2.1 INTRODUCTION

The PV system directly converts sunlight into electricity. The basic device of a PV system is the PV cell. Cells are grouped to form modules or arrays. The DC voltage and the DC current available at the terminals of a PV device can be directly fed to small loads such as lighting systems and DC motors.

Applications that are more sophisticated require electronic converters to process the electricity from the PV device. These converters are used for regulating the load voltage and load current, control the power flow in grid-connected systems, and track the maximum power point (MPPT) of the device.

This Chapter begins by describing the basic functioning of the solar (PV) cell. This is followed by the presentation of the simple equivalent circuit of the PV module. Next, the SOLKAR make 36 Wp PV module is taken as the reference module and the PV equations are modeled with Simulink blocks. The developed equation models are simulated for variations in irradiation and temperature. Then Simulink circuit model of the PV module is
formed with the developed blocks and validated. Finally, the results are discussed.

2.2 BASIC FUNCTIONING OF THE SOLAR CELL

PV cell is a semiconductor diode whose p-n junction is exposed to light. It is made from several types of semiconductors using different manufacturing processes. The mono-crystalline and polycrystalline silicon cells are mostly used in the commercial scale. Silicon (Si) PV cells is composed of a thin layer of bulk Si or a thin Si film connected to electrical terminals. One of the sides of the Si layer is doped to form a p-n junction. A thin metallic grid is placed on the Sun-facing surface of the semiconductor.

Figure 2.1 illustrates the p-n structure of a PV cell. The incident light on the cell generates charge carriers that originate an electric current if the cell is short circuited (Villalva et al 2009).

![Figure 2.1 Physical structure of a PV cell](image)

The silicon atom contains four electrons in the outer shell. These electrons are a part of the electron pairs that are bound with four other silicon atoms. By doping the silicon with boron (p-doped), which has only three electrons in the outer shell, the silicon becomes electron deficient. Thus, a ‘hole’ is present in the silicon lattice, and positive charges may move around in the lattice.
When doped with phosphorus (n-doped), which have five electrons in the outer shell, the silicon becomes electron saturated. These extra electrons are also free to move around in the lattice.

The p–n junction allows free electrons in the n-doped layer to move into the holes in the p-doped layer. As layers reach equilibrium, an internal field is built up.

An incoming photon may ‘knock’ off a carrier from the p-layer, which leaves a free hole, and the carrier moves around in the p-layer. If the carrier reaches the p–n junction before recombination, the internal field causes it to move into the n-layer.

On the other hand, the carrier may be a victim of recombination before it can reach the junction, thus it will not assist the current generation. Recombination is caused by irregularities in the lattice, impurities in the material, or simply coincidence. The carrier has two possible return paths as given in following paragraph. Figure 2.2 shows the cross-section of a p–n junction.
Once the electron has been forced into the p–n junction either the electron can pass through the p–n junction (which then works as a diode) or it can pass through an auxiliary circuit, the load. The minimum energy required to release a carrier from the p-layer to the load, $E_{g0}$, which is 1.11 eV for silicon.

The requirement for excitation of an electron into the n-doped layer is that the energy of the incoming photon is larger than the energy needed by the electron to overcome the p–n junction barrier.

Because some of the photons have energy lower than what is required, these do not assist the carrier generation. Thus, the energy associated with these photons is transformed into heat. The photons that have energy more than what is required generate the electric current. The scenarios are summarized below;

1) The photon is reflected at the surface,
2) The photon passes through the PV cell,
3) $E_{\text{photon}} < E_{\text{gap}} \rightarrow$ The photon is transformed into heat,
4) $E_{\text{photon}} = E_{\text{gap}} \rightarrow$ A free carrier is generated,
5) $E_{\text{photon}} > E_{\text{gap}} \rightarrow$ Free carrier + heat.

Guechi et al (2007) discussed in detail about the intensity and spectral distribution of the solar radiation that depends on the geographic position, time, day of the year, climatic conditions, composition of the atmosphere, altitude, and many other factors. Due to many factors that influence the solar radiation, the AM 1.5 spectral distribution serves as the reference for evaluation and comparison of the PV devices and is used as the standard in the PV industry. Datasheets generally give information on the characteristics and performance of PV devices with respect to the standard
test condition (STC), which means an irradiation of 1000 W/m² with an AM 1.5 spectrum at 25 °C.

2.3 MATHEMATICAL MODEL OF THE PV CELL

Figure 2.3 shows a single solar cell. Figure 2.4 shows a PV module or PV panel consisting of a set of connected cells. Cells/ modules are generally connected in series to obtain large output voltages. PV modules with large output currents are achieved by increasing the surface area of cells or by connecting the cells/ modules in parallel.

Figure 2.3 Single PV cell

Figure 2.4 PV module
In this thesis, the single diode model, shown in Figure 2.5, is used for modeling. This model offers a good compromise between simplicity and accuracy, with the basic structure consisting of a current source and a parallel diode. In Figure 2.5, \( I_{ph} \) represents the cell as well as the module photon generated current, \( I_0 \) is the diode current while \( R_{sh} \) and \( R_s \) are the intrinsic shunt and series resistances of the module respectively.

### 2.4 REFERENCE MODEL

SOLKAR make 36 Wp PV module is taken as the reference module for simulation and the datasheet details are given in Table 2.1.

![Figure 2.5 PV cell / module modeled as the single diode circuit](image)

**Table 2.1 Electrical characteristics of the SOLKAR 36 Wp PV module**

<table>
<thead>
<tr>
<th>Description</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>37.08 Wp</td>
</tr>
<tr>
<td>Voltage at Maximum power ((V_{mp}))</td>
<td>16.56 V</td>
</tr>
<tr>
<td>Current at Maximum power ((I_{mp}))</td>
<td>2.25 A</td>
</tr>
<tr>
<td>Open circuit voltage ((V_{OC}))</td>
<td>21.24 V</td>
</tr>
<tr>
<td>Short circuit current ((I_{SC}))</td>
<td>2.55 A</td>
</tr>
<tr>
<td>Total number of cells in series ((N_s))</td>
<td>36</td>
</tr>
<tr>
<td>Total number of cells in parallel ((N_p))</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: The electrical specifications are under test conditions of irradiance of 1kW/m\(^2\), spectrum of AM 1.5 and cell temperature of 25 °C.
2.5 PHOTON GENERATED CURRENT

National Aeronautics and Space Administration (1976) in their book “Solar Cell Array Design Handbook” provided the basic equations that mathematically describe the I-V characteristic of the PV cell and the PV module. These are obtained from the theory of semiconductors and photovoltaics. In Figure 2.5, the module photon generated current $I_{ph}$ of the PV module depends linearly on the solar irradiation and is influenced by the temperature according to the Equation (2.1).

$$I_{ph} = \left[I_{SCR} - K_i(T_k - T_{ref})\right] \times \frac{\lambda}{1000}$$  \hspace{1cm} (2.1)

Where $I_{ph}$ (A) is the light/photon-generated current at the nominal operating conditions (25 °C and 1000 W/m²), $K_i$ is the short circuit current/temperature co-efficient at $I_{SCR}$ (0.0017 A/K). $T_k$ and $T_{ref}$ are the actual and reference temperatures respectively in Kelvin, $\lambda$ (W/m²) is the irradiation on the device surface, and 1000 W/m² is the nominal irradiation and is taken as 1.

Figure 2.6 shows the detailed Simulink model of Equation (2.1) for the photon current $I_{ph}$. The value of the module short circuit current $I_{SCR}$, taken from the datasheet of the reference module is 2.55 A.
Table 2.2 gives the values of the $I_{ph}$ for different values of insolation and temperature.

**Table 2.2 $I_{ph}$ for various values of insolation and temperature**

<table>
<thead>
<tr>
<th>Insolation W/m²</th>
<th>Value of $I_{ph}$ (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25 °C</td>
</tr>
<tr>
<td>1000</td>
<td>2.55</td>
</tr>
<tr>
<td>700</td>
<td>1.785</td>
</tr>
<tr>
<td>500</td>
<td>1.275</td>
</tr>
<tr>
<td>250</td>
<td>0.6375</td>
</tr>
<tr>
<td>100</td>
<td>0.255</td>
</tr>
</tbody>
</table>

The photon current $I_{ph}$ is a function of the solar irradiation and temperature and is the only energy conversion process in which the light energy is converted to electrical energy. Figure 2.7 shows the variation of the photon current with respect to the module voltage.
For the equivalent circuit of the module given in Figure 2.5, the diode reverse saturation current or the module reverse saturation current $I_{rs}$ is given by Equation (2.2).

$$I_{rs} = I_{SCR} / \left[ \exp(qV_{oc} / N_s kAT) - 1 \right]$$  \hspace{1cm} (2.2)

Where $q$ is the electron charge ($1.6 \times 10^{-19}$ C), $V_{oc}$ is the solar module open circuit voltage (21.24 V), $N_s$ is the number of cells connected in series (36), $k$ is the Boltzmann constant ($1.3805 \times 10^{-23}$ J/K), and $A$ is the diode ideality factor (1.6). Figure 2.8 gives the detailed Simulink model of Equation (2.2).
Table 2.3 gives the variation of the module reverse saturation current with the temperature.

Table 2.3 $I_{rs}$ for various temperature

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Module reverse saturation current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>$1.182 \times 10^{-006}$</td>
</tr>
<tr>
<td>30</td>
<td>$1.503 \times 10^{-006}$</td>
</tr>
<tr>
<td>40</td>
<td>$2.377 \times 10^{-006}$</td>
</tr>
<tr>
<td>50</td>
<td>$3.654 \times 10^{-006}$</td>
</tr>
<tr>
<td>90</td>
<td>$1.609 \times 10^{-005}$</td>
</tr>
</tbody>
</table>
2.7 MODULE SATURATION CURRENT

Equation (2.3) gives module saturation current $I_0$ for the equivalent circuit of the module.

$$I_0 = I_{rs} \left( \frac{T}{T_r} \right)^3 \exp \left[ \frac{q * E_{g0}}{Bk} \left( \frac{1}{T_r} - \frac{1}{T} \right) \right]$$  \hspace{1cm} (2.3)

Where $E_{g0}$ is the band gap energy of the semiconductor ($E_{g0}=1.11$ eV for the polycrystalline Si at 25 °C). Figure 2.9 shows the Simulink model of Equation (2.3). The module operating temperature, the reference temperature and the module reverse saturation current are taken as the inputs. The module saturation current $I_0$ is calculated for different temperatures and is given in Table 2.4.

![Simulink model for the module saturation current](image)

Figure 2.9 Simulink model for the module saturation current
From Table 2.4, it can be seen that the increase in temperature causes the module saturation current $I_0$ to increase. These variations are plotted against the module voltage (V), as shown in Figure 2.10. Hence, the increase in the temperature could cause the diode to "turn ON" at lower voltages.

### Table 2.4 $I_0$ for various temperate

<table>
<thead>
<tr>
<th>Temperature($^\circ$C)</th>
<th>Module saturation current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>$1.182 \times 10^{-0.006}$</td>
</tr>
<tr>
<td>30</td>
<td>$2.456 \times 10^{-0.006}$</td>
</tr>
<tr>
<td>40</td>
<td>$9.920 \times 10^{-0.006}$</td>
</tr>
<tr>
<td>50</td>
<td>$3.686 \times 10^{-0.005}$</td>
</tr>
<tr>
<td>90</td>
<td>$3.491 \times 10^{-0.003}$</td>
</tr>
</tbody>
</table>

![Figure 2.10 Variation of the module saturation current $I_0$ at high temperature](image)

Figure 2.10 Variation of the module saturation current $I_0$ at high temperature
2.8 MODULE OUTPUT CURRENT

Equation (2.4) describes the current output \( I_{PV} \) of the PV module of the single-diode model presented in Figure 3.4.

\[
I_{PV} = N_p * I_{ph} - N_p * I_0 \left[ \exp \left( \frac{q \cdot (V_{PV} + I_{PV}R_s)}{N_s A k T} \right) - 1 \right] V_{PV} + (I_{PV}R_s) / R_{sh} \tag{2.4}
\]

Where, \( N_p \) and \( N_s \) are the number of cells connected in parallel and series respectively in the given PV module (\( N_p = 1 \) and \( N_s = 36 \)), \( V_{PV} = V_{oc} = 21.24 \) V, \( R_s \) is the equivalent series resistance of the module and \( R_{sh} \) is the equivalent parallel resistance.

Nishioka et al (2007) have given a detailed analysis of the parallel resistance \( R_{sh} \). The leakage current, the tunnel effect, breakdown by micro plasmas, leaks along surface channels etc. are modeled as a parallel resistance. The parallel resistance has its greatest effect when the voltage is the lowest, i.e. when the current passing through the diode in the equivalent circuit is very small. The effect of the parallel resistance, when it is sufficiently small, is to reduce the open circuit voltage and the fill factor. The short circuit current is not affected by it.

Grunow et al (2004) studied the low irradiation performance of the PV modules. Figure 2.11 gives the graph of the relative efficiency of the PV module versus isolation for different values of \( R_{sh} \). It can be seen from Figure 2.2 that for large values of \( R_{sh} \), the module efficiency at low isolation decreases by 3 to 5 percent.
Figure 2.11 Relative efficiency versus irradiation for different values of $R_{sh}$

Hence, when $R_{sh}$ is very large, we can neglect the same. In such a case, the simulation values would be higher than the actual values by 3 to 5 percent at low isolation only. However, there would not be any appreciable variation at normal/higher isolation.

The use of the simplified circuit model in this thesis makes it convenient for power electronics designers who are looking for an easy and effective model for simulating the PV devices with power converters. The value of the parallel resistance $R_{sh}$ is generally high and hence neglected to simplify the model, as given in Equation (2.5).

The series resistance $R_s (0.01 \, \Omega)$ is the sum of several structural resistances of the PV module and its influence is stronger especially at the maximum power point region. The current output of the PV module, given by Equation (2.4), can hence be modified as Equation (2.5).

$$I_{pv} = N_p \times I_{ph} - N_p \times I_0 \left[ \exp \left( \frac{q \times (V_{pv} + I_{pv} R_s)}{N_s A k T} \right) - 1 \right]$$  \hspace{1cm} (2.5)
The solution of Equation (2.5) involves iteration and requires solving of an algebraic loop in the Simulink. To avoid this problem, the functional model is used in other PV research papers for modeling the PV module.

2.9 ALGEBRAIC LOOP PROBLEM

Algebraic loop solving is an iterative process. A successful solution results only if the algebraic loop solver converges to a definite answer. Proper care is to be taken of the feedback element to obtain convergence. For quicker convergence, Equation (2.5) is simplified by excluding $R_{sh}$. Figure 2.12 shows the iterative MATLAB/ Simulink model for the output current $I_{pv}$.

From the equivalent circuit of the PV module, as shown in Figure 2.5, the output current $I_{PV}$ is given by Equation (2.6).

$$ I_{ph} - I_0 = I_{PV} \quad (2.6) $$

Figure 2.12 Simulink model for the module output current $I_{pv}$
Equation (2.6) is diagrammatically shown in Figure 2.13. The module output current $I_{PV}$ is the sum of the photon current $I_{ph}$ and the diode current $I_0$.

![Figure 2.13 I–V curve of the PV module](image)

The PV system has been simulated with operating temperature beyond 50°C namely 90°C in Tables 2.2 to 2.4 to indicate how the temperature affects the photo current, the reverse saturation current and the saturation current.

From Table 2.2 it can be seen that the module photo current increases slightly with increase in temperature while the module reverse saturation current and the module saturation current increase drastically with increase in temperature. This is to show that the PV module output voltage is affected to a very large extent at high temperatures.

### 2.10 DEVELOPMENT OF THE $I_{PV}$ MODEL

The MATLAB/Simulink models for Equations (2.1) to (2.5) are combined through subsystem combination to give the Simulink model for the $I_{PV}$, as shown in Figure 2.14.
Figure 2.14  Simulink model for the $I_{PV}$

Figure 2.15 shows the $I_{pv}$ model block of the PV Module. This model requires three inputs namely, insolation, temperature and voltage and can be used for plotting I-V and P-V output characteristics of the PV module.
2.11 SIMULATION SETUP

Figure 2.16 shows the simulation setup for obtaining the output characteristics from the $I_{pv}$ model block of the PV Module.

Figure 2.16 Simulation setup for obtaining the output characteristics from the $I_{pv}$ model
In the simulation setup, shown in Figure 2.16, the values of insolation and operating temperature are fed through signal builder blocks, and the value $V_{pv}$ is fed from the repeating sequence block. The signal builder block and the repeating sequence block are obtained from the Simulink source library. The repeating sequence has a time-period of 2 s with voltage variation between -0.5 V and 21.6 V.

Figures 2.17 to 2.20 show the I-V and P-V output characteristics under varying irradiation at the constant temperature of 25 °C.

Figure 2.17 shows the input irradiation. The irradiation is 200 W/m$^2$ for 0 s to 1 s, 600 W/m$^2$ for 1 s to 2 s, and 1000 W/m$^2$ beyond 2 s.

![Figure 2.17 Variation of irradiation with time](image)

Figure 2.17 Variation of irradiation with time

Figure 2.18 shows the constant temperature of 25 °C as input.
2.12 OUTPUT CHARACTERISTICS OF THE PV MODULE

Figure 2.19 shows the I-V output characteristics of the PV module with varying irradiation at the constant temperature of 25 °C.
Figure 2.20 shows the P-V output characteristics of the PV module with varying irradiation at constant temperature of 25 °C.

![Graph showing P-V characteristics with varying irradiation](image)

**Figure 2.20 P-V characteristics with varying irradiation**

From Figure 2.19 it is seen that as the irradiation increases, the current and voltage outputs also increase. Hence, the power output of the PV module increases with increase in irradiation when the temperature remains constant at 25 °C.

Figure 2.21 shows the variation of temperature with time as input. The temperature is 25 °C for 0 s to 1 s, 50 °C for 1 s to 2 s and 75 °C beyond 2 s. Figure 2.22 gives the I-V characteristics for varying temperature at a constant irradiation of 1000 W/m². Figure 2.23 gives the P-V characteristics for varying temperature at a constant irradiation of 1000 W/m².
Figure 2.21 Variation of temperature with time

Figure 2.22 I-V characteristics for varying temperature
From Figures 2.22 and 2.23 it is seen that at constant irradiation, with the increase in operating temperature of the PV module, the current output increases marginally. However, the voltage output decreases drastically. This results in a net reduction in the power output for increase in the temperature.

2.13 EXPERIMENTAL VALIDATION OF THE $I_{PV}$ MODEL

A simple and novel method to quickly obtain the characteristics of the PV module under field conditions is proposed in this section. Figure 2.24 shows the schematic of the proposed method. The op-amp, the MOSFET and the resistor $R_{sense}$ are connected such that the current from the solar panel is proportional to the voltage applied to the non-inverting port of the op-amp. A linear MOSFET (IRF 150/IRF 460) is used as a load resistance (Kuai and
Yuvarajan 2006). The gate-source port of the MOSFET is driven by a low frequency triangular wave signal. For good results, the gate signal is large enough to cover the entire range of the panel current, from open circuit to short circuit. To obtain the characteristics at end points, the panel current should increase beyond the short circuit value. For this purpose, a variable regulated power supply (RPS) is connected in series. When obtaining the characteristics at the normal mid values, the RPS is removed or set to zero. However, when obtaining the characteristics in the end points, the RPS is set to an appropriate voltage with the magnitude of the triangular triggering signal set so that the current swings between zero to near short circuit value. If a general-purpose CRO is used, then the voltage applied to the non-inverting port of the op-amp should be repertitive for observing a steady pattern. When the panel current varies from zero to a maximum, the output is obtained and the same output is retraced when the panel current varies from maximum to zero. Due to the large capacitance between the cells and the earth, the retraced pattern does not exactly follow the earlier pattern and therefore the two characteristics are seen on the screen of the CRO. The low frequency signal is applied to the non-inverting port of the op-amp to minimize the current flow in the capacitance. A signal frequency of 1 Hz is therefore used. For uniform intensity of the trace on the CRO screen, the slope of the trigger is kept constant and therefore, a triangular wave is used.
In this work, a digital storage oscilloscope (DSO) was used. Therefore the repetitive trigger signal was not required and only a slow changing ramp signal to change the current from zero to the short circuit value or beyond was sufficient to plot the complete characteristic. For equidistant samples, a linear slope was used.

Figure 2.24 shows the hardware setup of the electronic load. Figure 2.25 shows the experimental set up with DSO screen for the I-V plot of the PV module. GWINSTEK GDS-1022 digital storage oscilloscope (DSO) is used to trace the practical characteristics. It is calibrated using the Fluke 5500A Multi-Product Calibrator.
Figure 2.25  Experimental set up with the DSO screen for the I-V plot of the PV module

Figures 2.26 and 2.27 show the experimental characteristics smoothened by curve fitting along with the characteristics of the Simulink model.
Figure 2.26 Experimental and simulated I-V characteristics at $\lambda=1000 \text{ W/m}^2$ and $T = 25 \, ^\circ\text{C}$

Figure 2.26 shows that the simulated current value at $\lambda=1000 \text{ W/m}^2$ and $T = 25 \, ^\circ\text{C}$ is 2.55 A while the experimental current value is 2.49 A, giving a percentage error of 2.35.

As per the specifications of the PV module used for the experiment, the short circuit current is 2.55 A. The error calculation is based on the specifications of the PV panel given by the supplier, as given in Table 2.1.
Figure 2.27 Experimental and simulated P-V characteristics at 
\( \gamma = 1000 \text{ W/m}^2 \) and \( T = 25 \text{ °C} \)

The simulated values using the developed model are higher than the experimental values by about 3% at higher insolation and hence the \( I_{PV} \) model is reasonably accurate.

2.14 SIMULATION STRATEGY FOR THE CIRCUIT MODEL OF THE PV MODULE

The equivalent circuit of the PV module, shown in Figure 2.5, is used for simulating the PV module. In the above circuit, The \( I_{PV} \) model has been developed. For this \( I_{pv} \) model, the voltage required is given as the external input.
Veerachary (2006) developed the PSIM circuit-oriented simulator model in which the external DC voltage was fed to the model. This makes the model an approximate one.

To utilize this PV junction voltage in the model, Villalva et al (2009) discussed the detailed simulation strategy. Figure 2.28 shows the circuit model consisting of only one current source with the diode voltage fed back to $I_{PV}$ model. The value of the current is obtained by numerically solving the $I_{ph}$ equation.

![Figure 2.28 Current source model with the diode voltage fed back](image)

In the equivalent circuit of the PV module shown in Figure 2.5, PV output voltage is a function of the junction voltage of the diode, which is the material property of the semiconductor. Using this fact, the circuit model is developed in section 2.15.

2.15 CIRCUIT MODEL FOR THE PV MODULE

In Figure 2.5, in the equivalent circuit, the voltage available across the single PV cell is the p-n junction forward bias voltage of 0.6 V. The open circuit voltage of the PV module is $21.24 \, \text{V} / 36 \, \text{cells} = 0.594 \, \text{V} \approx 0.6 \, \text{V}$. 
Simulink model of the $I_{PV}$, developed as above, provides the module current $I_{ph}$ of the equivalent circuit. This photon current is calculated from the values of irradiation and temperature and is the input to be used directly in the Simulink circuit model. 36 cells are connected in series with the forward bias voltage of the diode being equal to the open circuit voltage of the PV module and is 21.24 V.

The voltage at the output terminal of the model is fed back as the voltage input $V_{in}$ for the Simulink model of the $I_{PV}$, as per the simulation strategy suggested by Villalva et al (2009). A small resistance of 0.01 $\Omega$ is added to the circuit to aid the charging of the capacitor that is normally used with the current source. Figure 2.29 shows the detailed circuit model of the PV module and Figure 2.30 shows the circuit model block of the PV module.

![Figure 2.29 Detailed circuit model of the PV module](image-url)
Here, the open circuit voltage value available in the nameplate is chosen and fed to $I_{PV}$ model where the power equation is iterated, as in the normal functional PV. Thus, the algebraic loop problem is avoided.

2.16 SIMPLE VALIDATION PROCEDURE FOR THE CIRCUIT MODEL

Villalva (2009) has pointed out that all PV module datasheets give the following information: the nominal open circuit voltage $V_{oc}$, the nominal short circuit current $I_{sc}$, voltage at the MPP $V_{mp}$, the current at the MPP $I_{mp}$, as shown in Figure 2.31. In section 2.13, I-V curve of the $I_{PV}$ model is validated experimentally. Now, using the $I_{PV}$ model, the circuit model of the PV module is formed. Hence, to test the validity of the developed circuit model, it is enough to test at the nominal remarkable points of the I-V curve.
The developed circuit model is validated at the three remarkable points of the I-V curve of the PV module viz., at open circuit $V=V_{oc}$, at short circuit $V=0$, and at the maximum power $V=V_{mp}$.

2.16.1 Remarkable Point at the Open Circuit at $I=0$

Figure 2.32 shows the circuit model that is used in the open circuit simulation circuit where $I=0$.

As per the nameplate details at $I=0$, Rated voltage $V=V_{oc}=21.24$ V.

The simulated value=20.25 V.

Hence, Error=21.24-20.25= 0.99 V (Since the simulated value is less than the rated value).

% Error=$(-0.99/21.24)*100=-4.66\%$. 

Figure 2.31 Three remarkable points in the I–V curve of the PV module
2.16.2 Remarkable Point at the Short Circuit \( V=0 \)

Figure 2.33 shows the circuit model that is used for the short circuit simulation circuit where \( V=0 \).

As per the nameplate at \( V=0 \), the rated current at \( I=I_{sc}=2.55 \) A.
Simulated value = 2.5 A.

Error = 2.55-2.5=-0.05 A (Since the simulated value is less than the rated value)

% Error = (-0.05/2.55)*100=-1.96%=-2%

2.16.3 Remarkable Point at the Maximum Power Point

To get the maximum power point (MPP) operation of the circuit model, the resistance is varied. Figure 2.34 shows the simulation circuit for circuit model with a variable resistance. The resistance of the circuit is varied from 0 Ω to 25 Ω and the results are tabulated in Table 2.5.

![Simulation circuit with the circuit model at the MPP](image)

Figure 2.34 Simulation circuit with the circuit model at the MPP

Table 2.5 gives the maximum power point operation of the circuit model at \( V_{mp}=16.64 \) V, \( I_{mp}=2.311 \) A, and \( P_{mp}=38.46 \) W corresponding to the resistance value of 7.2 Ω. From the nameplate details of the SOLKAR PV
module, given in Table 2.1, $V_{mp}=16.56$ V, $I_{mp}=2.25$ A, $P_{mp}=37.08$ W corresponds to the load resistance of $7.36\ \Omega$, at the maximum power point operation.

Table 2.5  Results of the variable resistance simulation with the circuit model for the insolation of 1000 W/m$^2$ and 25 ºC

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Variable resistance $(\Omega)$</th>
<th>PV current $(A)$</th>
<th>PV voltage $(V)$</th>
<th>PV power $(W)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Short circuit</td>
<td>2.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2.5</td>
<td>2.5</td>
<td>6.25</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2.5</td>
<td>5</td>
<td>12.5</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>2.5</td>
<td>7.499</td>
<td>18.75</td>
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<td>16.75</td>
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</table>

Rated power at $V_{mp}$ = 37.08 W

Simulated value = 38.45 W

Error = 38.45-37.08=1.37 W
% Error \quad = \quad (1.37/37.08)*100=3.694=3.7 \%

Rated voltage at \ V_{\text{mp}} \quad = \quad 16.36 \text{ V}

Simulated value \quad = \quad 16.75 \text{ V}

Error \quad = \quad 16.75-16.36=0.39 \text{ V}

% Error \quad = \quad (0.39/16.36)*100=2.383\% \approx 2.4 \%

Rated current at \ V_{\text{mp}} \quad = \quad 2.25 \text{ A}

Simulated value \quad = \quad 2.295 \text{ A}

Error \quad = \quad 2.295-2.25=0.035 \text{ A}

% Error \quad = \quad (0.035/2.25)*100=1.555 \% \approx 1.6 \%

Further, Table 2.5 shows that the values obtained follow the I-V curve shown in Figure 2.19 with reasonable accuracy. In the open and the short circuit conditions of the PV module, the simulated values were lower than the actual nameplate values. This was due to the effect of neglecting the parallel resistance.

The values in Table 2.5 show that the circuit operating points simulation values are higher than the nameplate values. Therefore, the developed model has been verified with nameplate details and has reasonable accuracy.

2.17 \quad BEHAVIORAL ASPECTS OF THE CIRCUIT MODEL

Generally, the mathematical model of the physical systems aims at obtaining identical numerical values of the simulation results and the experimental results at various operating conditions. Due to the nonlinearity present in the physical systems, the model is linearized at the operating point.
In this thesis, several approximations are made in the PV system’s modeling as discussed in the previous sections.

In this developed circuit model, the voltage and the current variations of the PV module with respect to the irradiation and the temperature are modeled. At the three remarkable points, I-V curve in the simulation circuit closely follows the experimental values. Thus, the simple validation circuit method of the developed circuit model for the crystalline PV module is experimentally verified. It is proposed to use the same technique for the thin-film PV modules in Chapter 5.

2.18 CONCLUSION

In this Chapter, the functioning of the PV cell and the equations of the PV module were presented with the systematic MATLAB / Simulink modeling procedure. The physical equations governing the PV module were elaborately presented with numerical values of the module saturation current at various temperatures.

From the results of modeling of Equation (2.1), it can be seen that the PV current $I_{ph}$ is a function of the solar irradiation and is the only energy conversion process in which the light energy is converted to electrical energy.

Equations (2.2) and (2.3) indicate that the PV voltage is a function of the junction voltage of the diode, which is the material property of the semiconductors, susceptible to failure at higher temperatures and clearly explained through tabulation of the simulation values of these equation models at higher temperature.

The results are also experimentally verified. To obtain the characteristics of the PV module practically, an electronic load circuit has been
developed. Using the circuit, the characteristics are obtained quickly and the data stored before any change in irradiance and/or temperature occurs. The simulated values using the developed model are higher than the experimental values by about 3% at normal insolation and hence the $I_{PV}$ model is reasonably accurate.

The mathematical model and Simulink modeling procedure serves as an aid to induce more people in photovoltaic research and gain a closer understanding of the I-V and the P-V characteristics of the PV module.

Using this $I_{PV}$ model, the circuit model of the PV module is formed that can be used as a common platform by material scientists as well as power electronic circuit designers to develop better PV power plant.

Simple validation procedure for the developed circuit model is proposed with the simulation circuit at the three remarkable points and it is found that the simulation values closely follows the experimental values.

The results obtained from the simulation and hardware prototype are compared with the specifications of the PV module namely, the short circuit current, the open circuit voltage and the maximum power point value. This is the conventional method of comparing the results of the simulation and hardware prototype with the specifications.