A Novel Approach for Evaluation of Parameters of Photovoltaic Modules

Vandana Jha  
Research Scholar, Electrical Engineering Department,  
National Institute of Technology Patna, Patna, Bihar, India.  
Orcid Id: 0000-0002-1871-8227

Uday Shankar Triar  
Professor, Electrical Engineering Department,  
National Institute of Technology Patna, Patna, Bihar, India.  
Orcid Id: 0000-0002-0702-2312

Abstract  
This paper proposes a novel approach for evaluation of parameters of photovoltaic (PV) modules. New flowcharts are proposed for evaluating unknown parameters of the non linear I – V equation of the single-diode model of PV module including series and parallel resistances, taking the manufacturer given data at standard test conditions as inputs. The new methods involved in proposed flowcharts for evaluation of unknown parameters are not based on assumptions or curve fitting rather on mathematical equations of PV modules. The proposed method is general and can be implemented by any software. In this paper, the proposed flowcharts are implemented by MATLAB programming, hence the most accurate values of the unknown parameters are obtained. Evaluated unknowns are used in generating module output characteristics at different environmental conditions. The effects of variation of ideality factor, series and parallel resistances on output characteristics are also studied. The generated characteristics are validated with experimental data of BP SX 150 and MSX-64 PV modules. The parameters evaluated by the proposed PV module model are validated with the datasheet values of four commercially available PV modules (mono-crystalline and poly-crystalline) at Standard Test Conditions and Nominal Operating Cell Temperature Conditions. The superiority of the proposed technique is proved.

Keywords: Photovoltaic (PV), single-diode model, flowcharts, MATLAB programming, mono-crystalline, polycrystalline.

INTRODUCTION

Photovoltaics (PV) is a phenomenon of conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect. A PV array of a PV network that produces and supplies electricity in power system is constituted of PV modules.

Before implementing a PV power system in reality, it is important to study its behaviour through modelling. The mathematical model of the PV device is very useful in studying various PV technologies, and in designing several PV systems along with their components for application in practical systems [1-5]. The equivalent circuit of the ideal PV module is represented generally by (i) single-diode model [1-10] and (ii) two-diode model [11-14]. The single-diode model is simple and accurate and is perfect for designers who are looking for a model for the modelling of PV devices where the intended result is achieved without great effort [1-10].

Among the unknown parameters of PV module model, the ideality constant, series resistance and parallel resistance are most difficult to evaluate.

Many authors discuss various ways to evaluate the ideality constant. For example, in [6], it has been assumed on the basis of PV cell technology. Since this constant affects the curvature of the I-V curve and its correct estimation improves the model accuracy, it must be evaluated accurately without assumption. Some authors estimate the ideality constant by iterating its value or by curve fitting [7], [8]. In [15], the concept of the minimum sum of squares has been applied for evaluating its value. But for evaluating ideality constant by any of the above methods, manufacturer given output characteristics are required. Thus, these processes can be cumbersome. Also, in some PV module datasheets, output characteristics are not given. Therefore, evaluating ideality constant of such modules becomes very difficult. A separate DC circuit is constructed to determine ideality constant, thus increasing the cost of the system [16].

Regarding the evaluation of series and parallel resistances, different authors have suggested different methods [17]. Some authors neglect parallel resistance to simplify the model as the value of this resistance is generally high [8], [18], [19]. Sometimes, the series resistance is also neglected, as its value is very low [20], [21], thus reducing the accuracy of the proposed model. Many authors have proposed curve fitting [22], [23] method in several ways to determine these resistances. These methods are quite poor, inaccurate and tedious mainly because series and parallel resistances are adjusted separately, which is not a good practice, if an accurate model is required. Moreover, these methods are applicable only if the manufacturers given output characteristics are provided. In [16], very complex equations are used to determine the resistances, making the process cumbersome. An explicit modelling method based on Lambert W-function for PV arrays that has been used in [14] to find...
the values of parameters, is very complex and time consuming. For modeling the I–V curves, artificial intelligence (AI) such as artificial neural network (ANN) [24], [25] and fuzzy logic [26] and genetic algorithms such as particle swarm optimization (PSO) [27] have also been proposed. The seven parameters of a double-diode PV module model can be extracted using differential evolution (DE) utilising only the information provided in the datasheets [11], [13]. PSCAD/EMTDC has been used to develop and demonstrate a circuit-based piecewise linear PV device model for parameter identification [28]. Despite the accurate results, these methods are not widely adopted as they are quite intricate, have high computation burden and are time consuming.

To overcome the above drawbacks, a novel method of evaluating ideality constant, series resistance and parallel resistance of the single-diode PV module model using MATLAB programming is proposed in this paper. The proposed method of evaluating ideality constant is based on the property that at the maximum power point, \( \frac{dP}{dV} = 0 \). Implementing simple set of equations using MATLAB programming, the ideality constant can be determined numerically simply by feeding few manufacturer given data as input to the program, hence removing the requirement of output characteristics provided in the datasheets and making the process simple, fast and accurate. In the new method of evaluating series and parallel resistances, by using simple set of equations, first the maximum values of series and parallel resistances are calculated and then using these values as initialisation constant (so as to decrease the required number of iterations), iterations are performed on the values of series and parallel resistances, so as to satisfy PV module equations.

The data required in the methods mentioned in this paper are obtained from manufacturer’s datasheets. Datasheets generally give information about the parameters, characteristics and performance of PV devices with respect to the standard test condition (STC), which is taken as 1000 \( \text{W/m}^2 \) solar irradiance and 25 \(^\circ\text{C}\) cell temperature [18]. Some datasheets also give information of PV devices at temperature and irradiance other than STC which is defined as nominal operating cell temperature condition (NOCTC).

### MATHEMATICAL EQUATION AND MODELLING OF PHOTOVOLTAIC MODULES

The equivalent circuit of the ideal PV cell is shown in fig. 1.

![Figure 1: Ideal single-diode model of the PV cell](image)

The output current \( I_{\text{cell}} \) of the ideal PV cell is obtained by the equation:

\[
I_{\text{cell}} = I_{p,v,\text{cell}} - I_{d,\text{cell}}
\]

(1)

\( I_{p,v,\text{cell}} \) is the photovoltaic current of the ideal PV cell, \( I_{d,\text{cell}} \) is the diode current of the ideal PV cell which is given by the equation (2):

\[
I_{d,\text{cell}} = I_{0,\text{cell}} \exp \left( \frac{qV_{\text{cell}}}{akT} \right) - 1
\]

(2)

where \( I_{0,\text{cell}} \) is the reverse saturation or leakage current of the diode, \( q \) is the electron charge \((1.60217664 \times 10^{-19} \text{ C})\), \( k \) is the Boltzmann constant \((1.3806503 \times 10^{-23} \text{ J/K})\), \( T \) (in Kelvin) is the temperature of the PV cell, and \( a \) is the diode ideality constant.

By combining equations (1) and (2), equation (3) is obtained:

\[
I_{\text{cell}} = I_{p,v,\text{cell}} - I_{0,\text{cell}} \exp \left( \frac{qV_{\text{cell}}}{akT} \right) - 1
\]

(3)

Equation (3) is the basic equation that mathematically describes the \( I-V \) characteristic of the ideal PV cell.

Equation (3) of the ideal PV cell does not represent the \( I-V \) characteristic of a practical PV module. Practical modules are composed of various PV cells connected in series or parallel. Fig. 2 shows the equivalent circuit of a practical PV device representing the single-diode photovoltaic model including series and parallel resistances.

![Figure 2: Practical model of the PV module including the series and parallel resistances](image)

Additional parameters are required to be included in the basic equation (3). The mathematical equation that describes the \( I-V \) characteristic of a practical PV module is [29]

\[
l = I_{p,v} - I_{0} \left[ \exp \left( \frac{V + R_s I}{V_{T}} \right) - 1 \right] - \frac{V + R_s I}{R_p}
\]

(4)

\[
l = I_{p,v,\text{cell}}N_p - I_{0,\text{cell}}N_p \left[ \exp \left( \frac{V + R_s I}{V_T} \right) - 1 \right] - \frac{V + R_s I}{R_p}
\]

(5)

where \( I_{p,v} = I_{p,v,\text{cell}}N_p \) is the photovoltaic (PV) current and \( I_{0} = I_{0,\text{cell}}N_p \) is the saturation current of the module, \( R_s \) is the equivalent series resistance of the module and \( R_p \) is the equivalent parallel resistance, \( V_T \) is the thermal voltage of the module which is given by equation (6).

\[
V_T = N_s kT/q
\]

(6)

\( N_s \) is the number of cells connected in series and \( N_p \) is the number of parallel connections of cells in the PV module. The equation that mathematically describes the \( P-V \) characteristic of a practical PV module is:

\[
P = V \left[ I_{p,v} - I_{0} \left[ \exp \left( \frac{V + R_s I}{V_{T}} \right) - 1 \right] - \frac{V + R_s I}{R_p} \right]
\]

(7)
For the observation of the characteristics of the PV module, it is required to evaluate all the parameters of equation (4) [6]. The parameters basically present in all PV module datasheets are: the open-circuit voltage \(V_{oc}\), the short-circuit current \(I_{sc}\), the voltage at the MPP \(V_{mp}\), the current at the MPP \(I_{mp}\), the maximum experimental peak output power \(P_{mp}\), the temperature coefficient of open-circuit voltage \(K_v\) and the temperature coefficient of short-circuit current \(K_i\). These data are always provided at standard test conditions (STCs) of temperature and solar irradiance.

Table 1 shows the values of the parameters of six different commercially available Photovoltaic modules at STC provided by the manufacturers [30-35].

Some of the parameters of equation (4) can be found in the manufacturer's datasheets. The remaining parameters such as the PV current, the diode ideality constant, the diode reverse saturation current and the series and shunt resistances have to be evaluated. They are usually not given by manufacturers because they cannot be measured and are unique for every module.

### EVALUATION OF THE PARAMETERS

The flowcharts proposed in this work attempt to evaluate the five unknown parameters \(I_{ppv}, I_o, R_{s} \) and \(R_{p}\) of a PV module at different environmental conditions.

#### Evaluation of photovoltaic current

Applying the STC to equation (3), the output current is:

\[
I_{cell,STC} = I_{ppv,cell,STC} - I_{o,cell,STC} \exp \left( \frac{V_{cell,STC}}{kT} \right) - 1
\]  
(8)

Applying the short circuit condition \(I_{cell,STC} = I_{sc,cell,STC}, V_{cell,STC} = 0\) to equation (8):

\[
I_{sc,cell,STC} = I_{ppv,cell,STC} - I_{o,cell,STC} \exp (0) - 1 = I_{ppv,cell,STC}
\]

\[
I_{sc,cell,STC} = I_{ppv,cell,STC}
\]  
(9)

The equality in equation (9) is valid only in the ideal case. In reality, equation (9) can be written as:

\[
I_{pv,cell,STC} \approx I_{sc,cell,STC}
\]  
(10)

\[
I_{pv,STC} \approx I_{sc,STC}
\]  
(11)

The photovoltaic current of a PV module at STC is approximately equal to the short-circuit current at STC which can be obtained from the datasheets. The photovoltaic current of the PV module depends on both solar irradiance and temperature.

\[
I_{pv} = I_{pv,cell}N_p = (I_{pv,cell}STC N_p + K_i \Delta T) \frac{g_{STC}}{g_{STC}}
\]  
(12)

\[
I_{pv} = (I_{pv,STC} + K_i \Delta T) \frac{g_{STC}}{g_{STC}}
\]  
(13)

where \(I_{pv,STC}: \) the photovoltaic current at STC (25°C and 1000 W/m²) \(\text{(A)},\)

\(K_i: \) the short-circuit current/temperature coefficient \(\text{(A/K)},\)

\(\Delta T = T - T_{STC} \) (Kelvin),

\(T: \) the actual cell temperature \(\text{(K)},\)

\(T_{STC}: \) the cell temperature at STC=25 + 273 = 298 K

\(G: \) Actual Irradiance \(\text{(W/m²)}\)

\(G_{STC}: \) Irradiance at STC=1000 W/m²

By using equation (13), the photovoltaic current at any temperature and irradiance can be obtained.

#### Evaluation of diode ideality constant

The parallel resistance \(R_p\) is generally very high, so the last term of the equation (4) can be eliminated for the further work.

\[
I = I_{pv} - I_{o} \exp \left( \frac{V + R_s I}{V_a} \right) - 1
\]  
(14)

By applying three remarkable conditions i.e. open-circuit (\(I =

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**Table 1**: Parameters of six different commercially available PV modules at STC (25 °C and 1000 W/m²) provided by the manufacturers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BP SX 150</th>
<th>MSX-64</th>
<th>HIT-N240SE10</th>
<th>KD260GX-LFB2</th>
<th>KU265-MCA</th>
<th>KD140GX-LFBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_{mp,STC}) W</td>
<td>150</td>
<td>62</td>
<td>240</td>
<td>260</td>
<td>265</td>
<td>140</td>
</tr>
<tr>
<td>(V_{mp,STC}) V</td>
<td>34.5</td>
<td>17.5</td>
<td>43.7</td>
<td>31.0</td>
<td>31.0</td>
<td>17.7</td>
</tr>
<tr>
<td>(I_{mp,STC}) A</td>
<td>4.35</td>
<td>3.66</td>
<td>5.51</td>
<td>8.39</td>
<td>8.55</td>
<td>7.91</td>
</tr>
<tr>
<td>(V_{oc,STC}) V</td>
<td>43.5</td>
<td>21.3</td>
<td>52.4</td>
<td>38.3</td>
<td>38.3</td>
<td>22.1</td>
</tr>
<tr>
<td>(I_{sc,STC}) A</td>
<td>4.75</td>
<td>4.0</td>
<td>5.85</td>
<td>9.09</td>
<td>9.26</td>
<td>8.68</td>
</tr>
<tr>
<td>(K_i)</td>
<td>(0.065±0.015) %/°C</td>
<td>(0.065±0.015) %/°C</td>
<td>0.03 %/°C</td>
<td>0.06 %/°C</td>
<td>0.06 %/°C</td>
<td>0.060 %/°C</td>
</tr>
<tr>
<td>(K_v)</td>
<td>- (160±20) mV/°C</td>
<td>- (80±10) mV/°C</td>
<td>-0.131 V/°C</td>
<td>-0.36 %/°C</td>
<td>-0.36 %/°C</td>
<td>-0.36 %/°C</td>
</tr>
<tr>
<td>(N_s)</td>
<td>72</td>
<td>36</td>
<td>72</td>
<td>60</td>
<td>60</td>
<td>36</td>
</tr>
<tr>
<td>(N_p)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
For equation (24) to be valid, the numerator of equation (24) must be zero as the denominator is finite.

\[
0 = I_{pv,STC} - I_{0,STC}\left[\exp\left(\frac{V_{oc,STC}}{V_{ISCSTC}}\right) - 1\right]
\]

(15)

\[
I_{SC,STC} = I_{pv,STC} - I_{0,STC}\left[\exp\left(\frac{I_{SC,STC}R_s}{V_{ISCSTC}}\right) - 1\right]
\]

(16)

\[
I_{mp,STC} = I_{pv,STC} - I_{0,STC}\left[\exp\left(\frac{V_{mp,STC} + I_{mp,STC}R_s}{V_{ISCSTC}}\right) - 1\right]
\]

(17)

By combining equations (11) and (15), equation (18) is obtained:

\[
0 = I_{SC,STC} - I_{0,STC}\left[\exp\left(\frac{V_{oc,STC}}{V_{ISCSTC}}\right) - 1\right]
\]

(18)

\[
I_{0,STC} = \frac{I_{SC,STC}}{\left[\exp\left(\frac{V_{oc,STC}}{V_{ISCSTC}}\right) - 1\right]}
\]

(19)

\[V_{ISC} : \text{the thermal voltage of } N_s \text{ series-connected cells at } 25^\circ C \text{ (temperature at STC)}\]

In the proposed method, the maximum power point at STC is considered for evaluating 'a' using the property \(dP/dV = 0\) at the maximum power point.

\[
P = VI
\]

(20)

\[
\frac{1}{V}\frac{dP}{dV} = \frac{di}{dv} + \frac{I}{V}
\]

(21)

By applying maximum power condition to equation (18), equation (19) is obtained:

\[
\frac{di}{dv} |_{mp} + \frac{I_{mp}}{V_{mp}} = 0
\]

(22)

By differentiating equation (14) and applying maximum power condition, equation (23) can be obtained:

\[
\frac{di}{dv} |_{mp} = \frac{-I_{mp}R_s\exp\left(\frac{V_{mp} + I_{mp}R_s}{V_{mp} + I_{mp}R_s/V_i}\right)}{aV_iR_s\exp\left(\frac{V_{mp} + I_{mp}R_s}{V_i}\right)}
\]

(23)

By substituting equation (23) in (22), equation (24) can be obtained:

\[
aI_{mp} + \left(I_{mp}R_s - V_{mp}\right)\frac{I_0}{V_i}\exp\left(\frac{V_{mp} + I_{mp}R_s}{V_i}\right) = 0
\]

(24)

When written at STC, equation (25) becomes equation (26):

\[
aI_{mp,STC} + \left(I_{mp,STC}R_s - V_{mp,STC}\right)\frac{I_0}{V_i}\exp\left(\frac{V_{mp,STC} + I_{mp,STC}R_s}{V_i}\right) = 0
\]

(26)

By applying maximum power point condition at STC to equation (14) and rearranging terms, equations (27) and (28) can be obtained:

\[
\exp\left(\frac{V_{mp,STC} + I_{mp,STC}R_s}{V_i}\right) = \frac{I_{SC,STC} - I_{mp,STC} + I_{0,STC}}{I_{0,STC}}
\]

(27)

\[
R_s = \frac{V_{ISCSTC}}{I_{mp,STC}} \ln\left(\frac{I_{SC,STC} - I_{mp,STC} + I_{0,STC}}{I_{0,STC}}\right) - \frac{V_{mp,STC}}{I_{mp,STC}}
\]

(28)

By combining equations (26), (27) and (28), equation (29) can be obtained:

\[
aI_{mp,STC} + \left(I_{SC,STC} - I_{mp,STC} + I_{0,STC}\right)\left[a \ln\left(\frac{I_{SC,STC} - I_{mp,STC} + I_{0,STC}}{I_{0,STC}}\right) - \frac{2V_{mp,STC}}{V_{ISCSTC}}\right] = 0
\]

(29)

Substituting equation (19) in (29), equation (30) is obtained:

\[
aI_{mp,STC} + \left(I_{SC,STC} - I_{mp,STC} + I_{0,STC}\right)\left[a \ln\left(\frac{I_{SC,STC} - I_{mp,STC} + I_{0,STC}}{I_{0,STC}}\right) - \frac{2V_{mp,STC}}{V_{ISCSTC}}\right] = 0
\]

(30)

When the data given in the manufacturer's datasheets are used, the left hand side of equation (30) becomes a function of 'a' and it is denoted by \(f(a)\).

\[
f(a) = aI_{mp,STC} + \left(I_{SC,STC} - I_{mp,STC} + I_{0,STC}\right)\left[a \ln\left(\frac{I_{SC,STC} - I_{mp,STC} + I_{0,STC}}{I_{0,STC}}\right) - \frac{2V_{mp,STC}}{V_{ISCSTC}}\right]
\]

(31)

Thus, 'a' is found by solving \(f(a) = 0\) as shown in fig. 3 and fig. 4. According to fig. 4, the diode ideality constant, \(a = 1.6420\) becomes the solution for BP SX 150 PV module [30].
Evaluation of diode reverse saturation current

By equation (19), the diode reverse saturation current at STC can be obtained.

The short circuit current and the open circuit voltage at any temperature can be calculated using the following equations:

\[ I_{SC} = I_{OC,STC} + K_{T}\Delta T \]  \hspace{1cm} (32)

\[ V_{OC} = V_{OC,STC} + K_{T}\Delta T \]  \hspace{1cm} (33)

The diode reverse saturation current is given by [4]:

\[ I_0 = DT^3 \exp\left(-\frac{qE_g}{akT}\right) \]  \hspace{1cm} (34)

\[ E_g: \text{ the bandgap energy of the semiconductor (} E_g = 1.12 \text{ eV for the polycrystalline Silicon at } 25 \text{ °C [7, 9].} \]

\[ I_{0,STC} = DT_{STC}^3 \exp\left(-\frac{qE_g}{akT_{STC}}\right) \]  \hspace{1cm} (35)

By combining equations (34) and (35), equation (36) can be obtained [9,12]:

\[ I_0 = I_{0,STC}\left(\frac{T}{T_{STC}}\right)^3\exp\left[\frac{qE_g}{ak}\left(\frac{1}{T_{STC}} - \frac{1}{T}\right)\right] \]  \hspace{1cm} (36)

By equation (31), the diode saturation current at any temperature can be obtained. But the value of \( E_g \) is different for different types of PV modules. Thus, the method in [9] is not generalised.

The more generalised expression for \( I_0 \) is obtained by combining equations (19), (32) and (33):

\[ I_0 = \frac{I_{OC,STC} + K_{T}\Delta T}{\left[\exp\left(\frac{V_{OC,STC} + K_{T}\Delta T}{kT}\right) - 1\right]} \]  \hspace{1cm} (37)

Evaluation of series and parallel resistances

Equating the maximum power calculated by the \( P - V \) model of equation (7) \( \left(P_{mp,cal,STC}\right) \) to the maximum experimental power from the datasheet \( \left(P_{mp,STC}\right) \) at STC, a relation between \( R_s \) and \( R_p \) will be obtained, i.e.

\[ P_{mp,cal,STC} = P_{mp,STC} \]  \hspace{1cm} (38)

\[ P_{mp,cal,STC} = V_{mp,STC}I_{mp,STC} = V_{mp,STC}(I_{PV,STC} - \ldots) \]
datasheet ($P_{mp,STC}$) at STC. Hence, the maximum value of series resistance $R_{s max}$ is obtained.

e) Initialising the value of $R_p = R_{p max}$ and $R_s = R_{s max}$, iterations are performed on equation (39) where $R_s$ is slowly decremented, till the maximum power calculated by the $P-V$ model ($P_{mp,calc,STC}$) becomes approximately equal to the maximum experimental power from the datasheet ($P_{mp,STC}$) at STC. Thus, $R_s$ is obtained. Putting the value of obtained $R_s$, in equation (40), the value of $R_p$ is also obtained.

Fig. 5 represents the flowchart for evaluation of diode ideality constant. The proposed algorithm is presented in the form of flowcharts shown in fig. 6, fig. 7 and fig. 8. Initialising the value of $R_p = R_{p max}$ and $R_s = R_{s max}$, and then iterating equation (39), reduces the required number of iterations and also increases the accuracy of the results obtained.

Table 2 shows the values of the evaluated parameters of six different commercially available PV modules at STC.
Table 2: Evaluated parameters of six different commercially available PV modules at STC (25 °C and 1000 W/m²)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BP SX 150</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$I_{pv,STC}$ A</td>
<td>4.75</td>
<td>4.00</td>
<td>5.85</td>
<td>9.09</td>
<td>9.26</td>
<td>8.68</td>
</tr>
<tr>
<td>$a$</td>
<td>1.6420</td>
<td>1.7859</td>
<td>1.4169</td>
<td>1.6327</td>
<td>1.6237</td>
<td>1.8329</td>
</tr>
<tr>
<td>$I_{0,STC}$ μA</td>
<td>2.841982</td>
<td>9.9722993</td>
<td>0.01202085</td>
<td>2.2187798</td>
<td>2.0773476</td>
<td>18.788037</td>
</tr>
<tr>
<td>$R_s$ Ω</td>
<td>0.331466</td>
<td>0.0516225</td>
<td>0.2393075</td>
<td>0.0990959</td>
<td>0.0996343</td>
<td>0.0352263</td>
</tr>
<tr>
<td>$R_p$ Ω</td>
<td>4367.596484</td>
<td>2136.303787</td>
<td>5277.156231</td>
<td>3861.552221</td>
<td>3862.0178</td>
<td>2223.70691</td>
</tr>
</tbody>
</table>

CURVES AND INFERENCES

$I − V$ and $P − V$ characteristics of the BP SX 150 PV module are plotted for $R_s = 0.3314659000930248$ Ω and $R_p = 4367.5964794763004$ Ω at 25 °C and 1000 W/m² as shown in figs. 9 and 10. The values of the resistances are found by the flowcharts proposed in this paper.

Figure 9: $I − V$ characteristic for the most representative $R_s$, $R_p$ pair of the BP SX 150 PV module at 25 °C and 1000 W/m²

As shown in figs. 11 and 12, $I − V$ and $P − V$ curves of the BP SX 150 PV module are generated for various pairs of $R_s$ and $R_p$, keeping $a$ constant. It can be noted that all the curves cross a particular point known as MPP (Maximum Power Point) and neither $I_{sc}$ nor $V_{oc}$ are affected by the change of the $R_s$, $R_p$ pair. The variation in the curves is observed up to a certain value of $R_s$, $R_p$ pair. But after exceeding a particular value, the curve remains the same irrespective of the increase in the value of $R_s$, $R_p$ pair.

Figure 10: $P − V$ characteristic for the most representative $R_s$, $R_p$ pair of the BP SX 150 PV module at 25 °C and 1000 W/m²

$I − V$ and $P − V$ curves of the BP SX 150 PV module are plotted again by varying $R_s$, keeping $a$ and $R_p$ constant (see figs. 13 and 14). As $R_s$ increases slightly, a large reduction in $V_{oc}$ is noticed that means only a small change in $R_s$ brings a large change in $V_{oc}$. However, $I_{sc}$ is not affected by the change of $R_s$.

Figure 11: $I − V$ characteristics for various pairs of $R_s$ and $R_p$ ($a$ constant) of the BP SX 150 PV module at 25 °C and 1000 W/m²

Figure 12: $P − V$ characteristics for various pairs of $R_s$ and $R_p$ ($a$ constant) of the BP SX 150 PV module at 25 °C and 1000 W/m²
Similarly, the curves of the BP SX 150 PV module are generated for constant $a$ and $R_s$ and varying $R_p$ (figs. 15 and 16). It is observed that $V_{oc}$ increases as $R_p$ increases. The increase in $V_{oc}$ is large for the increase in low values of $R_p$ but the variation in $V_{oc}$ reduces for high values of $R_p$. After a particular value of $R_p$, in spite of increasing the $R_p$, the curve remains the same. Again, $I_{sc}$ does not vary. The $V_{oc}$ increases with increase in $R_p$ whereas it decreases with increase in $R_s$.

$I - V$ and $P - V$ curves of the BP SX 150 PV module are plotted again by varying $a$, keeping the $R_s$ and $R_p$ constant (see figs. 17 and 18). It can be noted that as $a$ increases, the value of $V_{mp}$, $I_{mp}$ and $P_{mp}$ decreases and neither $I_{sc}$ nor $V_{oc}$ are affected by the change of $a$. The values of $V_{mp}$, $I_{mp}$ and $P_{mp}$ match the datasheet only when $a = 1.6420$, calculated by the proposed method is utilised.
VALIDATION OF THE MODEL

Figs. 19 and 20 show the mathematical $I - V$ and $P - V$ characteristics of the MSX-64 PV module [31] plotted for $R_s = 0.05162250000683344 \ \Omega$ and $R_p = 2136.303786978493 \ \Omega$ with the experimental data at 25 °C and 1000 W/m$^2$. The values of the resistances are found by the algorithms proposed in this paper. The experimental points are represented by circular markers in the curves. As the model is not perfect, some points are not exactly matched, although it is sufficiently accurate for majority points.

Figs. 21 and 22 show the mathematical $I - V$ and $P - V$ characteristics of the BP SX 150 PV module [30] plotted with the experimental data by varying irradiance from 200 W/m$^2$ to 1200 W/m$^2$ at 25 °C. Figs. 23 and 24 show the $I - V$ and $P - V$ curves by varying temperature from 0 °C to 75 °C at 1000 W/m$^2$. The experimental points are represented by the circular markers in the curves. As per the expectation, the proposed model accurately matches with the experimental data as proved by all the above curves. The experimental procedures are carried out in National Institute of Technology Patna (NITP), India.
The absolute errors of the proposed model with respect to the experimental data for the BP SX 150 PV module at 25 °C and 1000 W/m² are shown in fig. 25. The model proposed in this paper is compared with the models proposed in [6] and [8]. The absolute errors obtained by all the models are plotted on the same graphs. The model proposed in this paper is superior, because the values of absolute errors obtained by the proposed model are very small as compared to other models.

![Figure 25](image)

**Figure 25:** Relative errors of the model proposed in this paper (curve 1), in [6] (curve 2) and in [8] (curve 3) for the BP SX 150 PV module at 25 °C and 1000 W/m²

Tables 3 and 4 show the comparison of proposed model value with manufacturer’s value extracted from datasheet for four different commercially available PV modules [32-35].

### CONCLUSION

In this paper, a novel approach for evaluation of parameters of PV modules is proposed. New flowcharts are proposed for evaluating five unknown parameters ($I_{pv}, a, I_p, R_s$ and $R_p$) of the non linear $I-V$ equation of the single-diode model of PV module, taking the manufacturer given data at standard test conditions as inputs.

The proposed PV module parameter evaluation method surpasses the other methods already published, as it has the following novelties:

- The new method of evaluation of ideality constant ($a$) is not based on assumption or curve fitting rather on mathematical equations of PV modules. By implementing simple set of equations using MATLAB programming, the ideality constant can be determined numerically simply by feeding few manufacturer given data as input to the program.

- The new method of evaluation of series and parallel resistances ($R_s, R_p$) are also based on mathematical equations of PV modules rather than on assumptions or curve fitting. The mathematical equations are implemented using MATLAB programming, thus giving the accurate values of series and parallel resistances only by providing some manufacturer given data as input to the program.

- In addition to being generalised, the proposed method of evaluating unknown parameters is fast, simple and accurate due to the implementation of characteristic equations of PV modules using MATLAB programming.

- In this paper, for the first time, the effects of varying ideality constant, series resistance, parallel resistance and both resistances, on the output curves have been observed. It has been inferred that variations in $a$ and $R_s$ bring a large change in output characteristics as compared to $R_p$. The values of $a$, $R_s$ and $R_p$ should be evaluated accurately for improving the accuracy of the proposed model.

- The proposed method proves to be more precise in parameter evaluation of commercially available PV modules as compared to other techniques available in literature.

**Table 3: Comparison of proposed model value with manufacturer’s datasheet value**

<table>
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<tr>
<th>ENVIRONMENTAL CONDITIONS</th>
<th>Parameter</th>
<th>HIT-N240SE10</th>
<th>KD260GX-LFB2</th>
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<td><strong>STC (25 °C and 1000 W/m²)</strong></td>
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<td></td>
<td>$V_{mp}$ V</td>
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<td>$V_{oc}$ V</td>
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<td>$I_{sc}$ A</td>
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<td>45.8832</td>
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<tr>
<td></td>
<td>$I_{sc}$ A</td>
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Table 4: Comparison of proposed model value with manufacturer's datasheet value

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REFERENCES


