CHAPTER 2

PHOTOVOLTAIC SYSTEM

2.1 INTRODUCTION

Solar radiation reaches the Earth’s surface at a maximum flux density of about 1.0 kWm$^{-2}$ in a wavelength band between 0.3 and 2.5 μm. For inhabited areas, this flux varies from about 3 to 30 MJm$^{-2}$day$^{-1}$, depending on place, time and weather. This is an energy flux of very high thermodynamic quality, from an accessible source of temperature very much greater than from conventional sources. The flux can be used for photophysical processes like photovoltaic power and photosynthesis. PV power is mostly generated using solar cells or PV cells. These devices produce electricity directly from electromagnetic radiation, without any moving parts. PV power has been one of the fastest growing renewable energy technologies. Demand has been driven by the modular character, stand-alone and grid-linked opportunities, reliability, ease of use, lack of noise and emission, and reducing cost per unit energy produced. This chapter will detail the main sections and terms related to PV.

2.2 SOLAR RESOURCE

2.2.1 Energy from the Sun

The sun at the center of the solar system emits energy as electromagnetic radiation at an extremely large and relatively constant rate. The rate at which this energy is emitted is equivalent to the energy coming
from a furnace at a temperature of about 6000K. The rate at which solar energy reaches a unit area at the Earth is called the solar irradiance or insolation. Solar energy is the overabundant renewable resource. The amount of sunlight received by any surface on Earth will depend on several factors including; time of the day, geographical location, season, local landscape and local weather. The light's angle of incidence on a given surface will depend on the orientation since the Earth's surface is round and the intensity will depend on the distance that the light has to travel to reach the respective surface. The radiation received by a surface will have two components. The first one is direct and depends on the distance the rays travel. The second component is called diffuse radiation and is exemplified in Figure 2.1. The range of wavelengths of light that reach the Earth varies from 300nm to 400nm approximately. This is significantly different from the spectrum outside the atmosphere, which closely resembles 'black body' radiation, since the atmosphere selectively absorbs certain wavelengths.

![Diagram of Types of radiation from the sun](image)

**Figure 2.1** Types of radiation from the sun
2.2.2 Solar Spectrum

Nuclear fusion reactions in the active core of the sun produce inner radiation flux of uneven spectral distribution. There are two different spectral distributions defined for the sun. The AM0 (Air Mass Zero) spectrum relates to radiation in outer space and the AM 1.5 (Air Mass 1.5) global spectrum is at sea level at certain standard conditions (Garg and Prakash 2000). The PV industry and the American Society for Testing and Materials (ASTM), American government research and development laboratories have developed and defined two standard terrestrial solar spectral irradiance distributions: a standard direct normal and a standard total spectral irradiance. An instrument called the pyranometer is used to measure global solar radiation. Generally, this instrument is designed to respond to all wavelengths and therefore gives an accurate value of the total power in any incident spectrum. Figure 2.2 shows the spectral distribution of the solar irradiance at the Earth’s mean distance.

![Graph showing energy distribution and wavelengths](image)

**Figure 2.2 Solar spectral irradiance curve**
Important terms are defined as follows.

1. Spectral irradiance $I_i$ has units of $\text{W/m}^2\mu\text{m}^{-1}$ and refers to the power received by a unit surface area in a wavelength differential $d\lambda$.

2. Irradiance - has units of $\text{W/m}^2$ and refers to the integral of the spectral irradiance over all the respective wavelengths.

3. Radiation - refers to the integral of Irradiance over a specified time period.

### 2.2.3 Standard Test Conditions

It is essential to specify uniform conditions to make a performance comparison between different PV units (cell, modules). The parameters obtained from the testing are usually provided on the manufacturer's datasheet. Measurements are performed under these standard test conditions and the electrical characteristics obtained characterize the module accurately under these conditions (Ross 1980). The conditions are specified as follows:

1. The reference vertical irradiance with a typical value of 1000W/m$^2$.

2. Reference cell temperature for performance rating, with a typical value of 25°C and a tolerance of ±2°C.

3. A specified light spectral distribution with an air mass, AM =1.5. Air mass figures provide a relative measure of the path the sun must travel through the atmosphere.

In addition to supplying performance parameters at the Standard Test Conditions manufacturers also provide performance data under the
Nominal Operating Cell Temperature (NOCT). This is defined as the
temperature reached by the open circuited cells in a module under the
following conditions:

1. Sunlight irradiance on cell surface is 800W/m$^2$.
2. An average of 20°C (293 K) ambient temperature.
3. An average wind velocity of 1m/s, with the back side of the
solar panel open to that breeze.

To account for other ambient conditions the approximate
expression given in Equation (2.1) may be used.

$$T_c = T_{amb} + \frac{NOCT - 20}{0.8} G$$  \hspace{1cm} (2.1)

where $T_c$ is cell temperature, $T_{amb}$ is the ambient temperature, $NOCT$ is the
Nominal Operating Cell Temperature and $G$ is the solar irradiance (kW/m$^2$).

2.3 PHOTOVOLTAIC GENERATOR

A photovoltaic generator is a device which produces electricity
when the sunlight is available and in proportion to solar intensity. PV cell is
the basic component of a PV system. These cells have been the standard
source of power for space vehicles and satellites for many years. The
production and installation of solar cells have both increased worldwide in
significant manner in the past decade. Multiple cells are connected in series
and parallel to form solar modules or panels. Solar modules are connected in
series and parallel in order to make a PV array. The solar array produces DC
power which for grid tie systems must be adjusted by a maximum power
point tracker (MPPT) and then converted to AC by a DC to AC inverter.
These functions are performed by the power conditioning unit which is composed of the MPPT and power inverter.

2.3.1 Photovoltaic Cell

PV cell is a semiconductor device which behaves as a current source when drive by a flux of solar radiation from the sun. The PV cells are made of several types of semiconductors using different manufacturing processes. At the present time, the monocrystalline and polycrystalline silicon cells are generally found at commercial scale. Silicon PV cells are composed of a thin layer of bulk Si p-type substrate connected to an electric terminal. Top side of p-type substrate is doped with n-type material to form the p-n junction. A thin film metallic grid is placed on the sun facing surface of the semiconductor. Figure 2.3 illustrates the physical structure of the PV cell.

![Figure 2.3 Physical structure of PV cell](image_url)
The incidence of light on the cell generates charge carriers that originate an electric current if the cell is short circuited. Charges are generated when the energy of the incident photons is sufficient to detach the covalent electrons of the semiconductor. This phenomenon depends on the semiconductor material and on the wavelength of the incident light. Basically PV phenomenon may be described as the absorption of solar radiation, the generation and transport of free carriers at the p-n junction, and the collection of these charges at the terminals of the PV cell. (Rauschenbach 1980, Lasnier and Ang 1990).

The rate of generation of electric carriers depends on the flux of incident light and the capacity of absorption of the semiconductor. The capacity of absorption mainly depends on the semiconductor band gap, on the reflectance of the cell surface, on the intrinsic concentration of carriers of the semiconductor, on the electronic mobility, on the recombination rate, on the temperature, and on several other factors. The solar radiation is composed of photons of different energies. Photons with energies lower than the band gap of the PV cell are useless and generate no voltage or electric current. Photons with energy superior to band gap generate electricity, but only the energy corresponding to the band gap is used, the remainder of energy is dissipated as heat in the body of the PV cell. Semiconductors with lower band gaps may take advantage on a larger radiation spectrum, but the generated voltages are lower. Si is not the only, and probably not the best, semiconductor material for the PV cells, but it is the only one whose fabrication process is economically feasible in large scale. Other materials can achieve better conversion efficiency, but at higher and commercially unfeasible costs. The detailed study of the physics of the PV cell is considerably complicated and out of scope of the work considered. For the proposed work, it is sufficient to know the electrical characteristics of the PV cell.
In the absence of light, the ideal PV cell imitates the electrical characteristics of an ideal diode when connected to a forward bias, the relationship between the flow of current and imposed voltage is given by the Shockley Equation (2.2), where the current produced is referred to as the dark current.

\[ I_D = I_s \left[ \exp \left( \frac{Vq}{kT_c} \right) - 1 \right] \]  

(2.2)

where \( I_D \) is the dark current (A), \( I_s \) is the saturation current of the diode (A), \( V \) is the cell voltage (V), \( q \) is an electron charge (=1.6x10\(^{-19}\) C), \( k \) Boltzmann’s constant (=1.38x10\(^{-23}\)J/K) and \( T_c \) is cell temperature (K).

The current in the cell that results from solar radiation is called the photocurrent \( I_p \) which flows in the direction opposite to the forward dark current. Its value remains the same regardless of external voltage and it can be measured by the short circuit current. This current varies linearly with the intensity of solar radiation, as increased radiation is able to separate increased charge carriers. The overall current is then described as the difference between dark current and photocurrent. If the sign convention of current flow is reversed to describe the current which is produced by an illuminated cell then the cell equation can be written as shown in Equation (2.3)

\[ I = I_p - I_s \left[ \exp \left( \frac{Vq}{kT_c} \right) - 1 \right] \]  

(2.3)

Equation (2.3) is the mathematical equation which models the behavior of an ideal PV cell shown in Figure 2.4. The production of
photocurrent is modeled with a DC current source and the dark current is modeled with a diode referred to as the diffusion diode.

![Equivalent circuit of an ideal PV cell](image)

**Figure 2.4 Equivalent circuit of an ideal PV cell**

### 2.3.2 Characteristic Equation of the Non-ideal Photovoltaic Cell

The equivalent circuit of a PV cell often used for research purpose is shown in Figure 2.5. This model describes the static behavior of a PV cell, is commonly composed of a current source, a PN junction diode and a shunt resistor ($R_{sh}$) in parallel along with a series resistor ($R_s$). This is referred as standard five parameter model or single diode model of the PV cell (Duffie and Beckman 2006).

![Equivalent circuit of a non-ideal PV cell](image)

**Figure 2.5 Equivalent circuit of a non-ideal PV cell**

The current source models electron injection from light. Several elements of the solar cell contain resistive properties such as the semiconductor material itself, the metal grid which collects current from the semiconductor material, the collector bus and the internal contacts. It is
assumed that these series losses can be modeled using a lumped resistor $R_s$. Smaller $R_s$ values equate to increased solar cell efficiencies. Shunt resistor accounts for stray currents, such as recombination currents and leakage currents around the edge of devices. In this case a larger $R_{sh}$ value equates to increased solar cell efficiency, since it means that the stray currents are reduced. The value of series resistor is typically much lower than the shunt resistor.

2.3.3 Photovoltaic Modules and Arrays

The individual PV cells are connected and fitted into modules. In PV modules, multiple cells need to be connected in series or in parallel to produce enough voltage and power as shown in Figure 2.6. Traditionally, most modules had about 36 or 72 cells in series to achieve the desired output voltage. The cells are sandwiched in an inert filler between a clear front cover, usually ultraviolet resistant plastic, and a backing plate. The complete assembly is usually referred to as a module and manufacturers basically sell modules to customers. The modules serves another function of protecting individual cells from water, dust etc. as the PV cells are placed into an encapsulation of single or double flat glasses.

Figure 2.6 PV Module
When the cells are connected in series, the same current flows through all the cells and the voltage at the module terminals is the sum of the individual voltages of each cell. It is therefore, very critical for the cells to be well matched in the series string so that all cells operate at the maximum power points. In parallel connections the current will be the sum of the individual cell currents and the output voltage will be equal to that of a single cell.

A PV array is a structure that consists of a group of PV modules, mounted in a support frame with electrical connections to generate sufficient electrical power. The power capacity of the array may vary from a few hundred watts to tens of megawatts. The connection of modules in an array is similar to the connection of cells in a single module. The output voltage can be increased by series connection of modules and the current can be increased when they are connected in parallel. Very essential matching is again important for overall performance of the array. The structure of a typical array is shown in Figure 2.7.

![Figure 2.7 PV Array](image)

The performance of an array is deteriorated if all the modules are shaded since it will act as a load resulting in heat that may cause impairment. Bypass diodes are usually employed to avoid damage although they increase
the overall cost. Integration of bypass diodes in some large modules during manufacturing is not uncommon and reduces the extra wiring required.

2.4 PHOTOVOLTAIC PERFORMANCE

2.4.1 PV Characteristics

In a PV characteristics, the three classic parameters viz. open-circuit voltage ($V_{oc}$), short-circuit current ($I_{sc}$) and the maximum power point ($I_{mp}$; $V_{mp}$) are very important. Open circuit voltage is the potential that develops across PV cell terminal at which no current flows through the external circuit. It is the maximum voltage a PV cell can deliver. Similarly, the short circuit current is the current flowing with zero external resistance, and which is the maximum current delivered by the PV cell at any solar irradiance. The maximum power ($P_{max}$) that can be extracted from a PV cell are at the maximum power points ($I_{mp}$; $V_{mp}$). The classical points are shown in Figure 2.8 and are usually given as part of a manufacturer's data sheet for a PV cell as shown in Table 2.1.

![Figure 2.8 PV cell characteristics](image-url)
Another important parameter that characterizes the PV cell is called the Fill Factor (FF) or Curve Factor (CV). It is defined as the ratio of maximum power $P_{max}$ to the area of rectangle formed by $V_{oc}$ and $I_{sc}$. It is expressed as,

$$FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}}$$  (2.4)

After a simple manipulation Equation (2.4) is modified and is given in Equation (2.5).

$$V_{oc}I_{oc} \cdot FF = V_{mp}I_{mp} = P_{max}$$  (2.5)

**Table 2.1 PV characteristics provided on a datasheet**

<table>
<thead>
<tr>
<th>General Specification</th>
<th>Thermal Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Circuit Voltage ($V_{oc}$)</td>
<td>Temperature coefficient of $V_{oc}$ in V/°C</td>
</tr>
<tr>
<td>Short Circuit Current ($I_{sc}$)</td>
<td>Temperature coefficient of $I_{sc}$ in A/°C</td>
</tr>
<tr>
<td>Maximum Power ($P_{max}$)</td>
<td></td>
</tr>
<tr>
<td>Maximum Power Voltage ($V_{mp}$)</td>
<td></td>
</tr>
<tr>
<td>Maximum Power Current ($I_{mp}$)</td>
<td></td>
</tr>
<tr>
<td>Maximum System Voltage</td>
<td></td>
</tr>
</tbody>
</table>

The fill factor is a measure of the quality of a cell's semiconductor junction. When the output voltage of a PV cell is raised towards $V_{oc}$ the diode becomes increasingly forward biased, this increases the internal recombination current across the junction. It is noted that $FF$ is always $< 1$ and ranges from material to material. If the fill factor is closer to unity, the better operation of the PV cell is accomplished. Practically, for high quality cells, fill factors over 0.85 can be achieved. For typical commercial devices the value lies around 0.68.
2.4.2 Conversion Efficiency

The conversion efficiency $\eta$ of a PV cell is defined as the ratio of the generated maximum power $P_{\text{max}}$ by the PV cell to the solar power received by the cell surface $P_c$ and the expression is given in Equation (2.6).

$$\eta = \frac{V_{mp}I_{mp}}{P_c} \quad (2.6)$$

The incident power $P_c$ is equal to the irradiance of AM1.5 spectrum, normalized to 1000W/m$^2$. The incident power given in Equation (2.7) can be calculated from the spectral power density, $P(\lambda)$ at wavelength $\lambda$.

$$P_c = \int_0^\infty P(\lambda)d\lambda \quad (2.7)$$

PV cells are limited in efficiency by many losses; some of these are avoidable but others are intrinsic to the system. Some of these limits can be controlled independently, but others are complex and cannot be controlled (John Twidell and Tony Weir 2006). The conversion efficiency equation is written by taking different loss factors into account and is expressed as,

$$\eta = \frac{\int_0^{\lambda_g} P(\lambda)d\lambda \int_0^{\lambda_g} N(\lambda)d\lambda}{\int_0^{\lambda_g} P(\lambda)d\lambda} \cdot \frac{qV_{ac}}{E_g} \cdot FF \cdot (1 - \gamma) \cdot \frac{A_L}{A_{tot}} \cdot \eta_d \cdot \eta_{nl} \quad (2.8)$$

The first term $\int_0^{\lambda_g} P(\lambda)d\lambda / \int_0^{\lambda_g} P(\lambda)d\lambda$ accounts for loss due to non-absorption of long wavelengths. Photons with energy lower than the band gap energy of the semiconductor absorber cannot contribute to PV current.
generation. The term \( E_G \int_0^{\lambda_f} N(\lambda)d\lambda + \int_0^{\infty} P(\lambda)d\lambda \) accounts for loss due to thermalization of the excess energy of photons which appears as heat. The term \( qV_a/E_G \) accounts for loss due to the voltage factor. The doping levels and the recombination determine the voltage factor that is the ratio of the maximum voltage developed by the solar cell to the bandgap voltage. The maximum power generated by a solar cell is dependent on the fill factor. In practical the fill factor is lower than the ideal value due to carrier recombination, series resistance and shunt resistance losses. The preceding terms all represent fundamental losses. The remaining terms in Equation (2.8) account for losses due to limits in technology. A part of the incident energy is reflected by the surface of the cell, and this energy is not converted into usable energy. The term \( (1 - \gamma) \) accounts for loss due to the total reflection. Reflection losses can be reduced by using anti-reflective coatings and surface texturing. Term \( A_f/A_{tot} \) accounts for loss by metal electrode coverage and shading losses, where \( A_f \) is the area of the front surface not covered by metal contacts and \( A_{tot} \) is the total area. Incomplete absorption due to finite thickness is accounted for by term \( \eta_i \); special light trapping techniques are used to increase absorption. The last term \( \eta_{col} \) represents collection efficiency: Collection efficiency is defined as the proportion of radiation generated electron-hole pairs that produce the current in the external circuit.

2.5 PV MATERIAL

PV cells are basically made of semiconductor materials. Although the flat plate silicon PV cells have been the dominant commercial product, there is a great variety of alternative types and constructions. In the near future other thin film materials are likely going to transcend silicon PV cells in terms of energy conversion efficiency, manufacturing technology and
production cost. This section discusses the characteristics, advantages and limitations of the two major types of cell materials.

2.5.1 Crystalline Materials

Single-crystal silicon

Mono-crystalline silicon cells have been extensively used in the PV industry but have now been overtaken by polycrystalline silicon. The main technique for producing single-crystal silicon is the Czochralski method. Single-crystal silicon has a uniform molecular structure. Therefore, it gives higher energy conversion efficiency compared to noncrystalline materials. The conversion efficiency for single-silicon PV cells ranges between 15-20%. The greatest advantages of mono-crystalline silicon are good stability and desirable electronic, physical and chemical properties of silicon. But the manufacturing process is time consuming and costly (Tom Markvart and Luis Castaner 2003).

Poly-crystalline silicon

The production costs can be considerably reduced by using polycrystalline material (also called as multicrystalline material). Polycrystalline silicon material is stronger as compared to single-crystalline silicon, but the presence of boundaries between the crystal grains increases recombination of electron-hole pairs. Consequently polycrystalline solar cells have smaller efficiencies than single crystal material. Polycrystalline PV cells are produced by making thin wafers from blocks of cast polycrystalline silicon. The advanced ribbon growth method is also used, in which silicon is grown directly as thin ribbons or sheets. Since no sawing is needed, the manufacturing cost is lower. The energy conversion efficiency for a
commercial module made of polycrystalline silicon ranges between 10 to 14%.

**Micro-crystalline Silicon**

Micro-crystalline also known as nano-crystalline is a form of porous silicon. It is an allotropic form of silicon with para-crystalline structure. Nano-crystalline differs from poly-crystalline in a way that the former contains small grains of crystalline silicon within the amorphous phase whereas poly-crystalline consists solely of silicon crystalline grains. The factor that differentiates poly-crystalline and micro-crystalline silicon is the grain size. It has got several advantages over mono-crystalline and polycrystalline. It has got increased stability and also it is easier to fabricate.

**Gallium Arsenide (GaAs)**

This material is a compound semiconductor made of two elements: gallium (Ga) and arsenic (As). The crystal structure of GaAs is similar to that of silicon. The advantage of GaAs is that it has high level of light absorptivity. GaAs requires only a layer of few micrometers thick whereas crystalline silicon requires a wafer of about 200-300 micrometers thick to absorb the same amount of light. GaAs has higher energy conversion efficiency than silicon crystal, reaching about 25 to 30%. The main drawback of GaAs PV cells is its high cost. It is used in space applications and in concentrator systems.

**2.5.2 Thin-film Materials**

Thin film PV cells are made using very thin semiconductor layer of PV material deposited on some type of low-cost structural substrate such as glass, metal or plastic foil. Epitaxial processes such as vapour deposition,
sputter processes and electrolytic baths etc., are the common manufacturing processes. Because thin-film materials have high absorptivity, the deposited layer of PV material is extremely thin. This results in the reduction of the material cost. But cell conversion efficiency of thin film PV cells is poor due to non-single crystal structure. Thus it requires larger array areas and increases costs (Adolf Goetzbergera et al 2003). There are several types of thin-film materials.

**Amorphous silicon**

Amorphous silicon is a non-crystalline form of silicon i.e. its silicon atoms are irregular in structure. The advantage is that the light absorptivity of this material is 40 times higher than that of crystalline silicon. It can be deposited on various low cost substrates including steel, glass and plastic. The manufacturing process requires low temperature and therefore less energy. So the total material and manufacturing costs are lower. Amorphous silicon has two major drawbacks. One is low energy conversion efficiency, ranging between 5-9%, and the other is reduced efficiency with age, especially in the first few years of operation. An advantage is that the output of an amorphous silicon cells does not diminish as temperature increases.

**Cadmium Telluride (CdTe)**

This material is a poly-crystalline semiconductor compound made of cadmium (Cd) and tellurium (Te). CdTe is a direct bandgap semiconductor with $E_G = 1.5$eV which is near the optimum band gap for a solar cell. It can be deposited in thin polycrystalline films by electrodeposition. The production cost of CdTe PV cells is the lowest among the other thin-film technologies. Low-cost soda-lime glass is used as the substrate. The conversion efficiency for a CdTe PV cell is about 10%. The main disadvantage of CdTe PV cell is
performance instability. Another drawback is that cadmium is a toxic substance, which requires extra precautions during manufacturing process.

**Copper Indium Gallium Selenide (CIGS)**

CIGS is a polycrystalline semiconductor compound of copper, indium, gallium and selenium, and has been one of the major research areas in the solar industry. Thin-film cells based on this alloy have achieved close to 20% efficiency in laboratory. The energy conversion efficiency is high for this material. Also, the CIGS PV cells do not suffer from outdoor degradation problem. The absorption coefficient is also very high, with only 0.5 micrometers needed to absorb 90% of the solar spectrum. CIGS is efficient, but very complex material making it difficult to manufacture. Earlier development was based on CIS (no gallium), but its performance was limited by its low band gap. Table 2.2 shows the comparison of various PV modules.

### 2.6 Modeling and Simulation of PV Module

#### 2.6.1 PV Cell and Module Model

A general mathematical description of the I-V output characteristics is studied from literature. The equivalent circuit based model is primarily used for monitoring and evaluating the PV performance and exploring different PV MPPT techniques (Wasyczuk et al 1983 and Phang et al 1984). In order to model a PV cell, the equivalent circuit composed of photocurrent source, diode, series and parallel resistors as shown in Figure 2.5 is utilized. The voltage-current characteristic equation of a PV cell is given in Equation (2.9).

\[
I = I_p - I_0 \left( \exp \left( \frac{V + IR_s}{kT_A} \right) - 1 \right) - \frac{V + IR_s}{R_{sh}}
\]  

(2.9)
### Table 2.2 Comparison of different types of PV modules

<table>
<thead>
<tr>
<th><strong>Cell Material</strong></th>
<th><strong>Module Efficiency</strong></th>
<th><strong>Surface Area Needed for 1kWp</strong></th>
<th><strong>Cost</strong></th>
<th><strong>Additional Details</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-crystal silicon</td>
<td>15-20%</td>
<td>7-9 m²</td>
<td>Most expensive crystalline silicon</td>
<td>Most efficient PV modules, Easily available on the market, Highly standardised</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Most expensive, Waste of silicon in the production process</td>
</tr>
<tr>
<td>Poly-crystalline silicon</td>
<td>10-14%</td>
<td>8-9 m²</td>
<td>Cheapest crystalline silicon</td>
<td>Less energy and time needed for production than for single crystalline cells, Highly standardised</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Slightly less efficient than single crystalline cells</td>
</tr>
<tr>
<td>Micro-crystalline Silicon</td>
<td>7-10%</td>
<td>9-12 m²</td>
<td>Cheaper</td>
<td>High Stability, Easier to fabricate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>More space is required</td>
</tr>
<tr>
<td>Gallium Arsenide (GaAs)</td>
<td>25-30%</td>
<td>4-7 m²</td>
<td>Very Expensive</td>
<td>Higher energy conversion efficiency</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Very high cost</td>
</tr>
<tr>
<td>Amorphous silicon</td>
<td>5-9%</td>
<td>13-20 m²</td>
<td>Cheaper than crystalline silicon</td>
<td>Easy manufacturing process</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>It degrades under sun exposure, More space is required</td>
</tr>
<tr>
<td>Cadmium Telluride (CdTe)</td>
<td>7-11%</td>
<td>11-13 m²</td>
<td>Cheaper than crystalline silicon</td>
<td>Most cost-effective thin film technology</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Performance instability</td>
</tr>
<tr>
<td>Copper Indium Gallium Selenide (CIGS)</td>
<td>8-12%</td>
<td>9-11 m²</td>
<td>Cheaper than crystalline silicon</td>
<td>Free from outdoor degradation problems</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>More space is required</td>
</tr>
</tbody>
</table>
The photo current mainly depends on the solar radiant intensity and cell’s temperature, which is given in Equation (2.10).

\[ I_p = [I_{sc} + K_r (T_c - T_{ref})]G \]  

(2.10)

The cell’s saturation current given in Equation (2.11) varies with temperature.

\[ I_s = I_{s0} \left( \frac{T_c}{T_{ref}} \right)^3 \exp \left[ \frac{qE_G}{kA_f} \left( \frac{1}{T_{ref}} - \frac{1}{T_c} \right) \right] \]  

(2.11)

In a PV module several PV cells are connected electrically in series and parallel circuits to generate the required current and voltage. The equivalent circuit of the PV module with \( N_p \) number of parallel cells and \( N_s \) number of series cells is shown in Figure 2.9.

**Figure 2.9 Equivalent circuit of generalized PV module**

In order to model a PV module, an assumption is made that the current and voltage characteristics of each cell in the module is uniform. This assumption is taken for two reasons: First, it ensures the bypass diodes will be
reverse biased and treated as open circuits and the blocking diode is forward biased and is treated as a short. Second, it ensures that the exponential expression (2.9) may be scaled in a linear manner based on the series and parallel connection of cells because the parameters in the exponent will be identical for each cell. Now, with this assumption, a module can be simply represented as an $N_s \times N_p$ grid of cells.

The terminal equation for the current and voltage of the module is given in Equation (2.12).

$$I = N_p I_p - N_p I_s \left( \exp \left( \frac{V + IR_s}{N_s \frac{N_p}{kT_s A_d}} \right) \right) - 1 - \left( \frac{N_p V}{N_s} + \frac{IR_{sh}}{R_{sh}} \right) \quad (2.12)$$

The efficiency of the PV array is sensitive to small changes in series resistance but insensitive to variation in shunt resistance. So the series resistance becomes apparently important and the shunt resistance approaches infinity which is assumed to be open (Altas and Sharaf 2007 and Huan- Liang Tsai et al 2008). Commercially, PV cells are connected in series to form a PV module to obtain the desired voltage. These PV modules are then arranged in series-parallel structure to achieve the necessary power.

Equation (2.12) represents the five parameter model of single diode equivalent circuit. Some authors have proposed different models that present better accuracy and serve for different purposes. Gow and Manning 1999, Hyvarinen and Karila 2003, Pongratanakul and Kasparis 2004, Chowdhury et al 2007 have used an extra diode to represent the effect of recombination of carriers. A three diode model is proposed by Nishioka et al 2007 to include the influence of the effects that are not considered by the previous model. For
simplicity and reasonably good accuracy a single diode model of Figure 2.5 is considered for the present work. This model offers a good compromise between simplicity and accuracy (Vitorino et al 2007) and has been used by several other investigators, sometimes with simplifications but always with the same basic structure (Hiren Patel and Agarwal 2008, Eftichios Koutroulis et al 2009, Veerachary 2006, Geoff Walker 2001).

2.6.2 Determination of Model Parameters

The parameters in the model can be determined by examining the manufacturer’s specifications of PV products. The most significant parameters used to depict the PV cell electrical performance is its open-circuit voltage \( V_{oc} \) and short-circuit current \( I_{sc} \). The mathematical expressions obtained for the PV are implicit and nonlinear; therefore, it is difficult to arrive at an analytical solution for a set of model parameters at a specific temperature and irradiance (Tiwari 2002). Usually the photo current is much greater than cell’s saturation current. If the small diode and ground-leakage currents under zero-terminal voltage are ignored, the short-circuit current \( I_{sc} \) is approximately equal to the photocurrent \( I_p \).

The open circuit voltage \( V_{oc} \) is obtained by assuming the output current zero. Given the PV open-circuit voltage \( V_{oc} \) at reference temperature and ignoring the shunt-leakage current, the reverse saturation current at reference temperature can be approximately obtained as given in Equation (2.13)

\[
I_{rs} = I_{sc} \left( \exp \left[ \frac{qV_{oc}}{N_e k A_T} \right] - 1 \right)
\]  

(2.13)
2.6.3 MatLab Model and Simulation Results

The MatLab/Simulink software is used for the modeling and simulation purposes. This software contains all the electrical and mathematical blocks to develop the PV array model. Also, this software is very easy to use, and has many features of graphical user interface pertaining to building or modeling the circuits or mathematical equations. A generalized PV model is built using this software to illustrate and verify the nonlinear I-V and P-V output characteristics of PV module. The simulation model is shown in Figure A1.1.

The SOLKAR PV module is selected for modeling; since it is well suited for most of the practical applications of photovoltaics. The SOLKAR PV module provides 37W of nominal maximum power, and has 36 series connected monocrystalline silicon cells. The key specifications of this module are shown in Table 2.2.

Table 2.3 Electrical Characteristics of SOLKAR PV Module

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power</td>
<td>$P_{max}$</td>
<td>37.08 W</td>
</tr>
<tr>
<td>Voltage at maximum power</td>
<td>$V_{mp}$</td>
<td>16.48 V</td>
</tr>
<tr>
<td>Current at maximum power</td>
<td>$I_{mp}$</td>
<td>2.25 A</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>$I_{sc}$</td>
<td>2.55 A</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>$V_{oc}$</td>
<td>21.24 V</td>
</tr>
<tr>
<td>Size of solar module</td>
<td></td>
<td>990 mm x 440 mm</td>
</tr>
<tr>
<td>Number of series cells</td>
<td>$N_p$</td>
<td>36</td>
</tr>
</tbody>
</table>

Both I-V and P-V output characteristics of the Solkar PV module are shown in Figures 2.10 and 2.11. These non linear output characteristics
are obtained at the standard solar irradiance of 1000W/m² and temperature of 25°C. The output current and power of PV module depend on the cell’s terminal operating voltage and temperature, and solar irradiance as well. The model of PV module is simulated to obtain the output characteristics for various irradiance levels keeping the temperature constant and the curves are shown in Figures 2.12 and 2.13. It is observed from these curves that with increase in solar irradiance, both the short-circuit current of the PV module and the maximum power output are increased. The reason is the open-circuit voltage is logarithmically dependent on the solar irradiance, but the short-circuit current is directly proportional to it. On the other hand, the simulated I-V and P-V characteristics of the PV module for several temperatures are shown in Figures 2.14 and 2.15. It is found that with increase of working temperature, the short-circuit current of the PV module increases, whereas the maximum power output decreases. The increase in the short-circuit current is much less than the decrease in the open-circuit voltage, and the effect makes maximum power decreasing at high temperatures.

![I-V curve](image)

**Figure 2.10 MatLab model I-V curve (G=1000W/m², T_{c}=25°C)**
Figure 2.11 MatLab model P-V curve ($G=1000\text{W/m}^2$, $T_e=25^\circ\text{C}$)

Figure 2.12 MatLab model I-V curves for various solar irradiance levels
Figure 2.13 MatLab model P-V curves for various solar irradiance levels

Figure 2.14 MatLab model I-V curves for various temperatures
Figure 2.15 MatLab model P-V curves for various temperatures

2.7 VALIDATING THE MODEL

Due to randomly changing environmental conditions, it is very difficult to use voltmeter-ammeter method to draw the characteristics of the PV module. Several systems for measuring I-V characteristic of solar modules have been proposed. They use adjustable resistance (http://emsoar.ee.tuberlin.de/lehre/english/pv1/index.html), programmable electronic load (http://www.pvmeas.com/ivtester.html), active load (Benson et al 2004) or capacitors for variable load (Recart et al 2006). It is required to develop a simple, inexpensive and automatic I-V characteristic measurement system.

A simple and novel method to quickly draw the characteristics of the PV module under field conditions is proposed in this work. The schematic of the proposed plotter is shown in Figure 2.16. The op-amp, the MOSFET and the resistor $R_{\text{sense}}$ have been so connected that the current of the solar panel is proportional to the voltage applied to the non-inverting part of the op-amp. A linear MOSFET (IRF 150/ IRF 460) is used as a load resistance
(Yingying Kuai and Yuvarajan 2006). A low frequency wave signal is used as the driving pulse and is applied at gate-source port of the MOSFET. For good results, the gate signal should be large enough to cover the entire range of the panel current from open circuit to short circuit. If a general purpose cathode ray oscilloscope (CRO) is used then the voltage applied to non-inverting terminal of the op-amp should be repetitive to observe a steady pattern. When the panel current varies from zero to maximum, the full characteristic is drawn and the same characteristic is retraced when the current varies from maximum to zero. Due to large capacitance between the cells and Earth, the retraced pattern does not exactly follow the earlier pattern and therefore two characteristics are seen on the screen of CRO. As low frequency signal is applied at non-inverting terminal of the op-amp, to minimize the current flow in the capacitance. A signal frequency of 1 Hz was therefore used. For uniform intensity of the trace on the CRO screen, the slope of the trigger should be constant. Therefore triangular wave has been used. The hardware set up of the electronic load is shown in Figure A2.1.

![Diagram](image_url)

**Figure 2.16 Schematic of the proposed electronic load**

In this work, Digital Storage Oscilloscope (DSO) has been used therefore repetitive trigger signal is not required and only a slow changing
ramp signal to change the current from zero to short circuit value or beyond will be sufficient to plot the complete characteristic. For equidistant samples, a linear slope has been used. Figure 2.17 shows the sample snap shot of the CRO screen describing the I-V characteristics of the module. GWINSTEK GDS-1022 Digital Storage Oscilloscope is used to trace the practical characteristics. It is calibrated using Fluke 5500A Multi-Product Calibrator.

The practical characteristics of PV module are easily traced out for different solar irradiance levels and temperatures using proposed electronic load method and the relevant data traced by the DSO are stored in Excel spreadsheet for comparison of model parameters. Solar irradiance level of 1000 W/m² corresponds to a short circuit current of 2.55A as per the data sheet of SOLKAR modules. In all experiments the solar irradiance has been measured as proportional to short circuit current. It is observed that experimental and model derived characteristic closely match at remarkable points. The five suggested points of the model (Engin Karatepe 2006) against the practical characteristics are checked to know the suitability and accuracy of the developed model. These are presented in Table 2.3.

![Figure 2.17 Sample snap shot of DSO Screen](image)

Figure 2.17 Sample snap shot of DSO Screen
Table 2.4 Comparison of PV model values with practical values at remarkable points

<table>
<thead>
<tr>
<th>Remarkable voltage points</th>
<th>Current in amperes at $T_e = 30^\circ$C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( G = 1000 \text{ W/m}^2 )</td>
</tr>
<tr>
<td></td>
<td>( G = 750 \text{ W/m}^2 )</td>
</tr>
<tr>
<td></td>
<td>Model</td>
</tr>
<tr>
<td>( V=0 )</td>
<td>2.55</td>
</tr>
<tr>
<td>( V=0.5 \ V_{oc} )</td>
<td>2.49</td>
</tr>
<tr>
<td>( V=V_{mp} )</td>
<td>2.25</td>
</tr>
<tr>
<td>( V=0.5(V_{oc}+V_{mp}) )</td>
<td>1.65</td>
</tr>
<tr>
<td>( V=V_{oc} )</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Remarkable voltage points</th>
<th>Current in amperes at $T_e = 30^\circ$C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( G = 498 \text{ W/m}^2 )</td>
</tr>
<tr>
<td></td>
<td>( G = 245 \text{ W/m}^2 )</td>
</tr>
<tr>
<td></td>
<td>Model</td>
</tr>
<tr>
<td>( V=0 )</td>
<td>1.27</td>
</tr>
<tr>
<td>( V=0.5 \ V_{oc} )</td>
<td>1.24</td>
</tr>
<tr>
<td>( V=V_{mp} )</td>
<td>1.12</td>
</tr>
<tr>
<td>( V=0.5(V_{oc}+V_{mp}) )</td>
<td>0.79</td>
</tr>
<tr>
<td>( V=V_{oc} )</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Remarkable voltage points</th>
<th>Current in amperes at ( G = 985 \text{ W/m}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( T_e = 34^\circ )</td>
</tr>
<tr>
<td></td>
<td>( T_e = 42^\circ )</td>
</tr>
<tr>
<td></td>
<td>( T_e = 59^\circ )</td>
</tr>
<tr>
<td></td>
<td>Model</td>
</tr>
<tr>
<td>( V=0 )</td>
<td>2.56</td>
</tr>
<tr>
<td>( V=0.5 \ V_{oc} )</td>
<td>2.49</td>
</tr>
<tr>
<td>( V=V_{mp} )</td>
<td>2.27</td>
</tr>
<tr>
<td>( V=0.5(V_{oc}+V_{mp}) )</td>
<td>1.68</td>
</tr>
<tr>
<td>( V=V_{oc} )</td>
<td>0</td>
</tr>
</tbody>
</table>
The developed model agrees very accurately with the experimental set of readings at remarkable points.

2.8 SUMMARY

Distinct advantages to solar energy, such as zero pollution and absence of the need to transport fuel to the generating site, make it attractive in many applications. The efficiency improvements and manufacturing cost reductions will move solar power toward economic parity with conventional power. The mathematical expressions describe the behavior of a PV cell and help to understand the basic processes behind the operation. In this chapter, a generalized model of PV module has been presented and simulated in MatLab for a typical module. The model took solar irradiance and cell temperature as input parameters and outputs the I-V and P-V. A novel electronic load circuit has been developed so that the characteristic can be drawn quickly and data stored before any change in solar irradiance level and/or temperature occur. This electronic load method has been utilized for determining the parameters of the model experimentally. This method is a better circuit for displaying and recording of the characteristic in field conditions as compared to other known circuits. This chapter provides the information to easily develop the PV array model that can be interfaced with power electronics circuits.