + V_T(C - A) \right) + V_{oc}V_T\,(B - C) - V_{oc}V_{mp}\,(C+1) + 2\,V_{mp}V_T\,(A - B) = 0 \tag{16}$$

Similarly, substituting (14) into (16) produces a closed-form expression as a function of only one parameter, R_s, as presented in (17):

$$f\left(R_s\right) = V_{mp}\left(C+1\right)\left[I_{sc}V_{oc} - I_{sc}V_{mp} - I_{mp}V_{oc}\right] - I_{sc}V_{mp}V_T\left(A-C\right) + I_{mp}V_{oc}V_T\left(B-C\right) + 2\,I_{mp}V_{mp}V_T\left(A-B\right)$$
(17)

An iterative method using Newton–Raphson is used to find the root of the function $f(R_s)$. If (17) has a simple root near $R_{s(i)}$, then a closer estimate to this root is $R_{s(i+1)}$, where

$$R_{s\,(i+1)} = R_{s\,(i)} + \frac{f\left(R_{s\,(i)}\right)}{f'\left(R_{s\,(i)}\right)}$$
(18)

Here i is the iteration index.

To apply the Newton–Raphson algorithm given in (18), the derivative of $f\left(R_s\right)$ denoted by $f'\left(R_s\right)$ is required. This is presented in (19):

$$f'\left(R_s\right) = \frac{V_{oc}V_{mp}\left(C+1\right)}{V_T}\left[I_{sc} - I_{mp}\right] + I_{sc}\left(B+1\right)\left[V_{oc} - 2V_{mp}\right] + \left(C+1\right)\left[I_{sc}V_{mp} - I_{mp}V_{oc} - \frac{I_{sc}V_{mp}^2}{V_T}\right]$$
(19)

The iteration is begun with an initial estimate $R_{s(0)}$ and continues to find $R_{s(1)}$, $R_{s(2)}$, $R_{s(3)}$, …etc. until a suitably accurate estimate value of R_s is obtained. This is judged by the convergence of $R_{s(1)}$, $R_{s(2)}$, $R_{s(3)}$, …to a fixed value.

Assuming a tolerance of 10^{-7} is assigned for the term $\frac{f\left(R_{s\,(i)}\right)}{f'\left(R_{s\,(i)}\right)}$, the final value of R_s is determined based on (18), for i iterations.

Based on the value of R_s obtained from (17), the value of R_{sh} is obtained from (14). Then the value of I_{ph} is derived from (12). Finally, the value of I_o is determined from (5).

The proposed algorithm to obtain the four unknown R_s, R_{sh}, I_{ph}, and I_o is repeated for different values of the fifth parameter a starting from an initial value a_o to a final value a_f depending on the PV model type and experience. These parameters are applied to (1) to obtain the module current (I) to be compared to the datasheet current $(I_{\exp})$ in order to calculate the root mean square error (E_{rms}) as defined in (20):

$$E_{rms} = \sqrt{\frac{\sum\limits_{0}^{i}\left(I_{(i)} - I_{\exp(i)}\right)^2}{i}}$$
(20)

The most accurate values of the unknown parameters are those with minimum values of E_{rms}.

The flowchart in Figure 3 illustrates the procedure to accomplish our proposed approach as explained earlier.

3. Results and verification

The lack of detailed information in the manufacturer datasheet poses a problem for the verification process. Therefore, it is necessary to choose PV modules whose datasheets include the I-V characteristics. Two examples of such modules are BP SX-150 and MSX-60 modules, whose basic information is presented in Table 1. More
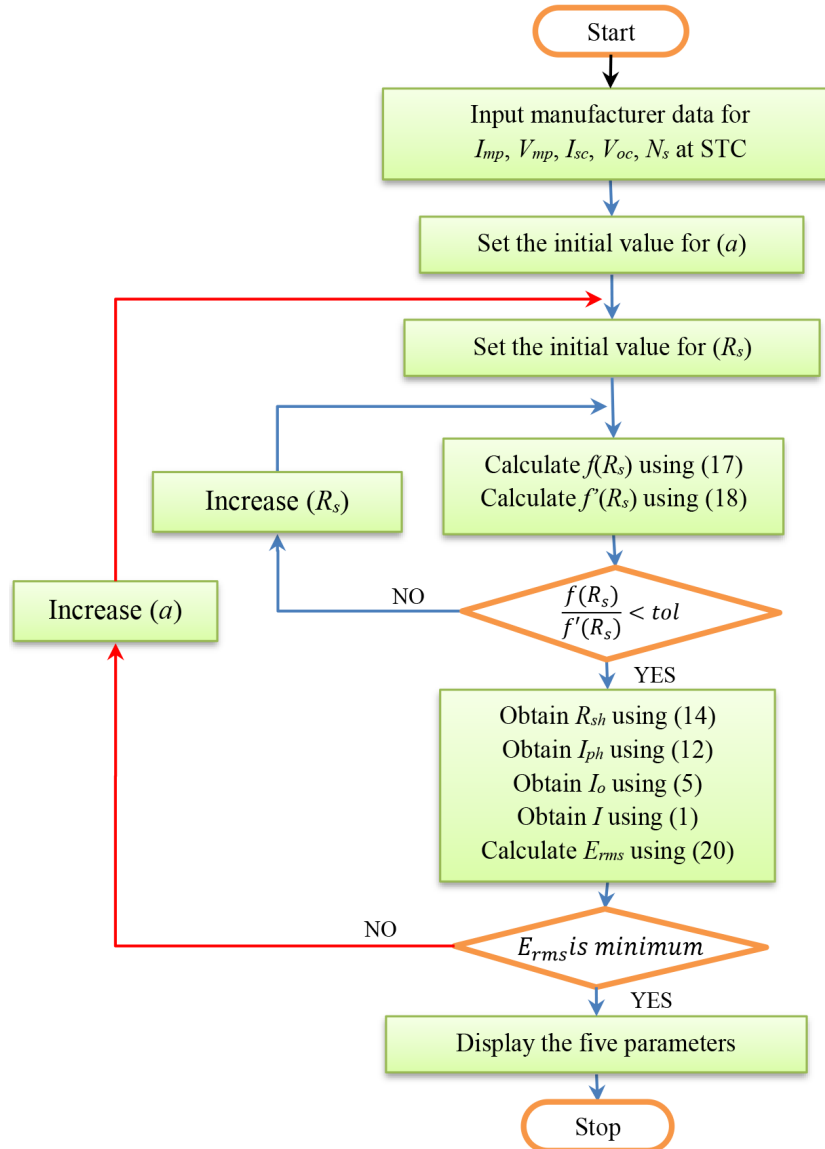
**Figure 3.** Flowchart illustrating the proposed approach.

details about these two PV modules are provided by manufacturer websites. These two modules will be used in our verification procedure.

Figures 4 and 5 show the RMS error when the ideality factor (a) is initialized at 1.2 and incremented in a step of 0.0001 for BP SX-150 and MSX-60 PV modules, respectively. It can be observed that the RMS error decreases with increase in a (until 1.64 in the case of SX-150 and 1.387 in the case of MSX-60), it reaches its minimum value, and after that it starts to increase again. Therefore, the optimum value of a is that indicated in both figures.

Based on the numerical solution of (17), the change in series resistance for the BP SX-150 and MSX-60 solar modules at different values of a are also shown in Figures 6 and 7, respectively, and their optimum values corresponding to the optimum a obtained are marked.

Table 1. Electrical characteristics of BP SX-150 and MSX-60 PV modules at STC.

Parameters	Datasheet value	
	BP SX-150	MSX-60
Maximum power (P_{max})	150 W	60 W
Voltage at MPP (V_{mp})	34.5 V	16.8 V
Current at MPP (I_{mp})	4.35 A	3.56 A
Short-circuit current (I_{sc})	4.75 A	3.87 A
Open-circuit voltage (V_{oc})	43.5 V	21.0 V
Temperature coefficient of I_{sc}	(0.065 ± 0.015) %/°C	(0.065 ± 0.015) %/°C
Temperature coefficient of V_{oc}	$-(160\pm20)$ mV/°C	$-(80\pm10)$ mV/°C
Series-connected cells (N_s)	72	36
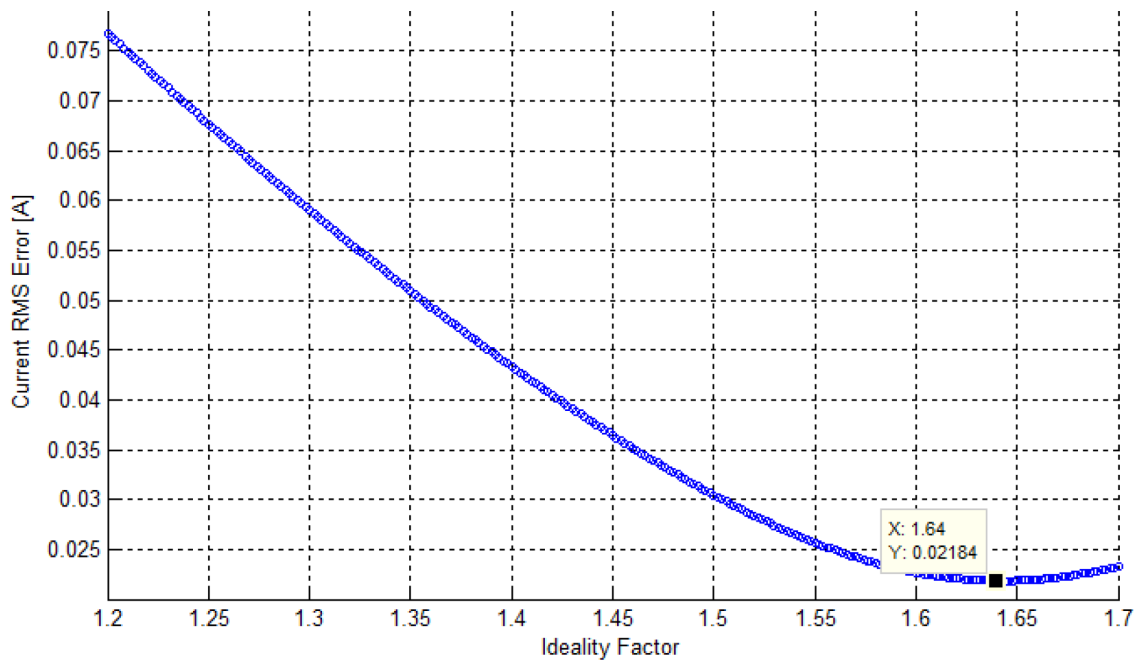
Figure 4. Current RMS error at different values of ideality factor (a) for BP SX-150 PV module.

Based on (14), the change in shunt resistance for the BP SX-150 and MSX-60 PV modules at different values of a are similarly shown in Figures 8 and 9, respectively, and their optimum values corresponding to the optimum a are marked.

The best parameters of BP SX-150 and MSX-60 PV modules are those corresponding to values of a that give minimum RMS error as listed in Table 2.

The $I-V$ characteristic provided by most manufacturers is presented as a graph rather than raw data. To visualize and make good use of this data, we digitize the graphical data using a freeware package enguage. Following this, the $I-V$ characteristics for both BP SX-150 and MSX-60 PV modules in Table 2 were compared alongside the digitized values. This is presented in Figures 10 and 11, respectively, revealing a correlation between datasheet values and calculated results. This suggests that the calculated values are in good agreement with the datasheet values.

To further show the correlation between the two results, the error between the module current realized
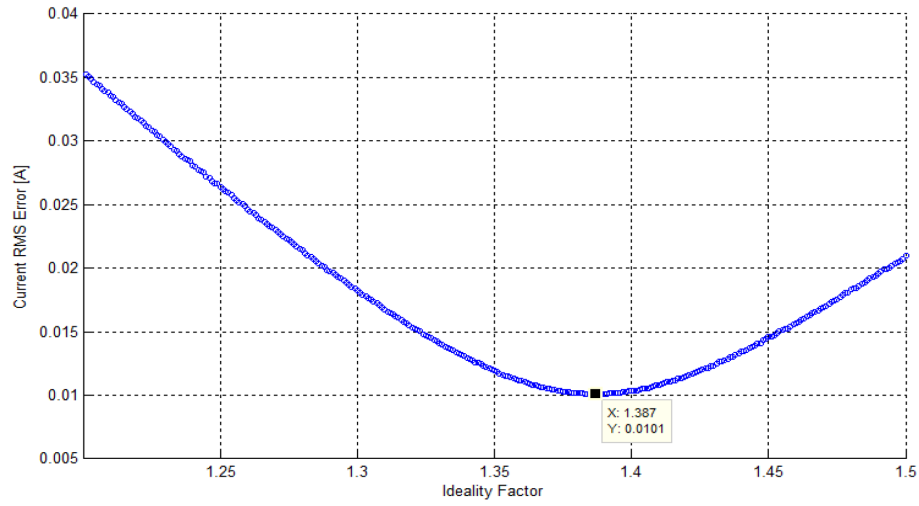
Figure 5. Current RMS error at different values of ideality factor (a) MSX-60 PV module.
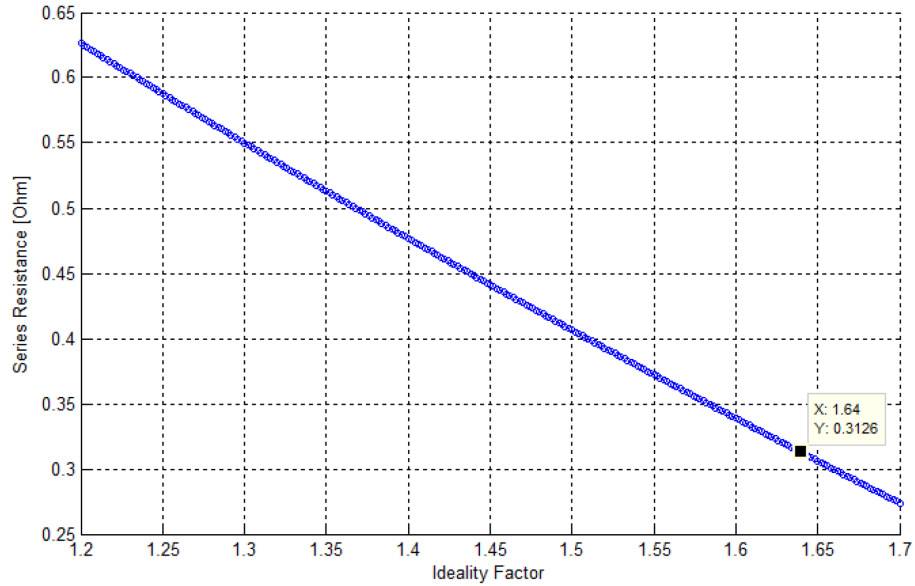

Figure 6. Changing of series resistance with ideality factor (a) for BP SX-150 PV module.

Table 2. Calculated parameters of BP SX-150 and MSX-60 PV modules.

Parameter	Calculated values	
	BP SX-150	MSX-60
a	1.64	1.387
R_{sh} (Ω)	1799.371625	406.346152
R_s (Ω)	0.312557	0.223427
I_o (A)	2.80161×10^{-6}	2.971556×10^{-6}
I_{ph} (A)	4.750827	3.872128

from the approach and those digitized from the datasheet (at the remarkable points) are presented in Figures 12 and 13 for the BP SX-150 and MSX-60 PV modules, respectively.
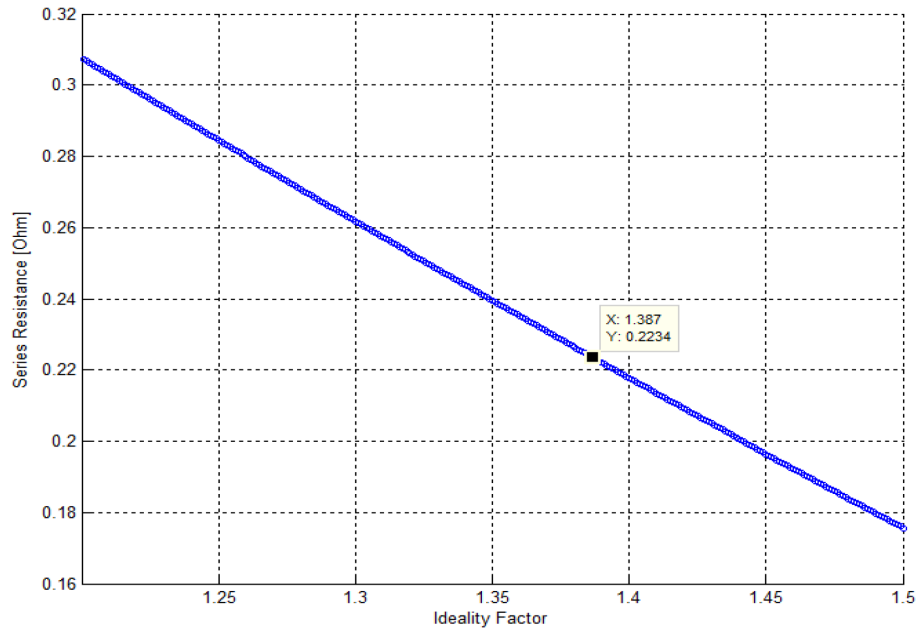
Figure 7. Changing of series resistance with ideality factor (a) for MSX-60 PV module.
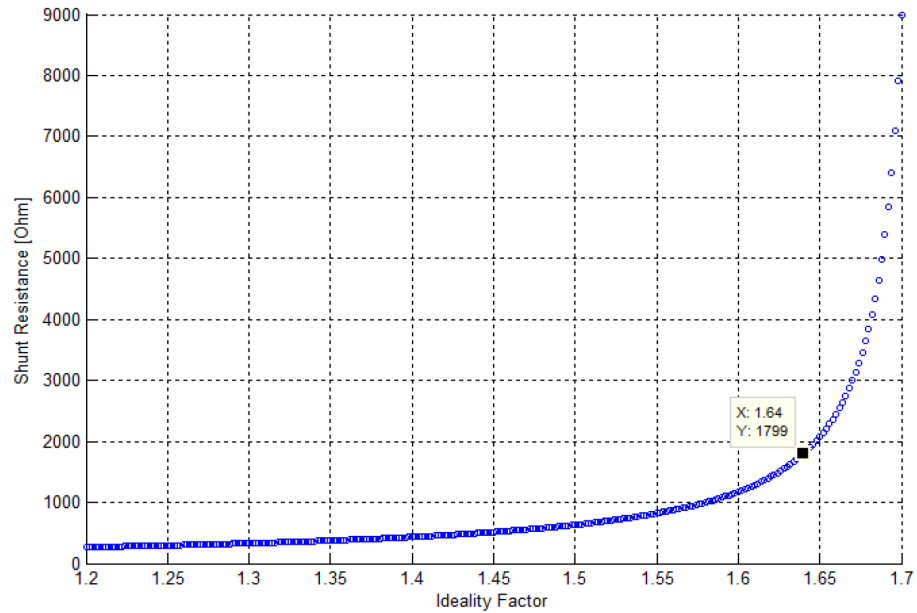

Figure 8. Changing of shunt resistance with ideality factor (a) for BP SX-150 PV module.

Based on Figures 10 to 13, we can observe that both the measured and calculated I-V characteristics are within a narrow error band of less than 0.035 A for the BP SX-150 PV module and 0.014 A for the MSX-60 PV module. This proves that the proposed set of equations used in modeling is within the acceptable range for real data provided by the manufacturers.

Table 3 summarizes the comparison between the calculated parameters for both PV modules and those in the published literature.
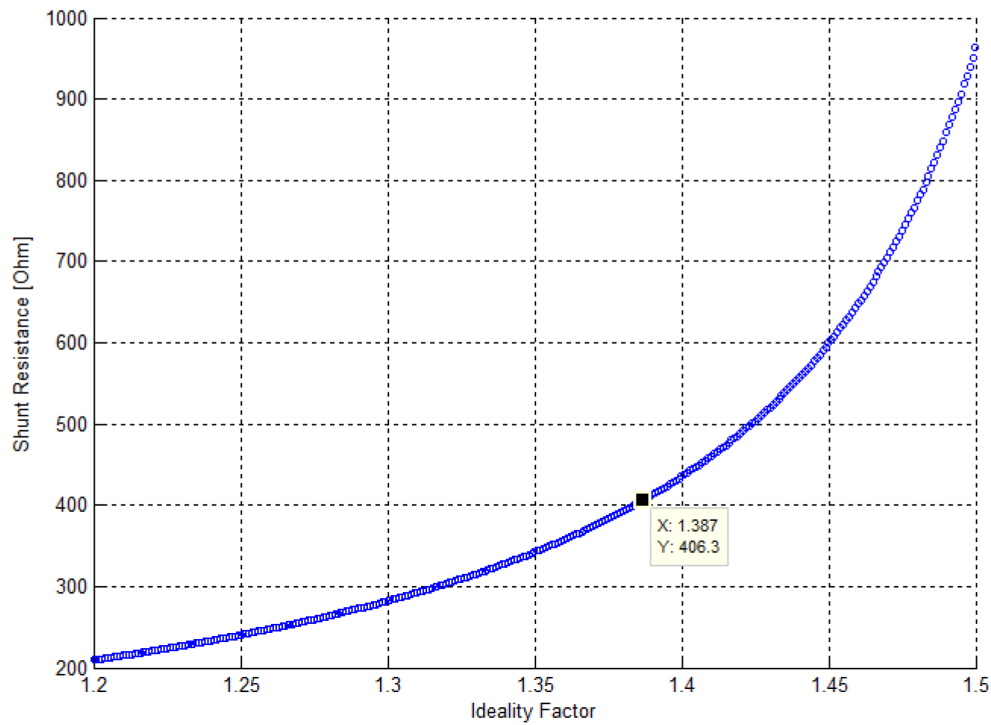
Figure 9. Changing of shunt resistance with ideality factor (a) for MSX-60 PV module.
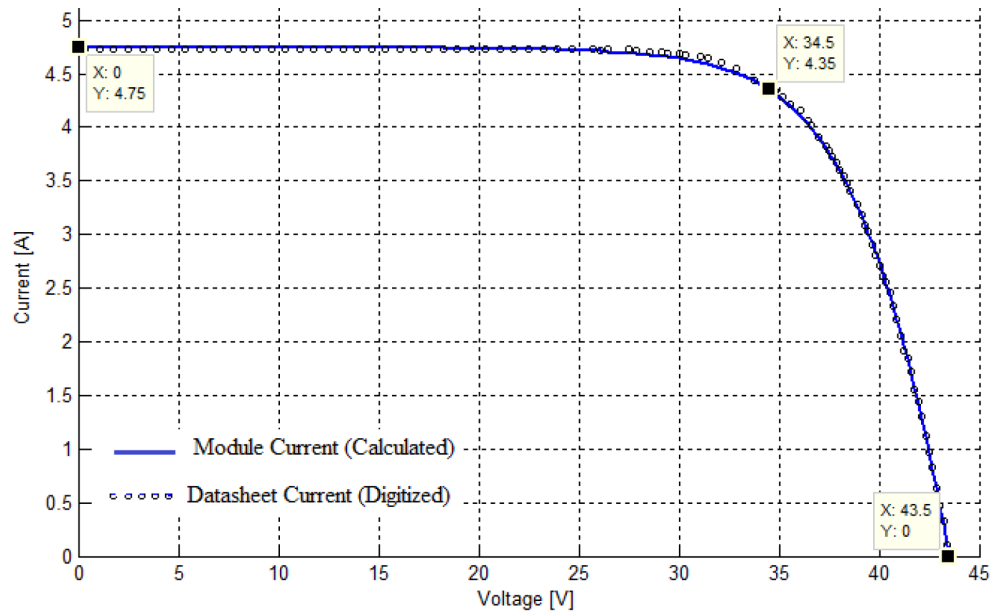

Figure 10. Comparison between module current and datasheet values for BP SX-150 PV module.

4. Conclusion

A simple but effective approach is presented for extracting unknown parameters of PV modules using the single-diode model based on three remarkable points provided in the manufacturer's datasheet. This is achieved by formulating a closed-form expression as a function of module series resistance and solving numerically while
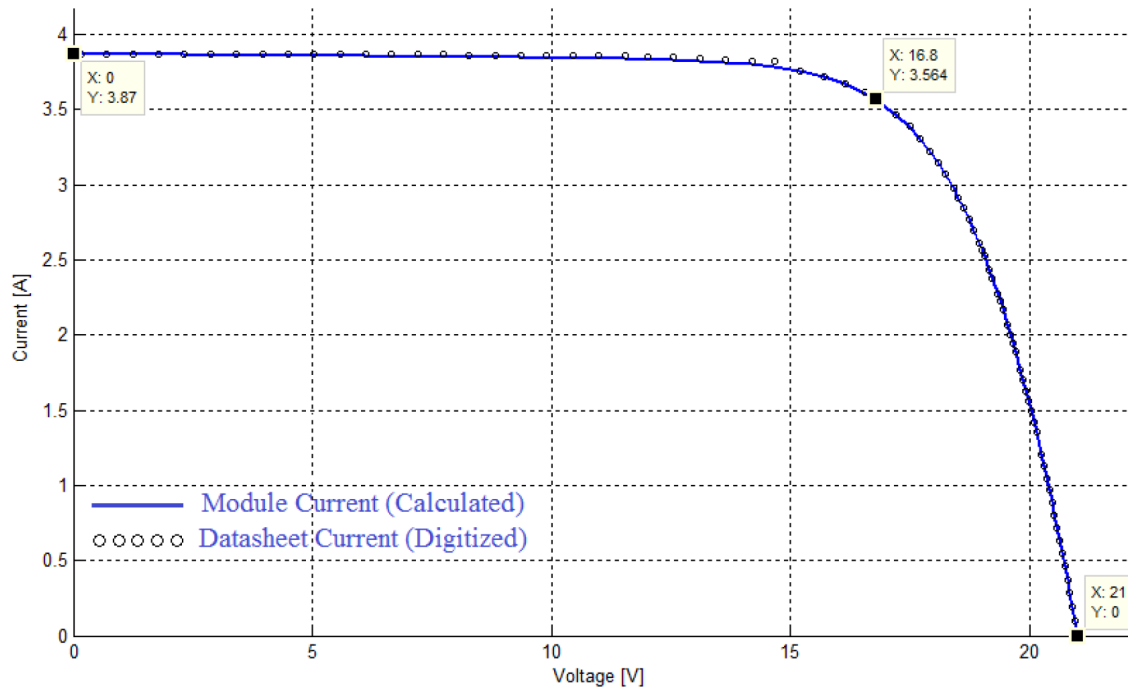
Figure 11. Comparison between module current and datasheet values for MSX-60 PV module.
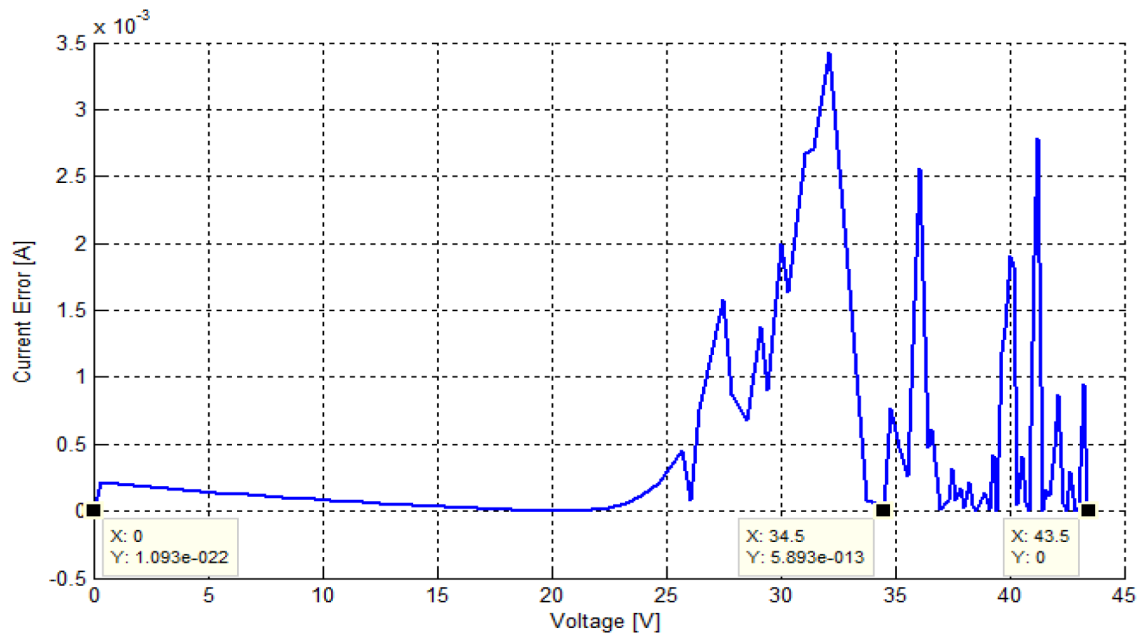

Figure 12. Difference between calculated current and datasheet values for BP SX-150 PV module.

increasing the value of the ideality factor (a) in small increments. The effectiveness of the formulation presented in the study is demonstrated by comparing the results alongside those from reference characteristics provided by manufacturers of the BP SX-150 and MSX-60 PV modules. The results show a close correlation in terms of the unknown parameters. Moreover, compared with similar computations in the literature, the computation results from our study for both PV modules produced better outcomes.
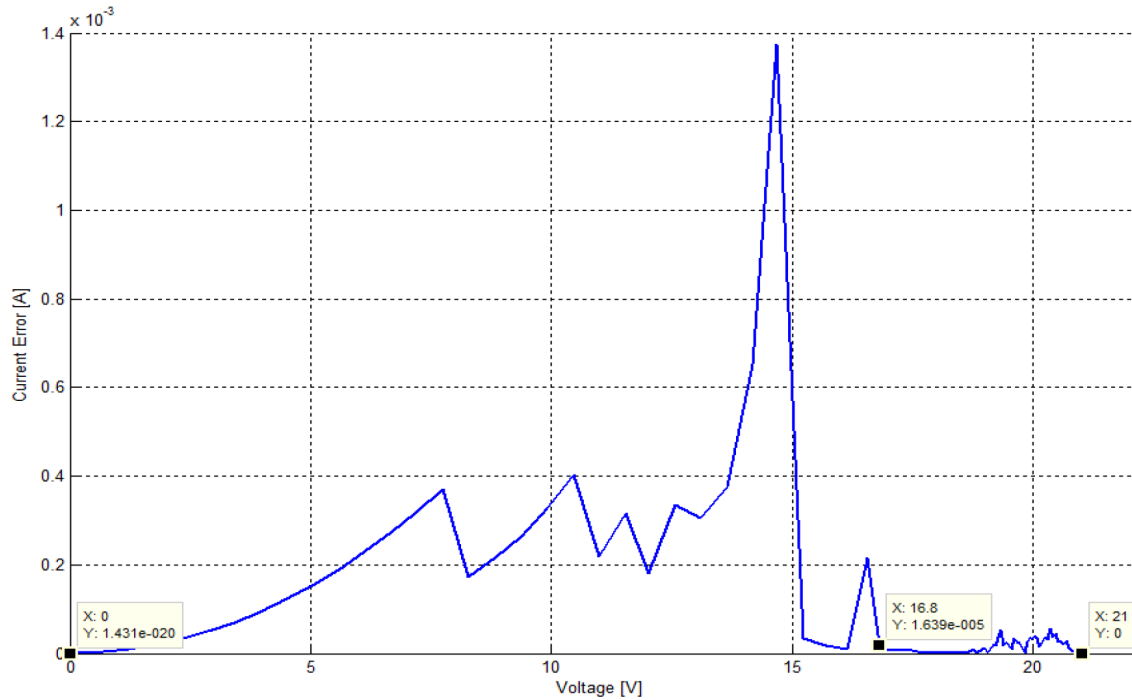
Figure 13. Difference between calculated current and datasheet values for MSX-60 PV module.

Table 3. Extracted parameters by proposed method and previous methods.

PV module	a	R_s (Ω)	R_{sh} (Ω)	I_o (A)	I_{ph} (A)
BP SX-150					
Previous work [3]	1.64	0.343	Ignored	2.83×10^{-6}	4.75
This work	1.64	0.312557	1799.372	2.8016×10^{-6}	4.7508
BP MSX-60					
Previous work [7]	1.277	0.2165	274.937	6.45×10^{-7}	3.812
Previous work [11]	1.36	0.180	360.002	1.859×10^{-7}	3.8119
This work	1.387	0.223427	406.3462	2.9716×10^{-6}	3.87213

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