

# Extraction of Unknown Parameters of PV Modules

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**Abstract**— All PV module's datasheets provide I-V curve as well as the values of selected parameters at Standard Test Conditions (STC). Other parameters such as series resistance ( $R_s$ ), shunt resistance ( $R_{sh}$ ), photocurrent ( $I_{ph}$ ), diode reverse-saturation current ( $I_o$ ) and ideality factor ( $a$ ) are not measurable. Therefore, they are not provided by manufacturers. These parameters are unique for the electrical characterization of any PV module. Based on the parameters  $I_{ph}$ ,  $I_o$ ,  $R_s$ , and  $R_{sh}$ , four equations are formed and used to obtain an exact, closed-form expression for  $R_s$  that solved numerically while increasing the value of  $a$  in small increments. To validate the proposed approach, a set of I-V curves are obtained at different values of  $a$ , and compared to the reference curve given by the manufacturer, then the parameters that corresponds to the curve that fits closest are taken. This process is done for BP SX150 and MSX60 solar modules. The proposed algorithm is compared with alternative methods available in the literature. The superiority of the proposed algorithm is verified.

**Keywords**— PV module; Newton Raphson; parameter estimation; Matlab

## I. INTRODUCTION

Solar power is considered as the best due to the abundant availability of sun especially in Gulf area and specifically in Kingdom of Saudi Arabia (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 small voltage in the range of 0.5 to 0.8 volts. 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 recommended to study their behavior through simulation before practical implementation of the solar system. For simulation purpose, the solar module is described by an equivalent circuit with single diode, or two diodes, or three diodes. Among these circuit models, the single-diode model, shown in Fig. 1, has become the most widely used model as it offers a good compromise between simplicity and accuracy [1-2].

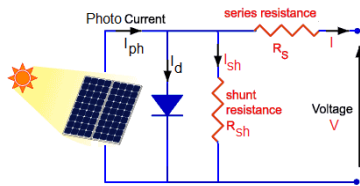


Fig. 1. Single-diode equivalent circuit of PV module

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

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

where  $I_{ph}$  and  $I_o$  are the photo-generated 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).

$$V_T = \frac{a N_s k T}{q} \quad (2)$$

Where  $a$  is the diode ideality factor,  $N_s$  is the series-connected solar cells/module,  $q$  is the electron charge =  $1.602176 \times 10^{-19}$  C,  $k$  is Boltzmann constant =  $1.3806503 \times 10^{-23}$  J/K, and  $T$  is the working temperature in Kelvin.

The graphical representation in Fig. 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.

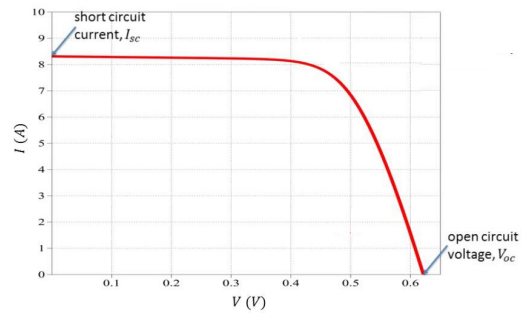


Fig. 2. Graphical representation of equation (1)

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 of the resistances are parasitic parameters that significantly affect the electrical characteristics of a PV module.

Equation (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. This implicit nature complicates the extraction of the five parameters.

The evaluation of these parameters has been the subject of several investigations of 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.

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

Villalva et al. [4][5], and Bellia et al. [6] proposed iterative methods to determine the values of  $R_s$  and  $R_{sh}$  that warranties an estimated maximum power expression that matches the maximum power given in the manufacturer datasheet. However, as a drawback, their approach assumed so many approximations.

Eltayyan [7], Conde et al. [8], Zhang et al. [9] and Ghani et al. [10] separately proposed approaches to extract the parameters of a solar cell/module using Lambert function. In later parts of this study, the unknown parameters obtained from Eltayyan [7] effort are compared with those obtained in our work.

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

Abdulhalim [12] didn't consider the shunt resistance and for simplicity he considered the ideality factor  $a$  equal 1, and built his model on a simple equivalent circuit to extract only three parameters.

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

Other techniques apply curve fitting methods to some assumed functional relationships [14-15]. 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 [16-17].

In our work, 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. This expression is solved numerically using Newton Raphson's method, 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. In order to validate the veracity of the proposed algorithm, it is applied to extract the unknown parameters of any solar cell, module or array.

## II. PROPOSED APPROACH

Manufacturers of PV modules provide limited information at remarkable points on the PV characteristic at standard test conditions (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-point 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  $a$ . Then, a set of  $I$ - $V$  curves are obtained and 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):

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

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:

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

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

$$I_o = \frac{I_{ph}}{A} - \frac{V_{oc}}{A R_{sh}} \quad (5)$$

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).

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

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

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

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

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

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

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

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

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

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

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

Solving the four unknown parameters presented in (5), (7), (9) and (11) are considered as the backbone of the proposed approach.

Substituting (5) into (7), gives:

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

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

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

Meanwhile, substituting (12) into (13), yields:

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

And by substituting (5) into (11), we obtain:

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

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

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

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

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

To solve (17) numerically using Newton-Raphson method, its derivative denoted by  $f'(R_s)$  is required. This is presented in (18)

$$f'(R_s) = \frac{V_{oc} V_{mp} (C + 1)}{V_T} [I_{sc} - I_{mp}] + I_{sc} (B + 1) [V_{oc} - 2 V_{mp}] + (C + 1) \left[ I_{sc} V_{mp} - I_{mp} V_{oc} - \frac{I_{sc} V_{mp}^2}{V_T} \right] \quad (18)$$

Based on the tolerance (specified in next section) for the term  $\frac{f(R_{s(i)})}{f'(R_{s(i)})}$ , the final value of  $R_s$  is determined based on (19), for  $i$  iterations.

$$R_{s(i+1)} = R_{s(i)} + \frac{f(R_{s(i)})}{f'(R_{s(i)})} \quad (19)$$

Based on the value of  $R_s$  obtained from (17), The value of  $R_{sh}$  can be 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).

$$E_{rms} = \sqrt{\frac{\sum_0^i (I_{(i)} - I_{exp(i)})^2}{i}} \quad (20)$$

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

### III. 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 module are BP SX-150 and MSX-60 modules whose basic information are presented in Table I. More details about these two PV modules are provided in [18-19]. These two modules will be used in our verification procedure.

Table I. 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 $P_{max}$ ( $V_{mp}$ )	34.5 V	16.8 V
Current at $P_{max}$ ( $I_{mp}$ )	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 $I_{sc}$	$(0.065 \pm 0.015) \% / ^\circ C$	$(0.065 \pm 0.015) \% / ^\circ C$
Temperature coefficient of $V_{oc}$	$-(160 \pm 20) mV / ^\circ C$	$-(80 \pm 10) mV / ^\circ C$
Series-connected cells ( $N_s$ )	72	36

Figs. 4 and 5 show the RMS error when the ideality factor ( $a$ ) is initialized at 1.2 and incremented in steps of 0.001 for BP SX-150 and MSX-60 PV modules, respectively. It can be observed that the RMS error decreases as  $a$  increases (until 1.64 in case of SX-150, and 1.387 in case of MSX-60), it reaches its minimum value, after which it restarts to increase again. Therefore, the optimum value of  $a$  is that indicated in figures.

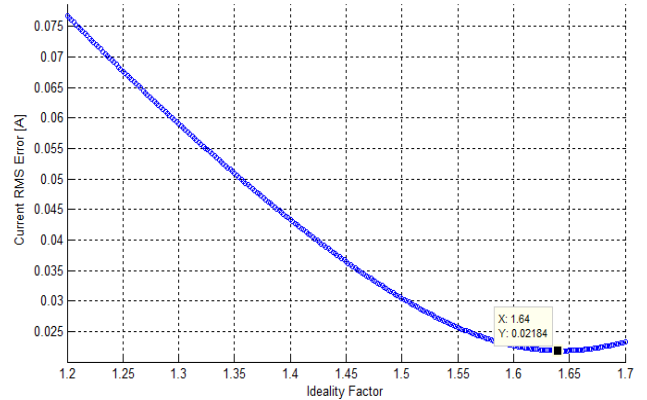


Fig. 4 RMS error of current at different values of  $a$  for BP SX-150 PV module

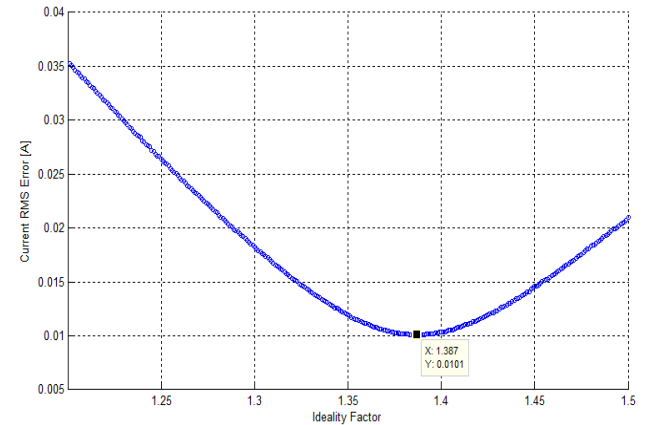


Fig. 5. RMS error of current at different values of  $a$  for MSX-60 PV module

The change in series resistance for the BP SX-150 and MSX-60 solar modules at different values of  $a$  are also shown in Figs. 6 and 7 with their optimum values corresponding the optimum  $a$  are marked in each figure.

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 Figs. 8 and 9 with their optimum values are shown marked in each figure.

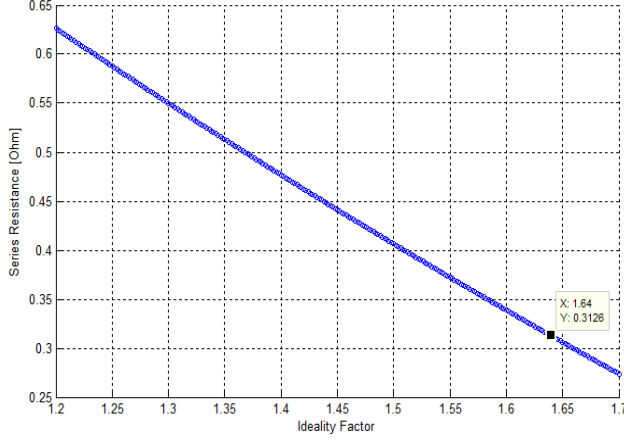


Fig. 6 Changing  $R_s$  with ideality factor  $a$  for BP SX-150 PV module

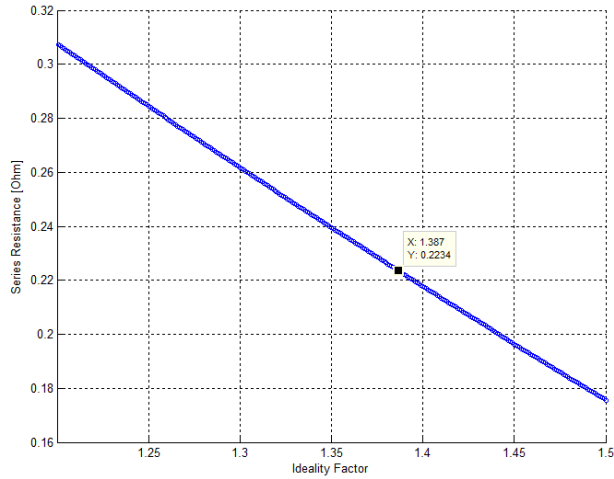


Fig. 7. Changing  $R_s$  with ideality factor  $a$  for MSX-60 PV module

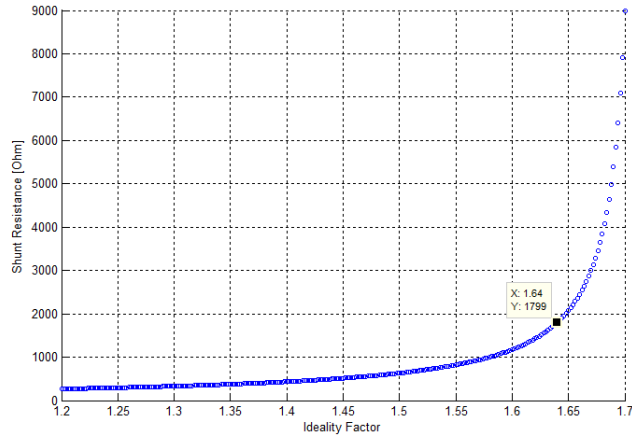


Fig. 8. Changing  $R_{sh}$  with ideality factor  $a$  for BP SX-150 PV module

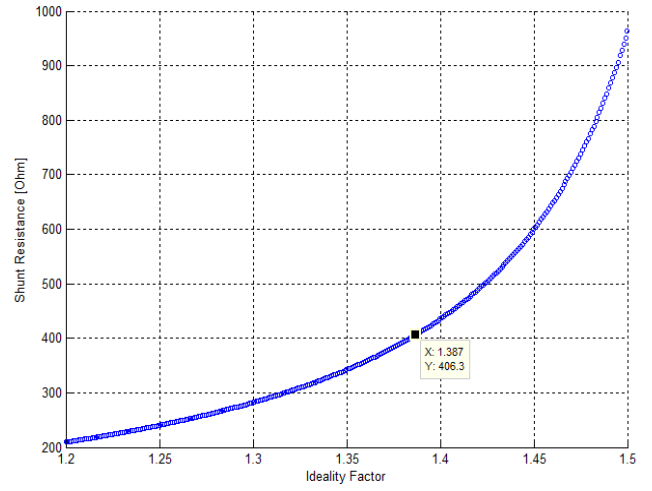


Fig. 9. Changing  $R_{sh}$  with ideality factor  $a$  for the MSX-60 PV module

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 II.

Table II. Calculated Parameters of BP SX-150 and MSX-60 PV Modules

Parameter	Calculated Values	
	BP SX-150	MSX-60
$a$	1.64	1.387
$R_{sh}$	1799.371625 $\Omega$	406.346152 $\Omega$
$R_s$	0.312557 $\Omega$	0.223427 $\Omega$
$I_o$	$2.80161 \times 10^{-6}$ A	$2.971556 \times 10^{-6}$ A
$I_{ph}$	4.750827 A	3.872128 A

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 language [20]. Following this, the  $I$ - $V$  characteristics for both BP SX-150 and MSX-60 PV modules in Table II were compared alongside the digitized values. This is presented in Figs. 10 and 11 for BP SX-150 and MSX-60 PV modules, respectively.

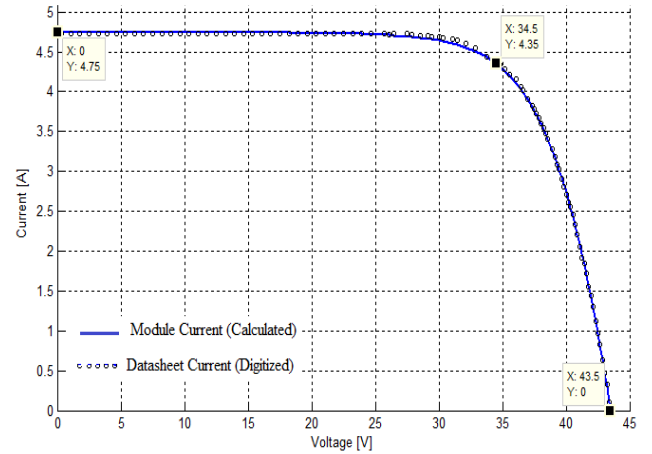


Fig. 10. Module current and datasheet values for BP SX-150 PV Module

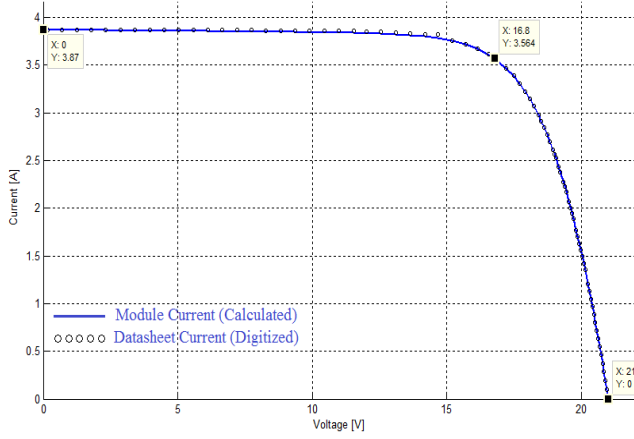


Fig. 11. Module current and datasheet values for MSX-60 PV Module

Figs. 10 and 11 reveal correlation between datasheet values and calculated results. Suggesting 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 from the approach and those digitized from the datasheet (at the remarkable points) are presented in Figs. 12 and 13 for the BP SX-150 and MSX-60 PV module, respectively.

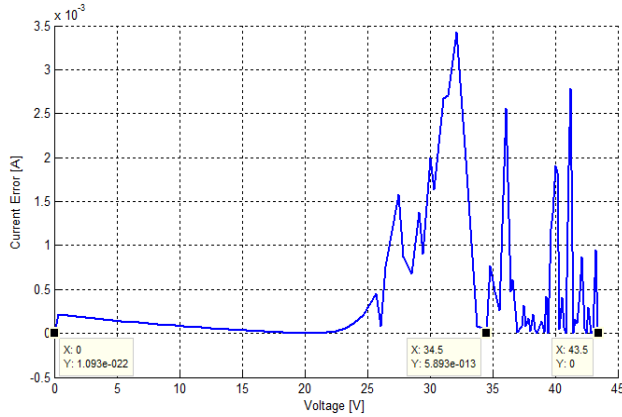


Fig. 12. Difference between calculated current and datasheet values for BP SX-150 PV module

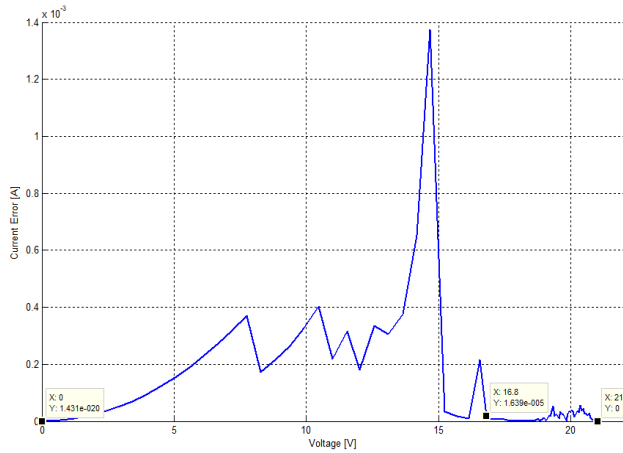


Fig. 13. Difference between calculated current and datasheet values for MSX-60 PV module

Based on Figs.10 to 13, we can observe that, both of 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 MSX-60 PV module. This proves that the proposed set of equations used in modeling is within the acceptable range for real data that is provided by the manufacturers.

Table III summarizes the comparison between the calculated parameters for both PV modules and those in published literature.

Table III Extracted parameters by proposed method and previous methods

PV Module	$a$	$R_s (\Omega)$	$R_{sh} (\Omega)$	$I_o (A)$	$I_{ph} (A)$
<b>BP SX-150</b>					
Pervious work [3]	1.64	0.343	Ignored	$2.83 \times 10^{-6}$	4.75
This work	1.64	0.312557	1799.372	$2.8016 \times 10^{-6}$	4.7508
<b>BP MSX-60</b>					
Pervious work [7]	1.277	0.2165	274.937	$6.45 \times 10^{-7}$	3.812
Pervious work [11]	1.36	0.180	360.002	$1.859 \times 10^{-7}$	3.8119
This work	1.387	0.223427	406.3462	$2.9716 \times 10^{-6}$	3.87213

To further show the accuracy of calculated parameters, the I-V characteristics at different irradiance are investigated. As we know, irradiance has a great effect on the performance of PV modules. It mainly affects the value of  $I_{ph}$ , thus affecting the output current and voltage of the PV module. Therefore, the I-V relation given by (1) can be rewritten as presented in (21):

$$I = G \times I_{ph} - I_o \left[ \exp \left( \frac{V + IR_s}{V_T} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad (21)$$

Where,  $G$  is the change in irradiance, which takes values between 1 and 0 as the irradiance varies between 1000 and 0 W/m<sup>2</sup>.

The effect of varying the irradiance on the current-voltage and power-voltage characteristics for BP SX-150 PV module at ten different irradiance levels are presented in Figs. 14 and 15, respectively.

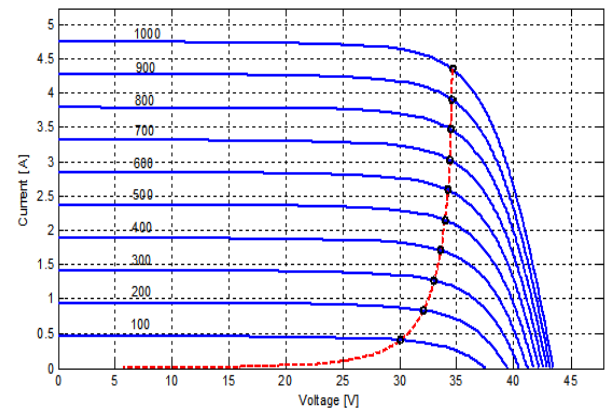


Fig. 14. Current-Voltage characteristics at ten irradiance levels for BP SX-150 PV module

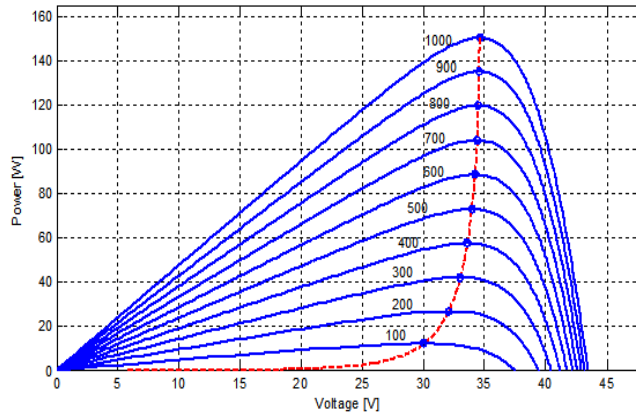


Fig. 15. Power-Voltage characteristics at ten irradiance levels for BP SX-150 PV module

#### IV. 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 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. The effect of changing the solar irradiance are also considered.

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