CHAPTER 3
MODELING AND SIMULATION OF PV ARRAY

3.1 INTRODUCTION

Due to the high investment cost of PV modules, the optimal utilization of the available solar energy has to be ensured. This necessitates a precise and reliable simulation of the PV system prior to installation. The most important component that affects the accuracy of the simulation is the PV cell model. This chapter presents the details of the most commonly used PV cell models. This is followed by the simulation of the PV array consisting of series-parallel connected panels, suitable for testing MPPT algorithms and evaluating the effects of environmental conditions. The experimental results from a real solar PV system under various atmospheric conditions, are also presented for comparison.

3.2 PV CELL MODEL

The basic element of a PV system is the PV cell. The PV cell converts solar energy directly into electricity. The purpose of modeling the PV cell is to predict the behavior and power output of the PV system under various environmental conditions, and to evaluate the effects of partial shadowing, module mismatch, and cell or module failure, on a PV system’s output P-V and I-V characteristics.

The modeling of a PV cell involves the estimation of the I-V and P-V characteristics curves to emulate the real cell under various environmental conditions. The most popular approach is to utilize the electrical equivalent circuit, which is primarily based on the diode. There are
two well-known and widely used models, the single-diode and the two-diode. Both these models are based on the well-known Shockley diode equation. They have different levels of complexity, depending on the purpose they are used for.

### 3.2.1 Single Diode model

The simplest PV model is the basic single-diode model (Glass, 1996). It consists of a linear independent current source, in parallel with a diode. This model also includes a series and a parallel resistance, as shown in Figure 3.1.

![Figure 3.1 Single diode model of a PV cell](image)

The characteristics of the PV cell can be represented by the following equation.

\[
I = I_{ph} - I_s \left( e^{V_{t}R_s - V} - 1 \right)
\]  

(3.1)

Here, \(I_s\) represents the saturation current of the diode; \(V_t\) represents thermal voltage where,

\[
V_t = \frac{N_s A k T}{q}
\]

(3.2)

Here,

- \(N_s\) – Number of series connected cells in the module
- \(A\) – Diode ideality factor
\( k \) – Boltzmann’s constant
\( T \) – Temperature (° K)
\( q \) – Charge of an electron (C)

\( N \) represents the quality factor and
\( I_{PH} \) represents the light generated current.
The value of \( I_{PH} \) is in proportion to the light intensity \((I_r)\), and is given by,

\[
I_{PH} = I_r \frac{I_{PH0}}{I_{r0}}
\]

(3.3)

In this expression, \( I_{PH0} \) is the light generated current under standard light intensity \((I_{r0})\). Due to its simplicity and computational efficiency, this model is the most widely used one, in a PV system simulation. This model requires five parameters to completely characterize the power – voltage (P-V) and current – voltage (I–V) curves, namely, short-circuit current \((I_{sc})\), open circuit voltage \((V_{oc})\), diode ideality factor \((A)\), series resistance \((R_s)\) and parallel resistance \((R_p)\). This model gives accurate results even at high temperatures. But its accuracy deteriorates at low irradiance, especially in the vicinity of the open circuit voltage, \( V_{oc} \). Further, the single-diode model is based on the assumption that the recombination loss in the depletion region is absent (Tan et al, 2004), but in a real PV cell it represents a substantial loss. Hence, a more precise model of the PV cell, known as the two-diode model is used.

### 3.2.2 Two Diode Model

![Figure 3.2 Equivalent circuit of a two-diode model of a PV cell](image)
Figure 3.2 shows the equivalent circuit of a two-diode model (Liu, et al, 2002) of a PV cell. Here, an additional diode is connected to account for the losses due to the carrier recombination in the space charge region of the junction, and those due to surface recombination. In this model, the first diode is responsible for the diffusion current component. The characteristics of the two-diode PV cell can be represented by the following equation.

\[
I = I_{PH} - I_{D1} \left( \frac{e^{v_{T}R_s}}{N_1} - 1 \right) - I_{D2} \left( \frac{e^{v_{T}R_s}}{N_2} - 1 \right) - \left( \frac{V + IR_s}{R_p} \right)
\]

(3.4)

Here \( I_{D1}, I_{D2} \) - Diode Saturation Currents of diode 1 and 2

\( V_t \) - Thermal Voltage

\( N_1, N_2 \) - Quality Factors (Diode emission Coefficients)

\( I_{PH} \) - Solar generated Current

The value of \( I_{PH} \) is in proportion to light intensity \( (I_r) \), and is given by,

\[
I_{PH} = I_r \frac{I_{PH0}}{I_{r0}}
\]

(3.5)

\( I_r \) - Light intensity (Irradiation)

\( I_{PH0} \) - Measured Solar generated current for \( I_{r0} \)

\( I_{r0} \) - Irradiation used for measurement (Here 1000W/m\(^2\))

The model of the PV cell presented above, can be expanded into the model of the photovoltaic module. A number of PV modules can be connected in series and parallel to get the desired voltage and current. Series connections are responsible for increasing the voltage of the module, whereas the parallel connection is responsible for increasing the current in the PV array. The basic characteristics of the series and parallel connections of PV modules are similar to those of the individual PV cells.
3.3 SIMULATION OF A PV ARRAY

This section presents the simulation of a PV array, using MATLAB/Simulink. Also, this section describes the I–V and P–V characteristics of the developed PV array.

3.3.1 Simulation of the PV Cell Using Simscape Tool

The Simscape Tool in MATLAB is used for simulating the PV array. Simscape provides an environment for modeling and simulating physical systems, spanning mechanical, electrical, hydraulic, and other physical domains. It has fundamental building blocks from these domains, that we can assemble into models of physical components.

A 3.3 kW PV array is considered for simulation. The parameters considered for simulation are taken from the PV module supplied by M/S Shenzhen Zhong Jing Solar Co., Ltd. The parameters of the PV module considered for simulation are $I_{SC} = 5.29\, \text{A}$, $V_{OC} = 45.2\, \text{V}$, $I_{10} = 1000\, \text{W/m}^2$, and $R_s = 0.65\, \text{Ohm}$. The PV module is established by the built-in modules of the PV cell in Simscape software. Here, 36 PV cells are connected in series to form a PV module. The configuration of the simulated photovoltaic module is shown in Figure 3.3.

![Figure 3.3 The configuration of a PV module in Simscape tool](image-url)
The variable resistances are connected as a load. By varying the resistance from the open circuit voltage to the short circuit voltage, the corresponding current and power are recorded to plot the P-V and I-V characteristics curve. The P-V and I-V characteristics curve of the simulated PV module is shown in Figure 3.4.

![Figure 3.4 I-V and P-V characteristics of a PV module](image)

The PV modules can in turn be connected in series and/or parallel in order to get the desired voltage and current. In this work, to simulate a PV array of 3.3 kW, 9 modules are connected in series to form a string with the voltage level of (9 x 45.2 =) 406.8 V. Two such strings are connected in parallel to get the current rating to (5.29 x 2 =)10.58 A. Figure 3.5 shows the configuration of the PV modules to form a PV string, and its P-V and I-V characteristic curves.
Figure 3.5  (a) PV String configuration, (b) P-V characteristics of a PV string (c) I-V characteristics of a PV string

Figure 3.6 shows the P-V and I-V characteristic curves of a 3.3 kW PV array, composed of two parallel strings.
3.3.2 Effect of Irradiation and Temperature on the PV Array

To evaluate the effects of irradiation and temperature on the characteristics of the PV array, two tests have been conducted on the simulated 3.3 kW PV array. Tests are conducted by keeping one of the input parameters constant, and the other one to vary. Figure 3.7 depicts the P-V and I-V curves respectively, for different solar radiations $G$ and constant temperature $T=25^\circ$C.
Figure 3.7  Simulated P-V and I-V characteristics curves of a PV String model at constant temperature $T=25^\circ C$

From the Figure, it can be noted, that the short circuit current is positively varying with solar radiation. However, the voltage in the open circuit remains constant. Figure 3.8 presents the P-V and I-V curves for different temperatures $T$ but with a constant solar radiation $G=1000 \text{ W/m}^2$.

Figure 3.8  Simulated P-V and I-V characteristics curves of a PV String model at a constant Irradiation $G = 1000 \text{ W/m}^2$

From the curve, it can be noted that the temperature has a negligible effect on the short circuit current. However, the open circuit voltage decays rapidly as the temperature increases. It can also be observed from Figures 3.7 and 3.8, that the temperature changes mainly affect the PV output voltage, while the irradiation changes mainly affect the PV output current.
3.3.3 Effect of Partial Shading on the PV Module

The nonlinearity of the PV characteristic curve becomes more complicated, if the entire PV array does not receive uniform solar irradiance due to trees, clouds, wires etc. The presence of non-uniform irradiation produces the hotspot problem, and the effect of a potential difference between the PV strings. The hotspot problem can occur in a PV array, where a single PV module in the series is less illuminated, and dissipates some of the power generated by the rest of the modules. To protect the PV modules from this problem, the bypass diodes are connected in parallel with each PV module. In addition, the blocking diode is connected in series with each string, to protect the modules from the effect of the potential difference between the series-connected PV strings. Because of these diodes in the PV array, multiple peaks will be exhibited in the PV characteristic curve under partial shading conditions.

To simulate the effect of a non-uniform / partial shading condition, out of 9 PV modules, 3 PV modules (last 3) are illuminated with 200 W/m$^2$ irradiation, and the remaining modules with 1000 W/m$^2$. The P-V and I-V curves obtained in this case are shown in Figure 3.9.
Figure 3.9  P-V and I-V curves for PV array (a) under partial shading pattern with bypass and blocking diode, (b) without bypass and blocking diode

It is seen from the P-V and I–V characteristics shown in Figure 3.9, that the presence of the diodes allows the unshaded modules to conduct their maximum current at a given irradiation and temperature. On the other hand, if the bypass diodes are not present, the shaded modules will limit the current output of the unshaded modules. This may not only lead to a thermal destruction of the PV modules, but may also decrease the available output power from the PV array. The blocking diodes will prevent the reverse current. This reverse current may cause excessive heat generation and thermal breakdown of the PV modules. Figure 3.9 (a) shows that the array having these diodes introduces multiple steps in the I–V characteristics and multiple peaks in the P–V characteristics curve, under partially shaded conditions.

3.4 EXPERIMENTS ON PV ARRAY

In order to validate the simulation results, experiments were conducted on the solar PV system installed at Sri BalaGanapathy Mills Pvt. Ltd, Sivakasi. The rating of the PV panel is given below: $I_{sc}= 5.29A$, $V_{oc}=45.2V$, $I_{mp}=4.97A$, $V_{mp}=36.2V$, $P_m=180W$ at irradiance of 1000W/m² at 25°C temperature. The PV panel has 9 series connected modules connected in parallel, with another 9 series connected module. Figure 3.10 shows the photograph of the hardware setup, data logger and the characteristics of the PV
array obtained, based on the measurements recorded at 1:00 P.M. on June 23, 2011.

Figure 3.10 (a) Experimental solar PV array, (b) Photograph of the data logger connected with the experimental setup, (c) I-V and P-V curves for Simulation and experimental setup under uniform irradiation
The characteristics are obtained by varying the load resistance in discrete steps. The maximum power obtained is 3.1 kW. The current and voltage at the maximum power are 8.21 A and 349 V, respectively. The recorded values of $V_{OC}$ and $I_{SC}$ are 398 V and 10 A, respectively. For comparison, the characteristics curves obtained through simulation are also plotted on the same graph. It is observed that the simulated results closely match the measured value. The small deviation between the two curves at some points is due to the change in irradiation over a time span, during which the measurements were carried out. The data of PV system/panel are given in Table 3.1.

### Table 3.1 PV Module Specification

<table>
<thead>
<tr>
<th>Name of the manufacturer</th>
<th>Shenzhen Zhong Jing Solar Co. Ltd.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model No</td>
<td>PWM-180 W</td>
</tr>
<tr>
<td>Watts peaks (Pm)</td>
<td>180 W</td>
</tr>
<tr>
<td>Short circuit current (Isc)</td>
<td>5.29 A</td>
</tr>
<tr>
<td>Open circuit voltage (Voc)</td>
<td>45.2 V</td>
</tr>
<tr>
<td>Optimum operating current (Imp)</td>
<td>4.97 A</td>
</tr>
<tr>
<td>Optimum power voltage (Vmp)</td>
<td>36.2 V</td>
</tr>
<tr>
<td>Maximum system voltage</td>
<td>1000 V DC</td>
</tr>
<tr>
<td>Dimension of panel</td>
<td>1580x808x46 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>16 kg</td>
</tr>
<tr>
<td>All technical data at Standard Test Condition</td>
<td>Irradiance = 1000W/m² T=25°C</td>
</tr>
</tbody>
</table>

Next, the measurements were taken under a partial shading condition by artificially covering the cells of 4 PV modules in each PV string, with a partially transparent sheet (polythene), as shown in Figure. 3.11. The P-V and I-V curves obtained in this case are shown in Figure 3.12. In the same Figure, the characteristic curves obtained from the simulated PV array are also given. It is observed that the simulated results closely match the experimental results.
The solar irradiation and the temperature of the panel are measured using pyranometer and temperature sensor available in the company. Since pyranometer was used for the measurement of irradiation and the measured value is global irradiation only. The solar irradiation, temperature and the output power delivered are measured on June 23, 2011 and are shown in Fig. 3.13, 3.14 and 3.15.
Figure 3.13 Hourly average solar irradiation on a typical day

Figure 3.14 Hourly average solar temperature on a typical day

Figure 3.15 Hourly average solar power delivered on a typical day
3.5 CONCLUSION

In this chapter, the characteristics of the PV array under various climatic conditions are analyzed. Furthermore, a PV array model, as a tool for evaluating the effects of different values of irradiation and temperatures, has been developed and implemented. Finally, the PV model characteristics are compared with those of the real PV plant. It is observed that the simulated results closely match the measured values, obtained from the experimental setup.