CHAPTER 2
NEW METHOD FOR ACCURATE ESTIMATION OF
SINGLE DIODE PV MODEL PARAMETERS AND
MAXIMUM POWER

2.1 INTRODUCTION

Nowadays, the renewable energy contribution to meet the world energy demand is increasing due to depletion of fossil fuels, increased global warming, long life and less maintenance cost of renewable energy resources. In developing countries, the villages get electric supply through the renewable energy sources and this avoids the unnecessary extension of existing grid in urban areas to supply power to villages. Especially, the photovoltaic systems are predominantly used worldwide compared to other renewable energy sources because of easy accessibility and implementation, and requirement of less labour cost for maintenance. The main disadvantage of the PV system is high cost of PV panel and inclusion of other components in the system such as DC/DC converter for maximum power tracking and DC/AC converter for connecting it to the grid.

Modelling of PV module is necessary to predict its output performance while integrating it with the existing microgrid for power system planning studies. The microgrid may be connected to the main grid or isolated from the main grid whenever needed (Serban & Serban 2010). Due to high cost of PV module, the maximum power generated from the PV module should be utilized efficiently. This imposes exact modelling of PV module to find the maximum power under different environmental conditions (Ishaque
et al 2011a). Accurate PV model is required to design an efficient PV module by the PV module designer. The manufacturer’s data sheet only provides the PV module parameters at STC. But, for the power system planning studies involving microgrid and for the PV module designer, the performance of PV module at different environmental conditions have to be found out. This urges the researchers to concentrate on developing an accurate PV model (Ma et al 2014).

The photovoltaic module generates power which depends on temperature and irradiation conditions. The two diode model of PV module is presented by some researchers (Ishaque et al 2011a and Ishaque et al 2011b) which provide a simulated current-voltage ($I-V$) characteristics curve that will exactly fit with the experimental $I-V$ curve of the PV module, and hence it is considered to be the best model. Though the accuracy of the two diode model is high, the single diode model is considered in most of the works due to the complexity of two diode model (Ishaque & Salam 2011).

In this chapter, an improved mathematical model of a single diode photovoltaic (PV) module is developed to predict the maximum power of the PV modules made by different photovoltaic technologies such as mono-crystalline, poly-crystalline and thin-film under varying environmental conditions. The PV module current-voltage characteristics equation is used to extract the PV module unknown parameters such as light generated current, reverse saturation current, ideality factor, series resistance and shunt resistance at standard test condition (STC). In the proposed PV model, numerical methods are used to calculate the PV module parameters at STC, by introducing new equations to estimate the value of series resistance and shunt resistance. Maximum power of different PV modules manufactured by various PV technologies at different environmental conditions is then found by introducing new equations to find $I_{mpp}$ and $V_{mpp}$. The percentage relative error
in the obtained maximum power is calculated by comparing with existing results in the literature for different PV modules. The maximum power obtained by the proposed PV model has good agreement with that of Sandia model. Further, the output performance of the developed PV model has very good agreement with the experimental data and two diode model.

The proposed PV model is simple to use and it can be used to quickly and accurately determine the performance of the PV module under different environmental conditions. The proposed model gets all the information from manufacturer’s datasheet of the PV module. The manufacturer’s data sheet provides the information about electrical parameters at STC, mechanical parameters and thermal parameters of the PV module. The electrical parameters of the PV module include short circuit current ($I_{sc}$), open circuit voltage and, maximum current and maximum voltage at MPP. The thermal and mechanical parameters of the PV module include short circuit current temperature coefficient $K_i$ (mA/°C), open circuit voltage temperature coefficient $K_v$ (mV/°C) and number of cells ($N_s$).

In Table 2.1, the manufacturer’s data sheet information of seven different PV modules is given which are used to verify the performance of proposed PV model. These PV modules are made by different PV technologies such as mono-crystalline, poly-crystalline and thin-film.

This chapter is organized as follows. In section 2.2, a single diode PV model is discussed. Extraction of the PV model parameters is discussed in section 2.3. The effect of temperature and irradiation on the current-voltage characteristics of PV module is discussed in section 2.4. In section 2.5, the maximum power of the PV module is estimated under different environmental conditions. The results are discussed in section 2.6. Finally, the results are concluded in section 2.7.
Table 2.1 Manufacturer’s datasheet values for various PV modules

<table>
<thead>
<tr>
<th>PV Module</th>
<th>Electrical parameters</th>
<th>Thermal parameters</th>
<th>Mechanical Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_{sc}$ (A)</td>
<td>$I_{mpp}$ (A)</td>
<td>$V_{oc}$ (V)</td>
</tr>
<tr>
<td>Shell SP70</td>
<td>4.70</td>
<td>4.25</td>
<td>21.4</td>
</tr>
<tr>
<td>Shell SM55</td>
<td>3.45</td>
<td>3.15</td>
<td>21.7</td>
</tr>
<tr>
<td>Kyocera KC60</td>
<td>3.73</td>
<td>3.55</td>
<td>21.5</td>
</tr>
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<td>Shell S36</td>
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</tr>
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<td>Shell ST40</td>
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<td>Shell ST36</td>
<td>2.68</td>
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</tr>
<tr>
<td>TDP125</td>
<td>5.21</td>
<td>4.87</td>
<td>44.4</td>
</tr>
</tbody>
</table>

### 2.2 SINGLE DIODE MODEL OF PV MODULE

Figure 2.1 shows the single diode PV model of a PV module. It consists of PV module parameters such as light generated current ($I_{LG}$), reverse saturation current ($I_{sat}$), ideality factor (A), series resistance ($R_{se}$) and shunt resistance ($R_{sh}$).

![Figure 2.1 Single diode model of PV module](image-url)
The PV module’s current-voltage characteristics equation is expressed as follows (Lo Brano & Ciulla 2013):

\[
I = I_{LG} - I_{sat}[e^{\frac{V + IR_{se}}{N_{s}V_{t}}} - 1] - \frac{V + IR_{se}}{R_{sh}} \tag{2.1}
\]

Where

- \( I \) – Output current at terminals in Amps
- \( V \) – Output voltage at terminals in Volts
- \( I_{LG} \) – Light generated current in amps
- \( N_{s} \) – Number of solar cells connected in series
- \( I_{sat} \) – Diode reverse saturation current in amps
- \( R_{se} \) – Series resistance of solar module in ohms
- \( R_{sh} \) – Shunt resistance of solar module in ohms

The diode thermal voltage, \( V_{t} \), is expressed as

\[
V_{t} = \frac{A k T_{c}}{q} \tag{2.2}
\]

Where

- \( A \) – Diode ideality factor
- \( k \) – Boltzmann constant (1.3806 X 10^{-23} J/°K)
- \( T_{c} \) – PV module temperature (STC) in °K
- \( q \) – Electronic charge (1.602 X 10^{-19} C)

In equation (2.1), the value of the term ‘\( e^{\frac{V + IR_{se}}{N_{s}V_{t}}} \)’ is very large when compared with the value of ‘1’ and hence the term ‘-1’ with in the bracket in the diode current is neglected and the modified equation is as follows:

\[
I = I_{LG} - I_{sat} e^{\frac{V + IR_{se}}{N_{s}V_{t}}} - \frac{V + IR_{se}}{R_{sh}} \tag{2.3}
\]
2.3 ESTIMATION OF PV MODEL PARAMETERS AT STC

Using equation (2.3), the PV model parameters $I_{LG}$, $V_t$, $I_{sat}$, $R_{se}$ and $R_{sh}$ are estimated using the conditions such as SCC, OCC, MPP, derivative of power with respect to voltage ($\frac{dP}{dV}$) at MPP and derivative of current with respect to voltage ($\frac{di}{dV}$) at SCC.

2.3.1 Short Circuit Condition (SCC)

Since $V=0$ and $I=I_{sc}$ at SCC, the following equation (2.4) is obtained from equation (2.3).

$$I_{sc} = I_{LG} - I_{sat} e^{\frac{I_{LG}}{N_{V_t} V_t}} - \frac{I_{sc} R_{se}}{R_{sh}}$$  

(2.4)

The diode current at SCC is negligibly small and hence the second term in the equation (2.4) can be neglected and the expression for $I_{LG}$ is obtained as follows (Kulaksiz 2013 and Bai et al 2014):

$$I_{LG} = \frac{I_{sc} (R_{se} + R_{sh})}{R_{sh}}$$  

(2.5)

2.3.2 Open Circuit Condition (OCC)

Under open circuit condition, $I=0$ and equation (2.6) is formed to find diode thermal voltage $V_t$ as follows (Lo Brano & Ciulla 2013):

$$V_t = \frac{V_{oc}}{N_{i} I_{n} \left( \frac{I_{LG} R_{sh} - V_{ac}}{R_{sh} I_{sat}} \right)}$$  

(2.6)

2.3.3 Maximum Power Point (MPP) Condition

The reverse saturation current $I_{sat}$ can be obtained when the maximum power point condition is applied in equation (2.3) and is given by Kulaksiz (2013):
\[ I_{sat} = \frac{(I_{sc} - I_{MPP})(R_{sc} + R_{sh}) - V_{MPP}}{R_{sh} e^{(V_{MPP} + I_{MPP} R_{sc})/N_s V_t}} \] (2.7)

Equations (2.5) and (2.7) are inserted into equation (2.6) and thermal voltage \( V_t \), can be expressed as follows:

\[ V_t = \frac{V_{sc}}{(I_{sc} (R_{sc} + R_{sh}) - V_{sc}) e^{(V_{MPP} + I_{MPP} R_{sc})/N_s V_t}} \] (2.8)

The derivative of current with respect to voltage using equation (2.3) is done and equation (2.9) is obtained.

\[ \frac{dI}{dV} = \frac{-I_{sat} e^{(V + IR_{sc})/N_s V_t} - 1}{1 + \frac{I_{sat} e^{(V + IR_{sc})/N_s V_t}}{N_s V_t}} \] (2.9)

At SCC, as per the result reported in Chatterjee et al (2011), the following relation is obtained:

\[ \frac{dI}{dV}_{V=0}^{I=I_{sat}} = -\frac{1}{R_{sh}} \] (2.10)

At SCC, the new equation (2.11) is formed for finding the PV module shunt resistance using equations (2.9) and (2.10).

\[ R_{sh} = \frac{N_s V_t (R_{sc} + R_{sh}) + R_{se} M}{M + N_s V_t} \] (2.11)

where \( M = ((I_{sc} - I_{MPP})(R_{sc} + R_{sh}) - V_{MPP}) e^{(I_{sc} R_{sc} - V_{MPP} - I_{MPP} R_{sc})/N_s V_t} \)

At MPP, as per the result reported in Chatterjee et al (2011), the following relation is obtained:

\[ \frac{dP}{dV}_{I=I_{MPP}}^{V=V_{MPP}} = 0 = I_{MPP} + V_{MPP} \frac{dI}{dV}_{I=I_{MPP}}^{V=V_{MPP}} \] (2.12)
At MPP, using equations (2.9) and (2.12), the new equation (2.13) for PV module series resistance is formed and is given below:

$$R_s = \frac{(R_{sh}(I_{MPP}N_sV_t - V_{MPP}(I_{sc} - I_{MPP}))) - V_{MPP}(V_{MPP} - N_sV_t)}{I_{MPP}(N_sV_t - V_{MPP}) + (I_{sc} - I_{MPP})(I_{MPP}(R_{se} + R_{sh}) - V_{MPP})} \quad (2.13)$$

Equations (2.5), (2.7), (2.8), (2.11) and (2.13) along with the manufacturer’s specifications are used to extract the PV module parameters $I_{LG}$, $I_{sat}$, $V_t$, $R_{se}$ and $R_{sh}$. The PV module parameters $V_t$, $R_{se}$ and $R_{sh}$ are determined by using Gauss Seidal (G-S) method in the following form (Chatterjee et al 2011):

$$X^k_i = f(X^{k-1}_i) \quad (2.14)$$

Generally, in G-S method, the initial value of ideality factor, series and shunt resistances are randomly generated. At room temperature (25°C), the value of thermal voltage ($V_t$) is 25.6mV and this value varies with temperature. In most of the literatures, it is found that the series resistance of PV panel is between 0.1 to 4 ohms and its shunt resistance is between 100 to 10000 ohms. Therefore, in this work, the initial value of the thermal voltage, series resistance and shunt resistance is selected as 0.0256 Volts, 0.1 ohm and 1000 ohms respectively. In most cases, the aforesaid initial values are suitable to obtain the convergence. However, in some of the cases, these values lead to divergence. In that case, the initial values are randomly selected with the constraint that shunt resistance value is much higher than the series resistance.

The flowchart for the evaluation of the five parameters of the PV module is shown in Figure 2.2. In Figure 2.2, the errors in $V_t$, $R_{se}$ and $R_{sh}$ in the two consecutive iterations which are mentioned as $e_1$, $e_2$ and $e_3$ are calculated. In G-S method, stopping the iterative process is based on error threshold value of the estimated parameters, which is chosen as $1\times10^{-6}$ in this work.
Figure 2.2  Flowchart to estimate the PV module parameters using G-S method
Using the equation (2.2), the ideality factor (A) of the PV model is estimated. The extracted value of the parameters \( V_t \), \( R_{se} \) and \( R_{sh} \) is substituted in equations (2.5) and (2.7), to estimate the remaining parameters of PV module such as \( I_{LG} \) and \( I_{sat} \). The value of the extracted parameters of the PV modules using G-S method is shown in Table 2.2.

Table 2.2 Different PV module’s parameters calculated using MATLAB simulation at STC

<table>
<thead>
<tr>
<th>PV Module</th>
<th>Estimated Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Shell SP70</td>
<td>1.974</td>
</tr>
<tr>
<td>Shell SM55</td>
<td>1.769</td>
</tr>
<tr>
<td>Kyocera KC60</td>
<td>1.031</td>
</tr>
<tr>
<td>Shell S36</td>
<td>1.105</td>
</tr>
<tr>
<td>Shell ST40</td>
<td>1.929</td>
</tr>
<tr>
<td>Shell ST36</td>
<td>2.798</td>
</tr>
<tr>
<td>TDP125</td>
<td>1.424</td>
</tr>
</tbody>
</table>

2.4 EFFECT OF IRRADIANCE AND TEMPERATURE ON I-V CHARACTERISTIC CURVES OF PV MODULE

To find the effect of irradiance and temperature on I-V characteristic curves of PV module, equation (2.8) is rearranged and the new equation (2.15) for \( V_{oc} \) is formed to express it as a function of irradiation.

\[
V_{oc(G)} = N_r V_t \ln \left( \frac{(I_{sc} - I_{MPP})(R_s + R_{sh}) - V_{MPP}}{N_r V_t} \right) \left( \frac{G}{G_{sc}} \right)
\]  

(2.15)

The short circuit current and open circuit voltage can be calculated as a function of temperature and are given by equation (2.16) and (2.17) (Soon & Low 2012).
The diode thermal voltage calculated as a function of temperature can be described as follows (Ma et al. 2014):

\[
V_{t(T)} = V_{t(stc)} \frac{T}{T_{stc}}
\]  

(2.18)

As a function of varying temperature and irradiance conditions, the diode reverse saturation current can be estimated by equation (2.19) and is obtained using equation (2.7) (Kulaksiz 2013):

\[
I_{sat(GT)} = \frac{(I_{sc(T)} - I_{MPP})(R_{se} + R_{sh}) - V_{MPP}}{N_s V_{t(T)}}
\]  

(2.19)

The light generated current, short circuit current and open circuit voltage can be calculated (Bai et al. 2014 & Lun et al. 2013), (Liu et al. 2011) and (Lo Brano & Ciulla 2013) respectively, under varying environmental conditions using the equations (2.20), (2.21) and (2.22) respectively.

\[
I_{LG(GT)} = (I_{LG(stc)} + K_i(T_e - T_{stc})) \frac{G}{G_{stc}}
\]  

(2.20)

\[
I_{sc(GT)} = (I_{sc(stc)} + K_i(T_e - T_{stc})) \frac{G}{G_{stc}}
\]  

(2.21)

\[
V_{oc(GT)} = V_{oc(G)} + K_i(T_e - T_{stc})
\]  

(2.22)

2.5 MAXIMUM POWER ESTIMATION IN THE PV MODULE

The maximum power at MPP mainly depends on the PV model parameters such as ideality factor, series and shunt resistances at any operating condition. New equation (2.23) is described to find \( V_t \) as a function of irradiance and temperature by modifying equation (2.8) and is given by: 

\[
I_{se(T)} = I_{se(stc)} + K_i(T_e - T_{stc})
\]  

(2.16)

\[
V_{oc(T)} = V_{oc(stc)} + K_v(T_e - T_{stc})
\]  

(2.17)
The PV module’s shunt resistance varies according to the open circuit voltage (Kandil et al 2011). This statement is used to form the new equation (2.24) and is given by

\[
R_{sh(GT)} = R_{sh} \frac{V_{oc(GT)}}{V_{oc}} \tag{2.24}
\]

The series resistance (Chatterjee et al 2011) is directly proportional to light generated current at different environmental conditions, and is calculated as follows:

\[
R_{se(GT)} = R_{se} \frac{I_{LG(GT)}}{I_{LG}} \tag{2.25}
\]

The calculated value of \(V_{oc}\) and \(I_{sc}\) at different environmental conditions is equal to the initial value of \(V_{mpp}\) and \(I_{mpp}\) (Esram & Chapman 2007) and can be expressed as follows:

\[
V_{MPP \_initial} \approx V_{oc(GT)} \tag{2.26}
\]
\[
I_{MPP \_initial} \approx I_{sc(GT)} \tag{2.27}
\]

At MPP, maximum voltage and maximum current value are extracted by manipulating the equations (2.8) and (2.13) respectively under varying environmental conditions and new equations (2.28) and (2.29) are formed.

\[
V_{MPP} = N_s V_{r(GT)} \ln(A) + V_{oc(GT)} - I_{MPP} R_{se(GT)} \tag{2.28}
\]
where \[ A = \frac{(I_{sc(GT)} - I_{MPP})(R_{se(GT)} + R_{sh(GT)}) - V_{MPP}}{(I_{sc(GT)}(R_{se(GT)} + R_{sh(GT)}) - V_{oc(GT)})} \]

\[ I_{MPP} = \frac{V_{MPP}(B + N_i V_{f1(GT)})}{N_i V_{f1(GT)}(R_{se(GT)} + R_{sh(GT)})} \] (2.29)

where \[ B = ((I_{sc(GT)} - I_{MPP})(R_{se(GT)} + R_{sh(GT)}) - V_{MPP}) \]

Equations (2.28) and (2.29) are solved by successive under relaxation (SUR) method which is expressed in the following form (Chatterjee et al. 2011):

\[ X_i^k = W X_i^k + (1 - W) f(X_i^k) \] (2.30)

where \[ W \] – extrapolation factor

The value of extrapolation factor must be less than 1, otherwise divergence may occur. In SUR method, to confirm the final value of PV module parameters, the minimum error value of \( V_{mpp} \) and \( I_{mpp} \) between two consecutive iterations is taken as \( 1 \times 10^{-6} \) (Ghani & Duke 2011). Finally, under varying environmental conditions, the calculated value of \( I_{LG} \), \( I_{sat} \), \( A \), \( R_{se} \) and \( R_{sh} \) are substituted in equation (2.1) and the \( I-V \) and \( P-V \) characteristics curves of PV module are plotted. The flowchart for finding the MPP at different irradiance and temperature conditions is illustrated in Figure 2.3. In Figure 2.3, \( e_1 \), \( e_2 \) and \( e_3 \) represent the error in \( V_{oc} \), \( V_{mpp} \) and \( I_{mpp} \) in the two consecutive iterations respectively.

2.6 RESULTS AND DISCUSSION

Three different PV modules are selected for validating the proposed PV model. The PV modules SP70 (mono-crystalline), KC60 (poly-crystalline) and ST40 (Thin-film) are used to test the performance of the proposed PV model at STC temperature and varying irradiation conditions as reported in Kulaksiz (2013).
Evaluate $V_{mpp}$ and $I_{mpp}$ from reformed equation of (2.28) and (2.29)

Calculate error values $e_2$ and $e_3$, $iter2=iter2+1$

If $e_2$ and $e_3\leqslant tolerance$

Calculate $P_{mpp}=V_{mpp} \times I_{mpp}$ and Formulate the $I-V$ relationship
Plot $I-V$ and $P-V$ curves

Stop

---

Figure 2.3 Flowchart to evaluate the MPP using SUR method

Initialize $W=0.3$, $iter1=1$, $iter2=1$, $maxiter1$, $maxiter2$ Assign the estimated parameter values $R_{se}$, $R_{sh}$, $A$, $I_{LG}$, $V_{oc}$ and $I_{sc}$ at STC

Divergence occurred

While $iter1\leqslant maxiter1$

Calculate $V_{oc(G)}$ from equation (2.15) and error value $e_1$, $iter1++$

If $e_1\leqslant tolerance$

Yes

No

Evaluate $I_{sc(T)}, I_{LG(GT)}, I_{sc(GT)}$ and $V_{oc(GT)}$ from equations (2.16), (2.20), (2.21) and (2.22) respectively

Evaluate $V_{t(T)}, I_{sat(GT)}, V_{t(GT)}, R_{sh(GT)}$ and $R_{se(GT)}$ from equations (2.18), (2.19), (2.23), (2.24) and (2.25) respectively

Divergence occurred

while $iter2\leqslant maxiter2$

Evaluate $V_{oc(G)}$ from equation (2.15) and error value $e_1$. $iter1++$

If $e_1\leqslant tolerance$

Yes

No

Stop
In Table 2.3, Table 2.4 and Table 2.5, maximum power using the proposed PV model has been calculated and the results are compared with the Sandia model and ANFIS model as reported by Kulaksiz (2013). The maximum power of PV panel obtained by the proposed model is also compared with that obtained by one of the conventional MPPT technique (Incremental & Conductance method) and the results are given in Table 2.3.

### Table 2.3 Comparison of proposed PV model’s maximum power with the Sandia model and Kulaksiz model for the Shell SP70 monocrystalline PV module at $T_c=25^\circ$C and different irradiation conditions

<table>
<thead>
<tr>
<th>Irradiation ($G$ (W/m$^2$))</th>
<th>Sandia model $P_{MPP}$ (W)</th>
<th>Kulaksiz ANFIS Model $P_{MPP}$ (W)</th>
<th>Relative error (%)</th>
<th>Proposed model $P_{MPP}$ (W)</th>
<th>Relative error (%)</th>
<th>Conventional MPPT (INC) Technique $P_{max}$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>69.96</td>
<td>69.56</td>
<td>0.57</td>
<td>70.15</td>
<td>-0.27</td>
<td>69.81</td>
</tr>
<tr>
<td>800</td>
<td>56.64</td>
<td>55.86</td>
<td>1.38</td>
<td>55.46</td>
<td>1.59</td>
<td>54.84</td>
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<tr>
<td>600</td>
<td>42.53</td>
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<td>2.12</td>
<td>40.67</td>
<td>4.37</td>
<td>40.01</td>
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<tr>
<td>400</td>
<td>28.12</td>
<td>27.15</td>
<td>3.45</td>
<td>26.05</td>
<td>7.36</td>
<td>25.39</td>
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<tr>
<td>200</td>
<td>13.81</td>
<td>12.74</td>
<td>7.75</td>
<td>12.00</td>
<td>13.11</td>
<td>11.60</td>
</tr>
</tbody>
</table>

The accuracy of the different models of PV module is evaluated based on the relative error in the maximum power which is obtained by comparing the obtained maximum power with that of sandia model. The maximum power obtained by the proposed PV model is very much closer to the maximum power obtained in sandia model at STC. The maximum relative error in the maximum power with the proposed PV model are 13.11%, -8.47% and -5.05% for the PV modules SP70, KC60, and ST40 respectively, and while comparing with Kulaksiz ANFIS model, it is 7.75%, 6.04% and 5.34% respectively. The relative error in the maximum power of the SP70 PV
module, has slightly higher deviation for irradiation value at 200 W/m² in the proposed PV model and is less for other irradiation conditions. These results ascertain the proposed PV model performance is good compared with the ANFIS model as reported in Kulaksiz (2013).

Table 2.4 Comparison of proposed PV model’s maximum power with the Sandia model and Kulaksiz model for the Kyocera KC60 polycrystalline PV module at $T_c=25^\circ$C and different irradiation conditions

<table>
<thead>
<tr>
<th>Irradiation</th>
<th>Sandia model</th>
<th>Kulaksiz Model</th>
<th>Proposed model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$ (W/m²)</td>
<td>$P_{MPP}$ (W)</td>
<td>$P_{MPP}$ (W)</td>
<td>$P_{MPP}$ (W)</td>
</tr>
<tr>
<td>relative error (%)</td>
<td>relative error (%)</td>
<td></td>
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<tr>
<td>1000</td>
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<td>800</td>
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<td>400</td>
<td>23.43</td>
<td>22.59</td>
<td>3.59</td>
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<tr>
<td>200</td>
<td>11.10</td>
<td>10.43</td>
<td>6.04</td>
</tr>
</tbody>
</table>

Table 2.5 Comparison of proposed PV model’s maximum power with the Sandia model and Kulaksiz model for the Shell ST40 thin-film PV module at $T_c=25^\circ$C and different irradiation conditions

<table>
<thead>
<tr>
<th>Irradiation</th>
<th>Sandia model</th>
<th>Kulaksiz ANFIS Model</th>
<th>Proposed model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$ (W/m²)</td>
<td>$P_{MPP}$ (W)</td>
<td>$P_{MPP}$ (W)</td>
<td>$P_{MPP}$ (W)</td>
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<td>relative error (%)</td>
<td>relative error (%)</td>
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<tr>
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<td>39.94</td>
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<td>31.86</td>
<td>32.05</td>
<td>-0.59</td>
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<td>23.48</td>
<td>23.86</td>
<td>-1.62</td>
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<td>15.08</td>
<td>15.26</td>
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<td>200</td>
<td>6.93</td>
<td>6.56</td>
<td>5.34</td>
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I-V curves and P-V curves for Shell SP70 (mono-crystalline), Kyocera KC60 (poly-crystalline) and Shell ST40 (thin-film) PV modules at 25°C and different irradiation conditions such as 1000 W/m², 800 W/m², 600 W/m², 400 W/m² and 200 W/m² are shown in Figure 2.4, Figure 2.5 and Figure 2.6 respectively.

In these figures, all the points in the I-V and P-V curves are shown for the proposed PV model and only the maximum power point is shown for Sandia model and Kulaksiz ANFIS model since the objective of this chapter is to find the maximum power under different environmental conditions. These figures clearly illustrate that the proposed PV model’s maximum power is very much closer to Sandia PV model, and the proposed PV model shows good results nearer to ANFIS model as reported in Kulaksiz (2013) for poly-crystalline and thin-film PV technologies.

At irradiation level of 200 W/m², the calculated relative error in the proposed PV model is slightly less in the thin-film PV technology compared to the Kulaksiz ANFIS model. Thus, the proposed PV model has good agreement with the Sandia model and the proposed PV model is used to predict the performance of the PV module accurately.

The ANFIS based PV model needs more training data, collection of which consumes more time and also the ANFIS has to be properly trained. But in the proposed PV model, there is no need for collection of data and training which saves time.
Figure 2.4  (a) I-V curves and (b) P-V curves for Shell SP70 PV module, under different irradiation conditions (Temperature at 25°C)
Figure 2.5  (a) *I*-V curves and (b) *P*-V curves for Kyocera KC60 PV module, under different irradiation conditions (Temperature at 25°C)
Figure 2.6  (a) I-V curves and (b) P-V curves for Shell ST40 PV module, under different irradiation conditions (Temperature at 25ºC)
In Table 2.6, the accuracy of the proposed PV model is validated by using the PV modules SP70 (mono-crystalline), S36 (poly-crystalline), ST40 (Thin-film) at 1000 W/m$^2$ and varying temperature conditions and comparing the results with the Ishaque PV model. For SP70, S36 and ST40 PV modules, the calculated maximum relative error at maximum power point using the proposed PV model is nearer to the experimental data reported in the literature and two diode PV model (Ishaque et al 2011b).

<table>
<thead>
<tr>
<th>PV module</th>
<th>$T_c$ (ºC)</th>
<th>Experimental power (W)</th>
<th>Ishaque 2-diode model</th>
<th>Proposed model</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>$P_{MPP}$ (W)</td>
<td>Relative error (%)</td>
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<tr>
<td>SP70</td>
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<td>62.13</td>
<td>61.89</td>
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<td>77.91</td>
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<td>85.75</td>
<td>85.70</td>
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<td>S36</td>
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<td>31.95</td>
<td>31.90</td>
<td>0.156</td>
</tr>
<tr>
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<td>40.09</td>
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<td>44.10</td>
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<td>33.71</td>
<td>0.853</td>
</tr>
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<td>0</td>
<td>46.00</td>
<td>46.33</td>
<td>0.717</td>
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<td>-25</td>
<td>52.00</td>
<td>52.69</td>
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</tr>
</tbody>
</table>

Figure 2.7, Figure 2.8 and Figure 2.9 shows the $I$-$V$ curves and $P$-$V$ curves of Shell SP70, Shell S36 and Shell ST40 PV modules. $I$-$V$ curves and $P$-$V$ curves are illustrated at 1000 W/m$^2$ and different temperature conditions such as 50ºC, 25ºC, 0ºC and -25ºC (Ishaque et al 2011b). In these figures, all
the points in the $I-V$ and $P-V$ curves are shown for the proposed PV model and only the maximum power point is shown for experimental data and Ishaque model. From these figures, it can be concluded that the proposed PV model gives much closer performance with experimental data and two diode PV model (Ishaque et al. 2011b) for Shell SP70, Shell S36 PV and Shell ST40 modules.

2.7 (a)  

2.7 (b)  

Figure 2.7(a) $I-V$ curves and (b) $P-V$ curves for Shell SP70 PV module, under different temperature conditions (Irradiation at 1000 W/m²)
Figure 2.8 (a) *I-V* curves and (b) *P-V* curves for Shell S36 PV module, under different temperature conditions (Irradiation at 1000 W/m²)
Figure 2.9 (a) $I-V$ curves and (b) $P-V$ curves for Shell ST40 PV module, under different temperature conditions (Irradiation at 1000 W/m$^2$)
2.7 CHAPTER SUMMARY

In this chapter, an enhancement of one diode model of PV module is developed to predict its maximum power for different PV technologies under varying environmental condition. An analytical method and numerical methods such as G-S and SUR are employed to estimate the PV module parameters at STC by introducing new equations to estimate the value of series resistance and shunt resistance. Maximum power of different PV modules manufactured by various PV technologies at different environmental conditions is then found by introducing new equations to find $I_{mpp}$ and $V_{mpp}$.

The accuracy of the proposed PV model is analysed against experimental data reported in the literature for constant temperature and varying irradiation conditions by comparing the relative error in the obtained maximum power with that of Sandia model for different PV technologies. In the proposed PV model relative error is found to be nearer to that obtained in Kulaksiz ANFIS model. ANFIS model needs more training data and it has to be properly trained which consumes more time. For mono-crystalline, polycrystalline and thin-film technologies, the maximum power at MPP in the proposed PV model at constant irradiation and varying temperature conditions is closer to that of experimental power and Ishaque two diode PV model. The two diode PV model gives better results than single diode proposed PV model. Even then, our proposed single diode PV model shows good correlation with two diode PV model and it takes less computation time compared to that of two diode model. Therefore the proposed PV model is useful tool for PV module designer, power system planning studies involving microgrid with PV systems and power electronic converter designer for maximum power tracking applications in PV systems.