ISLAMIC UNIVERSITY OF TECHNOLOGY (IUT)
THE ORGANIZATION OF THE ISLAMIC CONFERENCE (OIC)

STUDY OF TEMPERATURE EFFECT ON PV CELL USING MATLAB/SIMULINK

BY

MD. TANZIN FARHAT (112465)

MD. ASHFAQUE RAHMAN (112470)

SYED MAHMUDUL HASAN (112476)

Submitted for the Degree of

Bachelor of Science in

Electrical & Electronic Engineering

November 2015

Study of Temperature Effect on PV Cell Using MATLAB/SIMULINK

A thesis submitted to the department of Electrical & Electronic Engineering of Islamic University of Technology in partial fulfillment of the requirement for the degree of

BACHELOR OF SCIENCE IN ELECTRICAL & ELECTRONIC ENGINEERING

Prepared by-

Md. Tanzin Farhat (112465)

Md. Ashfaque Rahman (112470)

Syed Mahmudul Hasan (112476)

Supervised by-

Mr. Muhammad

Assistant Professor

EEE Department

IUT, Bangladesh

CERTIFICATE OF APPROVAL

The thesis titled **'Study of Temperature Effect on PV Cell Using MATLAB/SIMULINK'** submitted by Md. Tanzin Farhat (112465), Md. Ashfaque Rahman (112470), Syed Mahmudul Hasan (112476) of academic year 2014-15 has been found as satisfactory and accepted as partial fulfillment of the requirement for the Degree of BACHELOR OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING.

Thesis Supervisor:

____

Mr. Muhammad

Assistant Professor

Electrical and Electronic Engineering Department

Islamic University of Technology (IUT), Gazipur.

Head of the Department:

____

Prof. Dr. Md. Shahid Ullah

Head

Electrical and Electronic Engineering Department

Islamic University of Technology (IUT), Gazipur

Declaration of Candidate

It is hereby declared that this thesis report or any part of it has not been submitted elsewhere for the award of any Degree or Diploma.

Md. Tanzin Farhat

Student No.: 112465

Academic Year: 2014-2015

Md. Ashfaque Rahman

Student No.: 112470

Academic Year: 2014-2015

Syed Mahmudul Hasan

Student No.: 112476

Academic Year: 2014-2015

Dedicated to our parents.

Table of Contents

Certificate of Approval III

Declaration of Candidate IV

Dedication V

List of Figures VIII

List of Tables VIII

Symbols & Abbreviations IX

Acknowledgements X

Abstract XI

Chapter 1- Introduction 1

1.1 Research Introduction 1

1.2 Research Motivation 2

1.3 Research Outline 2

Chapter 2- Background Information 3

2.1 Solar energy 3

2.2 Solar cell history 5

2.3 Properties of light 5

2.4 Energy of photon 7

2.5 The sun 9

2.6 Solar radiation at the earth's surface 11

2.7 Measurement of solar radiation 12

Chapter 3- Semiconductor 14

3.1 Semiconductor structure 14

3.2 Conduction in semiconductors 15

3.3 Band gap 16

3.4 Doping 17

Chapter 4- Solar Cell 18

4.1 Solar Cell Structure 18

4.2 Light Generated Current 19

4.3 Principle of Operation 20

4.4 Important Quantities 22

4.5 Solar Photovoltaic Module 25

4.6 Equivalent Circuit of a PV Cell 25

Chapter 5- Software Simulation 26

5.1 MATLAB Code 26

5.2 Simulink Model 28

Chapter 6- Results & Discussions 29

6.1 Characteristics Curve 29

6.2 Effect of Varying Solar Irradiance 30

6.3 Effect of Cell Temperature Variation 32

6.4 Effect of Varying R_s 33

6.5 Effect of Varying R_{sh} 35

6.6 Electrical Specification of the Test Panel 36

Chapter 7- Summary 37

7.1 Overview of the Work 37

7.2 Future Work 37

7.3 Conclusion 38

Bibliography 39

List of Figures

Fig. 2.1: Solar powered light house at Montague Island 4
Fig. 2.2: Spectrum of Light 6
Fig. 2.3: Surface properties of the SUN 9
Fig. 2.4: Different wavelengths of Sunlight 10
Fig. 2.5: The Earth's Surface 11
Fig. 2.6: Solar radiation measurement 12

Fig. 3.1: Semiconductor Structure 14
Fig. 3.2: Band Gap 16
Fig. 3.3: Doping 17

Fig. 4.1: Cross section of a solar cell 18
Fig. 4.2: The ideal short circuit flow of electrons and holes at a *p-n* junction 19
Fig. 4.3: Operation of a p-n junction 20
Fig. 4.4: Close-up of a PV Cell 21
Fig. 4.5: PV cell equivalent circuit 25

Fig. 5.1: MATLAB/Simulink Based block diagram of PV Cell 28

Fig. 6.1: I-V curve for a PV cell 29
Fig. 6.2: P-V curve for a PV cell 29
Fig. 6.3: I-V curve for varying solar irradiance 30
Fig. 6.4: P-V curve for varying solar irradiance 31
Fig. 6.5: I-V curve for varying cell temperature 32
Fig. 6.6: P-V curve for varying cell temperature 33
Fig. 6.7: I-V curve for varying R_s 34
Fig. 6.8: P-V curve for varying R_s 34
Fig. 6.9: I-V curve for varying R_{sh} 35
Fig. 6.10: P-V curve for varying Rsh 36

List of Tables

Table 6.1: Electrical Specification of Tata Solar Gold 40 Series 36

Symbols & Abbreviations

I	Current (A)
I_L	Photocurrent (A)
I_F	Forward current (A)
I_S	Saturation current (A)
n	Ideality factor
k	Boltzmann constant (JK^{-1})
T	Absolute temperature (K)
q	Charge of an electron (C)
I_{sc}	Short-circuit current (A)
V_{oc}	Open-circuit voltage (V)
P_m	Maximum output power (W)
V_m	Voltage at maximum power point (V)
I_m	Current at maximum power point (A)
FF	Fill Factor
V_{ocn}	Normalized open-circuit voltage (V)
η	Energy conversion efficiency (%)
E	Solar irradiance (W/cm^2)
A	Area of the solar cell (cm^2)
J_{sc}	Short-circuit current density (A/cm^2)

Acknowledgements

We are grateful to our thesis supervisor, Mr. Muhammad, for his continuous guidance and motivation in completing our thesis. His constant demand for making the work more and more elaborate finally resulted in satisfactory outcomes. We extend our gratitude to all faculty members of EEE department of IUT, OIC for being sources of inspiration and guidance.

Abstract

Solar cell performance decreases with increasing temperature, fundamentally owing to increased internal carrier recombination rates, caused by increased carrier concentrations. The operating temperature plays a key role in the photovoltaic conversion process. Both the electrical efficiency and the power output of a photovoltaic (PV) module depend linearly on the operating temperature. The various correlations proposed in the literature represent simplified working equations which can be apply to PV modules or PV arrays mounted on free-standing frames, PV-Thermal collectors, and building integrated photovoltaic arrays, respectively. The electrical performance is primarily influenced by the material of PV used. Numerous correlations for cell temperature which have appeared in the literature involve basic environmental variables and numerical parameters which are material or system dependent. In this paper, a brief discussion is presented regarding the operating temperature of one-sun commercial grade silicon- based solar cells/modules and its effect upon the electrical performance of photovoltaic installations. Generally, the performance ratio decreases with latitude because of temperature. However, regions with high altitude have higher performance ratios due to low temperature, like, southern Andes, Himalaya region, and Antarctica. PV modules with less sensitivity to temperature are preferable for the high temperature regions and more responsive to temperature will be more effective in the low temperature regions. The geographical distribution of photovoltaic energy potential considering the effect of irradiation and ambient temperature on PV system performance is considered.

Chapter 1- Introduction

1.1 Research Introduction

Photovoltaic is the process of converting sunlight directly into electricity using solar cells. Today it is a rapidly growing and increasingly important renewable alternative to conventional fossil fuel electricity generation, but compared to other electricity generating technologies, it is a relative newcomer, with the first practical photovoltaic devices demonstrated in the 1950s. Research and development of photovoltaic received its first major boost from the space industry in the 1960s which required a power supply separate from "grid" power for satellite applications. These space solar cells were several thousand times more expensive than they are today and the perceived need for an electricity generation method apart from grid power was still a decade away, but solar cells became an interesting scientific variation to the rapidly expanding silicon transistor development with several potentially specialized niche markets. It took the oil crisis in the 1970s to focus world attention on the desirability of alternate energy sources for terrestrial use, which in turn promoted the investigation of photovoltaic as a means of generating terrestrial power. Although the oil crisis proved short-lived and the financial incentive to develop solar cells abated, solar cells had entered the arena as a power generating technology. Their application and advantage to the "remote" power supply area was quickly recognized and prompted the development of terrestrial photovoltaic industry. Small scale transportable applications (such as calculators and watches) were utilized and remote power applications began to benefit from photovoltaic.

In the 1980s research into silicon solar cells paid off and solar cells began to increase their efficiency. In 1985 silicon solar cells achieved the milestone of 20% efficiency. Over the next decade, the photovoltaic industry experienced steady growth rates of between 15% and 20%, largely promoted by the remote power supply market. The year 1997 saw a growth rate of 38% and today solar cells are recognized not only as a means for providing power and increased quality of life to those who do not have grid access, but they are also a means of significantly diminishing the impact of environmental damage caused by conventional electricity generation in advanced industrial countries.

The increasing market for, and profile of photovoltaic means that more applications than ever before are "photovoltaically powered". These applications range from power stations of several megawatts to the ubiquitous solar calculators. PVCDROM aims to provide an overview of terrestrial photovoltaic to furnish the non-specialist with basic information. It is hoped that having used PVCDROM you will understand the principles of photovoltaic devices and system operation, you will be able to identify appropriate applications, and you will be capable of undertaking photovoltaic system design. By gradually increasing the number of people who are familiar with photovoltaic concepts and applications, we hope to increase the use of photovoltaic in appropriate applications.

1.2 Research Motivation

The main motivation of this study is to understand the temperature effect on a photovoltaic cell. As we know solar panel efficiency is affected negatively by temperature increases. As the temperature of the solar panel increases, its output current increases exponentially, while the voltage output is reduced linearly. In fact, the voltage reduction is so predictable, that it can be used to accurately measure temperature. As a result, heat can severely reduce the solar panel's production of power. If we understand the behavior of temperature effect on the photovoltaic cell, it will help a lot to increase the efficiency of photovoltaic cell output.

1.3 Research Outline

In our study we tried to determine the temperature effect on photovoltaic cells. For this purpose we have considered TATA SOLAR GOLD 40 SERIES as our base model using MATLAB/Simulink. We have implemented different real time scenario in the MATLAB such as Characteristics curve, Effect of varying Solar Irradiance, Effect of cell Temperature Variation, Effect of varying Rs and Effect of varying Rsh and finally generated the ouput curve for both Current versus Voltage and Power versus Voltage curve.

Chapter 2- Background Information

2.1 Solar Energy

Solar energy in one form or another is the source of nearly all energy on the earth [1, 2]. Humans, like all other animals and plants, rely on the sun for warmth and food. However, people also harness the sun's energy in many other different ways. For example, fossil fuels, plant matter from a past geological age, is used for transportation and electricity generation and is essentially just stored solar energy from millions of years ago. Similarly, biomass converts the sun's energy into a fuel, which can then be used for heat, transport or electricity. Wind energy, used for hundreds of years to provide mechanical energy or for transportation, uses air currents that are created by solar heated air and the rotation of the earth. Today wind turbines convert wind power into electricity as well as its traditional uses. Even hydroelectricity is derived from the sun. Hydropower depends on the evaporation of water by the sun, and its subsequent return to the Earth as rain to provide water in dams. Photovoltaic (often abbreviated as PV) is a simple and elegant method of harnessing the sun's energy. PV devices (solar cells) are unique in that they directly convert the incident solar radiation into electricity, with no noise, pollution or moving parts, making them robust, reliable and long lasting. Solar cells are based on the same principles and materials behind the communications and computer revolutions, and this thesis covers the operation, principles and important parameters of photovoltaic cells.

Fig. 2.1: Solar powered light house at Montague Island, a National Parks and Wildlife sanctuary on the East coast of Australia. The small panel on the left powers the light house. The large panel on the right powers the cottages which can partially be seen in the background. The cottages contain facilities for the National Parks' caretaker and facilities for researchers on the island.

2.2 Solar Cell History

Solar cells are semiconductor devices which convert incident light into electricity by the absorption of photons and subsequent generation of electron-hole pairs. This effect of electricity generation from light absorption, which is known as the photovoltaic effect, was first observed by the French physicist A. E. Becquerel in 1839 [3]. The first solid-state photovoltaic cell was built many years later, by Charles Fritts, in 1883. He coated Selenium (Se) with an extremely thin layer of gold to form the junction. The photovoltaic device was less than 1% efficient [4]. The first practical photovoltaic cell was developed in 1954 at Bell Laboratories [5] by the three scientists- Daryl Chapin, Calvin Souther Fuller and Gerald Pearson. They used a diffused Silicon p-n junction that achieved 6% efficiency.

At present, solar cells are built with many different technologies, and the efficiency level that these devices can achieve is pretty good. In today's world, we have bulk Si solar cells, we have thin film solar cells fabricated from Si or CdTe, we have dye-sensitized solar cells, and so on. There are even more advanced concept solar cells like Quantum Dot (QD) solar cells, hot carrier solar cells etc. Today, solar cells are used for mass generation of electricity. The added advantage of solar power plants is that they require minimum maintenance, and the input energy is clean and free.

2.3 Properties of Light

The light that we see every day is only a fraction of the total energy emitted by the sun incident on the earth. Sunlight is a form of "electromagnetic radiation" and the visible light that we see is a small subset of the electromagnetic spectrum shown at the right.

The electromagnetic spectrum describes light as a wave which has a particular wavelength. The description of light as a wave first gained acceptance in the early 1800's when experiments by Thomas Young, François Arago, and Augustin Jean Fresnel showed interference effects in light beams, indicating that light is made of waves. By the late 1860's light was viewed as part of the electromagnetic spectrum. However, in the late 1800's a problem with the wave-based view of light became apparent when experiments measuring the spectrum of wavelengths from heated objects could not be explained using the wave-based equations of light. This discrepancy was resolved by the works of [6] in 1900, and [7] in 1905. Planck proposed that the total energy of light is made up of indistinguishable energy elements, or a quanta of energy. Einstein, while examining the photoelectric effect (the release of electrons from certain metals and semiconductors when struck by light), correctly distinguished the values of these quantum energy elements. For their work in this area Planck and Einstein won the Nobel Prize for physics in 1918 and 1921, respectively and based on this work, light may be viewed as consisting of "packets" or particles of energy, called photons.

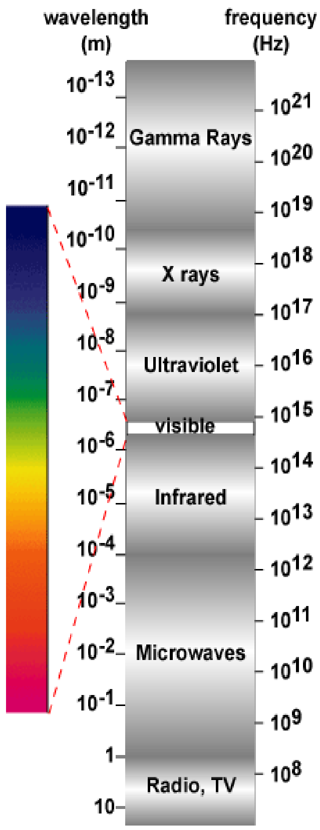

Fig. 2.2: Spectrum of Light

Today, quantum-mechanics explains both the observations of the wave nature and the particle nature of light. In quantum mechanics, a photon, like all other quantum-mechanical particles such as electrons, protons etc., is most accurately pictured as a "wave-packet". A wave packet is defined as a collection of waves which may interact in such a way that the wave-packet may either appear spatially localized (in a similar fashion as a square wave which results from the addition of an infinite number of sine waves), or may alternately appear simply as a wave. In the cases where the wave-packet is spatially localized, it acts as a particle. Therefore, depending on the situation, a photon may appear as either a wave or as a particle and this concept is called "wave-particle duality".

A complete physical description of the properties of light requires a quantum-mechanical analysis of light, since light is a type of quantum-mechanical particle called a photon. For photovoltaic applications, this level of detail is seldom required and therefore only a few sentences on the quantum nature of light are given here. However, in some situations (fortunately, rarely encountered in PV systems), light may behave in a manner which seems to defy common sense, based on the simple explanations given here. The term "common sense" refers to our own observations and cannot be relied on to observe the quantum-mechanical effects because these occur under conditions outside the range of human observation. For further information on the modern interpretation of light please refer to [3].

There are several key characteristics of the incident solar energy which are critical in determining how the incident sunlight interacts with a photovoltaic converter or any other object. The important characteristics of the incident solar energy are:

- The spectral content of the incident light;
- The radiant power density from the sun;
- The angle at which the incident solar radiation strikes a photovoltaic module; and
- The radiant energy from the sun throughout a year or day for a particular surface.

2.4 Energy of Photon

A photon is characterized by either a wavelength, denoted by λ or equivalently an energy, denoted by E. There is an inverse relationship between the energy of a photon (E) and the wavelength of the light (λ) given by the equation:

$$E = hc\lambda$$

Where h is Planck's constant and c is the speed of light. The value of these and other commonly used constants is given in the constants page.

$$h = 6.626 \times 10^{-34} \text{ joules-s}, \; c = 2.998 \times 10^{8} \text{ m/s}$$

By multiplying to get a single expression,

$$hc = 1.99 \times 10^{-25} \text{ joules-m}$$

The above inverse relationship means that light consisting of high energy photons (such as "blue" light) has a short wavelength. Light consisting of low energy photons (such as "red" light) has a long wavelength.

When dealing with "particles" such as photons or electrons, a commonly used unit of energy is the electron-volt (eV) rather than the joule (J). An electron volt is the energy required to raise an electron through 1 volt, thus a photon with an energy of **1 eV = 1.602 × 10^{-19} J**.

Therefore, we can rewrite the above constant for *hc* in terms of eV:

$$hc = (1.99 \times 10^{-25} \text{ joules-m}) \times (1\text{ev}/1.602 \times 10^{-19} \text{ joules}) = 1.24 \times 10^{-6} \text{ eV-m}$$

Further, we need to have the units be in µm (the units for λ):

$$hc = (1.24 \times 10^{-6} \text{ eV-m}) \times (10^{6} \text{ µm/ m}) = 1.24 \text{ eV-µm}$$

By expressing the equation for photon energy in terms of eV and µm we arrive at a commonly used expression which relates the energy and wavelength of a photon, as shown in the following equation:

$$E \text{ (eV)} = 1.24\lambda \text{ (µm)}$$

The exact value of 1 × 10^{6}(hc/q) is 1.2398 but the approximation 1.24 is sufficient for most purposes.

2.5 The SUN

The sun is a hot sphere of gas whose internal temperatures reach over 20 million degrees kelvin due to nuclear fusion reactions at the sun's core which convert hydrogen to helium. The radiation from the inner core is not visible since it is strongly absorbed by a layer of hydrogen atoms closer to the sun's surface. Heat is transferred through this layer by convection [8].

The surface of the sun, called the photosphere, is at a temperature of about 6000K and closely approximates a blackbody (see graph). For simplicity, the 6000 K spectrum is commonly used in detailed balance calculations but temperatures of 5762 ± 50 K Backus1976 and 5730 ± 90 K Parrott1993 have also been proposed as a more accurate fit to the sun's spectrum.

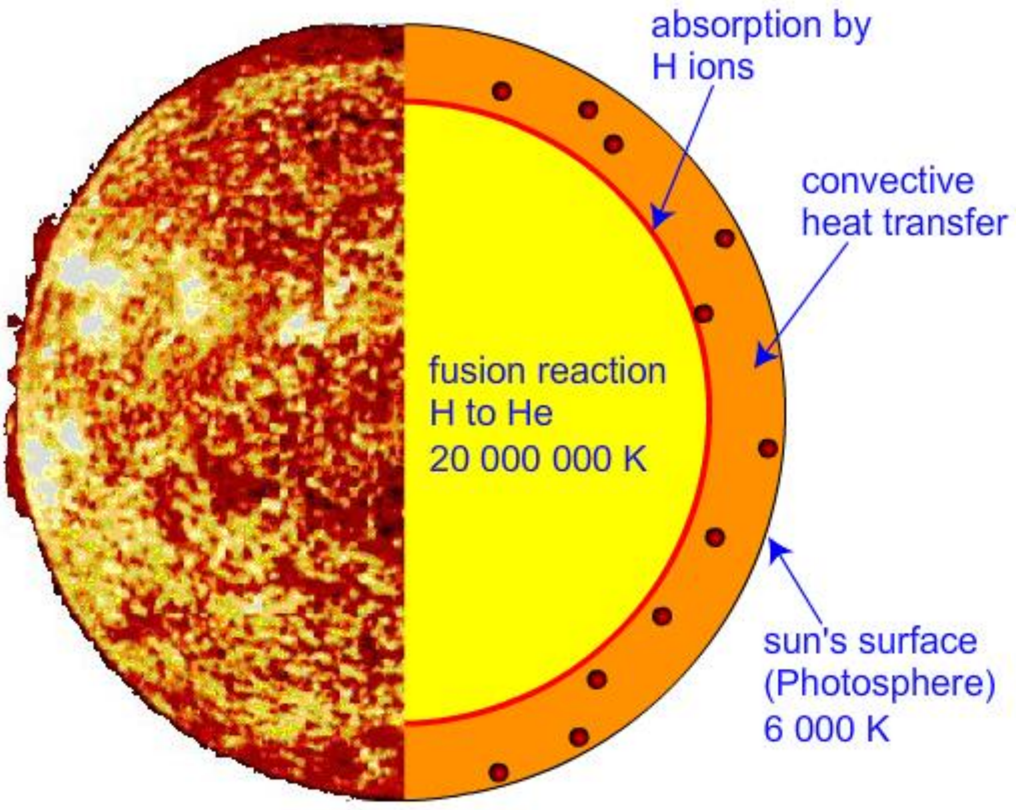

Fig. 2.3: Surface properties of the SUN

The total power emitted by the sun is calculated by multiplying the emitted power density by the surface area of the sun which gives 9.5 x 10^{25} W.

The total power emitted from the sun is composed not of a single wavelength, but is composed of many wavelengths and therefore appears white or yellow to the human eye. These different wavelengths can be seen by passing light through a prism, or water droplets in the case of a rainbow. Different wavelengths show up as different colors, but not all the wavelengths can be seen since some are "invisible" to the human eye.

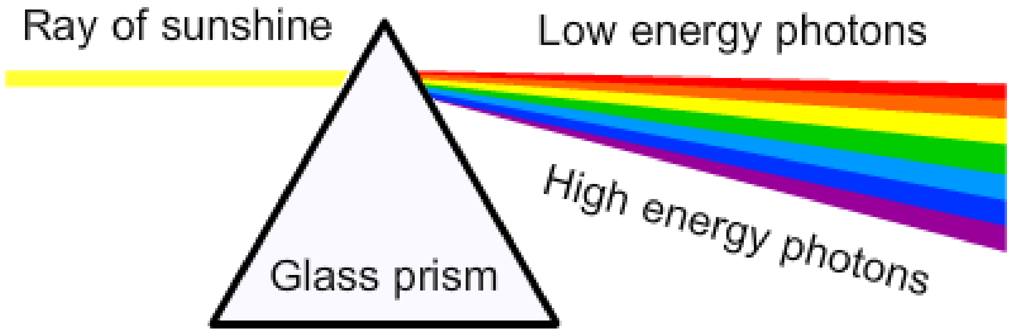

Fig. 2.4: Different wavelengths of Sunlight

2.6 Solar Radiation at the Earth's Surface

While the solar radiation incident on the Earth's atmosphere is relatively constant, the radiation at the Earth's surface varies widely due to:

- Atmospheric effects, including absorption and scattering;
- Local variations in the atmosphere, such as water vapors, clouds, and pollution;
- Latitude of the location; and
- The season of the year and the time of day.

The above effects have several impacts on the solar radiation received at the Earth's surface. These changes include variations in the overall power received, the spectral content of the light and the angle from which light is incident on a surface. In addition, a key change is that the variability of the solar radiation at a particular location increases dramatically. The variability is due to both local effects such as clouds and seasonal variations, as well as other effects such as the length of the day at a particular latitude. Desert regions tend to have lower variations due to local atmospheric phenomena such as clouds. Equatorial regions have low variability between seasons.

The amount of energy reaching the surface of the Earth every hour is greater than the amount of energy used by the Earth's population over an entire year.

Fig. 2.5: The Earth’s Surface

2.7 Measurement of Solar Radiation

In PV system design it is essential to know the amount of sunlight available at a particular location at a given time. The two common methods which characterize solar radiation are the solar radiance (or radiation) and solar insolation. The solar radiance is an instantaneous power density in units of kW/m^2. The solar radiance varies throughout the day from 0 kW/m^2 at night to a maximum of about 1 kW/m^2. The solar radiance is strongly dependent on location and local weather. Solar radiance measurements consist of global and/or direct radiation measurements taken periodically throughout the day. The measurements are taken using either a pyrometer (measuring global radiation) and/or a pyrheliometer (measuring direct radiation). In well-established locations, this data has been collected for more than twenty years.

An alternative method of measuring solar radiation, which is less accurate but also less expensive, is using a sunshine recorder. These sunshine recorders (also known as Campbell-Stokes recorders), measure the number of hours in the day during which the sunshine is above a certain level (typically 200 mW/cm^2). Data collected in this way can be used to determine the solar insolation by comparing the measured number of sunshine hours to those based on calculations and including several correction factors.

A final method to estimate solar insolation is cloud cover data taken from existing satellite images.

Fig. 2.6: Solar radiation measurement

While solar irradiance is most commonly measured, a more common form of radiation data used in system design is the solar insolation. The solar insolation is the total amount of solar energy received at a particular location during a specified time period, often in units of kWh/(m^2 day). While the units of solar insolation and solar irradiance are both a power density (for solar insolation the "hours" in the numerator are a time measurement as is the "day" in the denominator), solar insolation is quite different than the solar irradiance as the solar insolation is the instantaneous solar irradiance averaged over a given time period. Solar insolation data is commonly used for simple PV system design while solar radiance is used in more complicated PV system performance which calculates the system performance at each point in the day. Solar insolation can also be expressed in units of MJ/m^2 per year and other units and conversions are given in the unit page.

Solar radiation for a particular location can be given in several ways including:

- Typical mean year data for a particular location
- Average daily, monthly or yearly solar insolation for a given location
- Global isoflux contours either for a full year, a quarter year or a particular month
- Sunshine hours data
- Solar Insolation Based on Satellite Cloud-Cover Data
- Calculations of Solar Radiation

Chapter 3- Semiconductor

3.1 Semiconductor Structure

Semiconductors, such as Silicon (Si) are made up of individual atoms bonded together in a regular, periodic structure to form an arrangement whereby each atom is surrounded by 8 electrons. An individual atom consists of a nucleus made up of a core of protons (positively charged particles) and neutrons (particles having no charge) surrounded by electrons. The number of electrons and protons is equal, such that the atom is overall electrically neutral. The electrons surrounding each atom in a semiconductor are part of a covalent bond. A covalent bond consists of two atoms "sharing" a single electron. Each atom forms 4 covalent bonds with the 4 surrounding atoms. Therefore, between each atom and its 4 surrounding atoms, 8 electrons are being shared. The structure of a semiconductor is shown in the figure below.

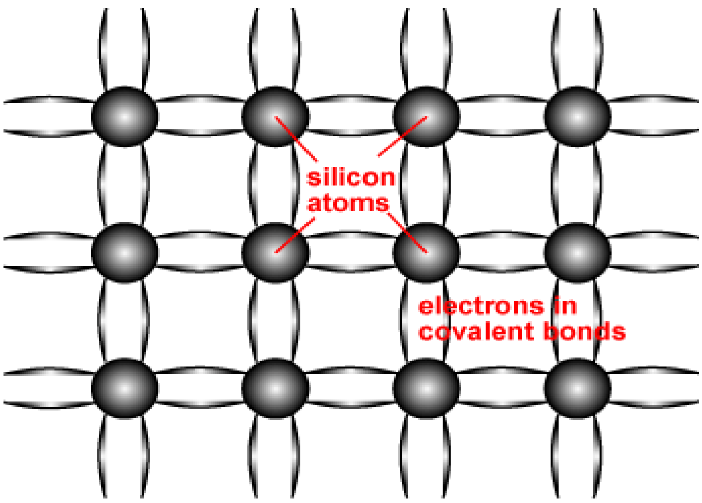

Fig. 3.1: Semiconductor Structure

3.2 Conduction in Semiconductors

The bond structure of a semiconductor determines the material properties of a semiconductor. One key effect are the energy levels which the electrons can occupy and how they move about the crystal lattice. The electrons in the covalent bond formed between each of the atoms in the lattice structure are held in place by this bond and hence they are localized to the region surrounding the atom. These bonded electrons cannot move or change energy, and thus are not considered "free" and cannot participate in current flow, absorption, or other physical processes of interest in solar cells. However, only at absolute zero are all electrons in this "stuck," bonded arrangement. At elevated temperatures, especially at the temperatures where solar cells operate, electrons can gain enough energy to escape from their bonds. When this happens, the electrons are free to move about the crystal lattice and participate in conduction. At room temperature, a semiconductor has enough free electrons to allow it to conduct current. At or close to absolute zero a semiconductor behaves like an insulator.

When an electron gains enough energy to participate in conduction (is "free"), it is at a high energy state. When the electron is bound, and thus cannot participate in conduction, the electron is at a low energy state. Therefore, the presence of the bond between the two atoms introduces two distinct energy states for the electrons. The electron cannot attain energy values intermediate to these two levels; it is either at a low energy position in the bond, or it has gained enough energy to break free and therefore has a certain minimum energy. This minimum energy is called the "band gap" of a semiconductor. The number and energy of these free electrons, those electrons participating in conduction, is basic to the operation of electronic devices.

The space left behind by the electrons allows a covalent bond to move from one electron to another, thus appearing to be a positive charge moving through the crystal lattice. This empty space is commonly called a "hole", and is similar to an electron, but with a positive charge.

The most important parameters of a semiconductor material for solar cell operation are:

- The band gap;
- The number of free carriers (electrons or holes) available for conduction; and
- The "generation" and recombination of free carriers (electrons or holes) in response to light shining on the material.

3.3 Band Gap

The band gap of a semiconductor is the minimum energy required to excite an electron that is stuck in its bound state into a free state where it can participate in conduction. The band structure of a semiconductor gives the energy of the electrons on the y-axis and is called a "band diagram". The lower energy level of a semiconductor is called the "valence band" (E_V) and the energy level at which an electron can be considered free is called the "conduction band" (E_C). The band gap (E_G) is the gap in energy between the bound state and the Free State, between the valence band and conduction band. Therefore, the band gap is the minimum change in energy required to excite the electron so that it can participate in conduction.

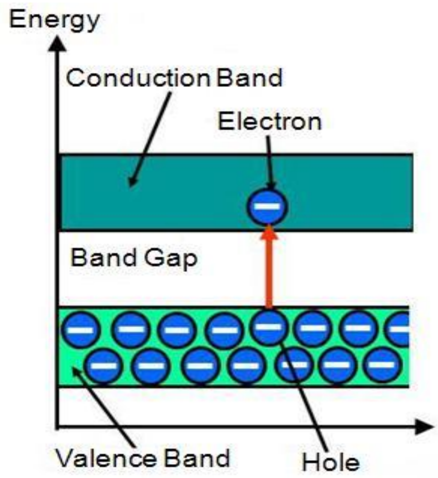

Fig. 3.2: Band Gap

Once the electron becomes excited into the conduction band, it is free to move about the semiconductor and participate in conduction. However, the excitation of an electron to the conduction band will also allow an additional conduction process to take place. The excitation of an electron to the conduction band leaves behind an empty space for an electron. An electron from a neighboring atom can move into this empty space. When this electron moves, it leaves behind another space. The continual movement of the space for an electron, called a "hole", can be illustrated as the movement of a positively charged particle through the crystal structure. Consequently, the excitation of an electron into the conduction band results in not only an electron in the conduction band but also a hole in the valence band. Thus, both the electron and hole can participate in conduction and are called "carriers".

The concept of a moving "hole" is analogous to that of a bubble in a liquid. Although it is actually the liquid that moves, it is easier to describe the motion of the bubble going in the opposite direction.

3.4 Doping

It is possible to shift the balance of electrons and holes in a silicon crystal lattice by "doping" it with other atoms.

Atoms with one more valence electron than silicon are used to produce "*n*-type" semiconductor material. These *n*-type materials are group V elements in the periodic table, and thus their atoms have 5 valence electrons that can form covalent bonds with the 4 valence electrons that silicon atoms have. Because only 4 valence electrons are needed from each atom (silicon and *n*-type) to form the covalent bonds around the silicon atoms, the extra valence electron present (because *n*-type materials have 5 valence electrons) when the two atoms bond is free to participate in conduction. Therefore, more electrons are added to the conduction band and hence increases the number of electrons present.

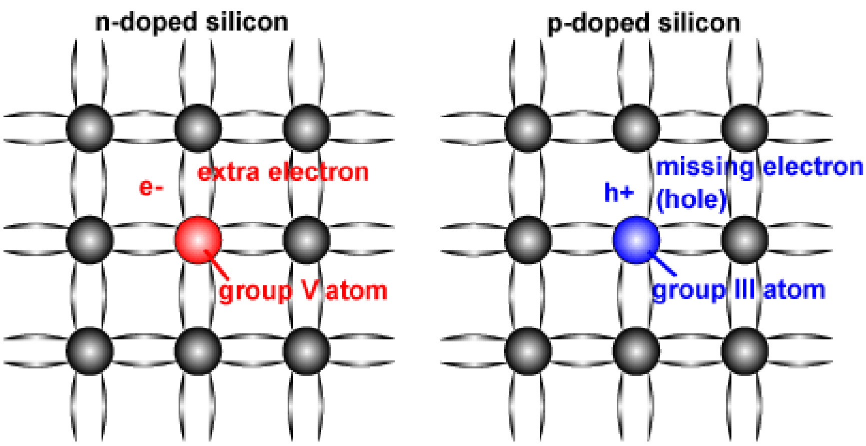

Fig. 3.3: Doping

Atoms with one less valence electron result in "*p*-type" material. These *p*-type materials are group III elements in the periodic table. Therefore, *p*-type material has only 3 valence electrons with which to interact with silicon atoms. The net result is a hole, as not enough electrons are present to form the 4 covalent bonds surrounding the atoms. In *p*-type material, the number of electrons trapped in bonds is higher, thus effectively increasing the number of holes. In doped material, there is always more of one type of carrier than the other and the type of carrier with the higher concentration is called a "majority carrier", while the lower concentration carrier is called a "minority carrier."

Chapter 4- Solar Cell

4.1 Solar Cell Structure

A solar cell is an electronic device which directly converts sunlight into electricity. Light shining on the solar cell produces both a current and a voltage to generate electric power. This process requires firstly, a material in which the absorption of light raises an electron to a higher energy state, and secondly, the movement of this higher energy electron from the solar cell into an external circuit. The electron then dissipates its energy in the external circuit and returns to the solar cell. A variety of materials and processes can potentially satisfy the requirements for photovoltaic energy conversion, but in practice nearly all photovoltaic energy conversion uses semiconductor materials in the form of a *p*-*n* junction.

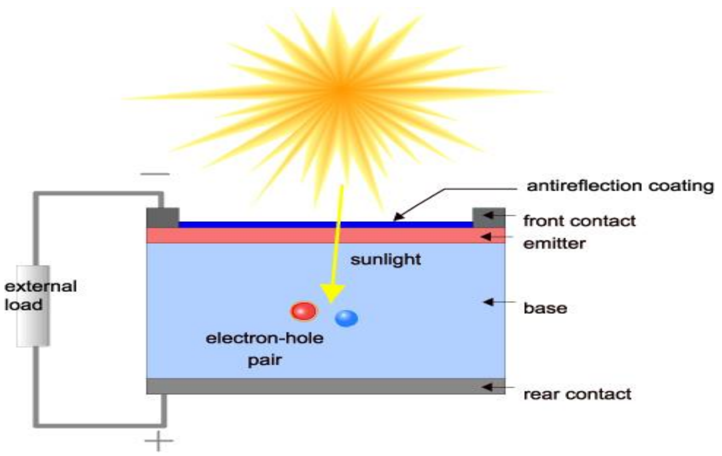

Fig. 4.1: Cross section of a solar cell.

The basic steps in the operation of a solar cell are:

- The generation of light-generated carriers;
- The collection of the light-generated carries to generate a current;
- The generation of a large voltage across the solar cell; and
- The dissipation of power in the load and in parasitic resistances.

4.2 Light Generated Current

The generation of current in a solar cell, known as the "light-generated current", involves two key processes. The first process is the absorption of incident photons to create electron-hole pairs. Electron-hole pairs will be generated in the solar cell provided that the incident photon has an energy greater than that of the band gap. However, electrons (in the *p*-type material), and holes (in the *n*-type material) are meta-stable and will only exist, on average, for a length of time equal to the minority carrier lifetime before they recombine. If the carrier recombines [9], then the light-generated electron-hole pair is lost and no current or power can be generated.

A second process, the collection of these carriers by the *p-n* junction, prevents this recombination by using a *p-n* junction to spatially separate the electron and the hole. The carriers are separated by the action of the electric field existing at the *p-n* junction. If the light-generated minority carrier reaches the *p-n* junction, it is swept across the junction by the electric field at the junction, where it is now a majority carrier. If the emitter and base of the solar cell are connected together (i.e., if the solar cell is short-circuited), the light-generated carriers flow through the external circuit. The ideal flow at short circuit is shown in the figure below.

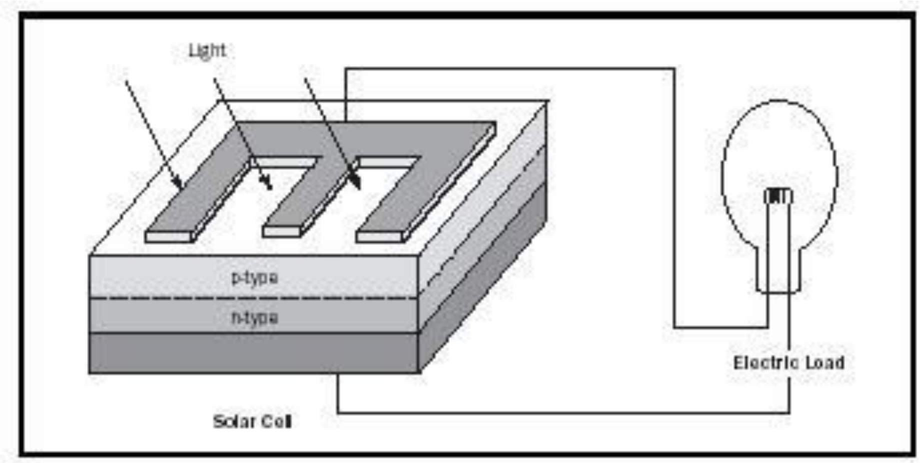

Fig. 4.2: The ideal short circuit flow of electrons and holes at a *p-n* junction. Minority carriers cannot cross a semiconductor-metal boundary and to prevent recombination they must be collected by the junction if they are to contribute to current flow.

4.3 Principle of Operation

Figure 4.3 presents a simplified diagram [10] of a solar cell that utilizes a single p-n junction. With no voltage applied to this junction, an electric field exists in the depletion region of the p-n junction. A simple diagram shows the p-n junction at work which is the fundamental concept of a solar cell.

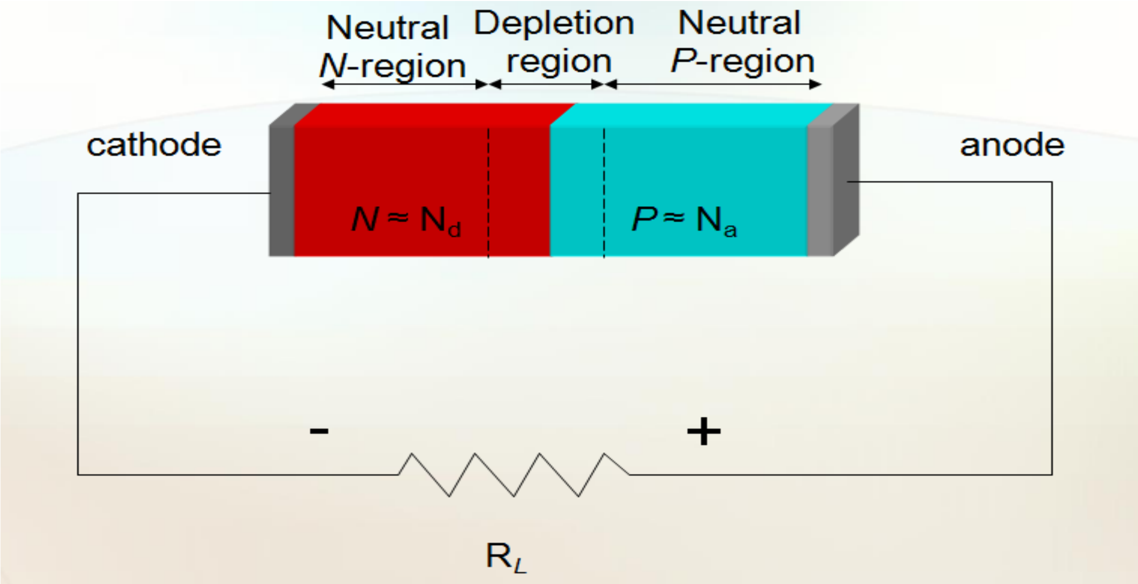

Fig. 4.3: Operation of a p-n junction

For simplicity, we consider that a resistive load is connected with the device. Now, photons incident on the device can create electron-hole pairs in the space-charge region, which are forcibly swept out of the depletion region by the built-in electric field, as the depletion region must be depleted of free charges. This swept out carriers produce a photocurrent I_L, in the reverse-bias direction for the p-n junction. Now, the photocurrent I_L produces a voltage drop across the resistive load, which forward biases the p-n junction. This forward bias produces a forward current, I_F, in the forward-bias direction for the p-n junction.

The net current, I, in the reverse bias direction for the p-n junction, is given by equation (1). fig. 4.4 shows a simplified schematic diagram of a solar cell.

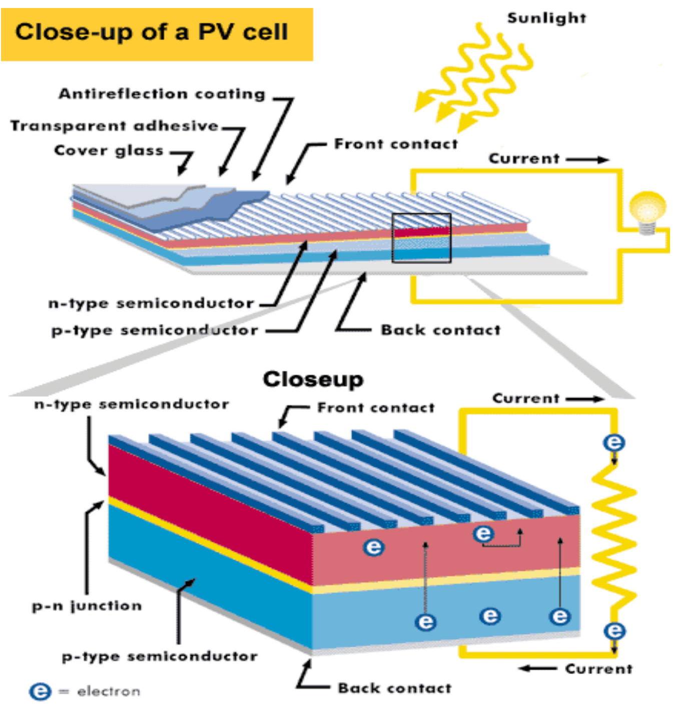

Fig. 4.4: Close-up of a PV cell

$$I = I_L - I_F = I_L - I_S\ [\exp(qV / nkT) - 1] \qquad (1)$$

Where,

n = Ideality factor (taken as 1)

k= Boltzmann constant

T= Temperature in K

q = charge of an electron

I_s= *Saturation Current*

4.4 Important Quantities

Now, there are two quantities of practical interest, the short-circuit current (I_{SC}) and the open- circuit voltage (V_{OC}). The short-circuit condition occurs when the resistive load is zero, so that V= 0. In this case, I_F is zero, and the short-circuit current, I_{SC}, is given by equation (2).

$$I_{SC}=I_L \quad \textbf{(2)}$$

Open-circuit condition occurs when the load resistance is infinity. The net current is zero in this case, which finally gives the expression of the open-circuit voltage, V_{OC}, as shown in equation (3).

$$Voc = (nkT/q)\ ln\ (1 + (IL / IS)) \quad \textbf{(3)}$$

It is to be noted that at both short-circuit and open-circuit condition, the power output of a solar cell is zero. Actually, there is a maximum power point on the I-V characteristics graph of a solar cell where $dP/dV = 0$ (P is the output power). This point is called the maximum power point. The maximum output power, Pm, is given by [11]

$$Pm = VmIm \quad \textbf{(4)}$$

Where,

Vm= Voltage at Maximum PowerPoint

Im= Current at Maximum PowerPoint

Now, a quantity, termed as „Fill Factor", is used to measure the "squareness" of the I-V curve of a solar cell. This is the ratio of the maximum output power, P_m, to the product of short- circuit current (I_{SC}) and the open-circuit voltage (V_{OC}). Fill factor is commonly abbreviated as FF. A higher FF is desirable, since it increases the maximum output power. The theoretical FF from a solar cell can be determined by differentiating the power from a solar cell with respect to the voltage and finding the voltage value for which the derivative equals to zero.

This is the voltage corresponding to the maximum power point, which is denoted by V_m. An equation involving V_m is given in (5).

Vm= Voc – [(nkT / q) × [ln (qVm / nkT) + 1] **(5)**

Solving equation (5) by iteration gives the value of V_m. Now, determining the value of I_m requires the knowledge of I_L and I_S. So, this method does not give a closed form solution for determining the maximum output power P_m, the knowledge of which is required for determining FF. So, for all the simulations in our work, we have used the formula (5) given by equation (6) for the calculation of FF.

$$\boldsymbol{FF = \frac{Vocn - \ln(Vocn + .72)}{Vocn + 1}} \qquad \textbf{(6)}$$

Where,

Vocn = (q/nkT) Voc **(7)**

Here,

Voc= Open-circuit voltage (in Volt)

n = Ideality factor

q= Charge of an electron = 1.6 × 10-19 Coulomb

k= Boltzmann constant

T= Temperature in K

For all the simulations, we have considered n=1, and T = 300K. The energy conversion efficiency of a solar cell, η, is given in (8).

$$\boldsymbol{\eta} = \frac{\boldsymbol{Voc} \times \boldsymbol{Isc} \times \boldsymbol{FF}}{\boldsymbol{E} \times \boldsymbol{A}} \times \mathbf{100}\% \tag{8}$$

Here,

Isc= Short-circuit current (in Amperes)

FF= Fill Factor

E= Solar irradiance (in W/cm^2)

A= Area of the solar cell (in cm^2)

Now, Isc/Acan be termed as Jsc, which is the short-circuit current density (in A/cm2). So, equation (8) can be rewritten as,

$$\boldsymbol{\eta} = \frac{\boldsymbol{Voc} \times \boldsymbol{Jsc} \times \boldsymbol{FF}}{\boldsymbol{E}} \times \mathbf{100}\% \tag{9}$$

Where,

Jsc= Short-circuit current density (in A/cm^2)

We are considering the use of the solar cell for terrestrial applications. So, to account for the incident sunlight, AM1.5G illumination was considered in the simulation code, as this is the standard terrestrial illumination. According to this, the solar irradiance, E, is taken to be 1000 W/m2, or, 0.1 W/cm2. It was also considered that the device is working under 1 sun i.e. no concentrator is used. Using Equation (9), the energy conversion efficiency was calculated.

4.5 Solar Photovoltaic Module

Generally a typical solar PV cell has the capability to generate 0.5 to 0.8 volts depending on the semiconductor material. This voltage is too low to be used for any purpose. So in order to generate sufficient amount of voltage it requires tens of PV cells to be connected in series or parallel (36 to 72). In this paper the reference model contains an external control block permitting an uncomplicated variation of the models' parameters. In this model, a module is formed by interconnecting 36 PV cells in series. Therefore the module voltage is calculated by multiplying the cell voltage by the number of cells and the module current is the same as the cell's one.

4.6 Equivalent Circuit of a PV cell

General equivalent circuit of a PV cell consisting a photo current, a diode, a parallel resistor which is mainly used to represent the leakage current and a series resistor is shown in fig. 4.5 [12,13]. In view of that the current to the load can be given as [14, 15, 16]:

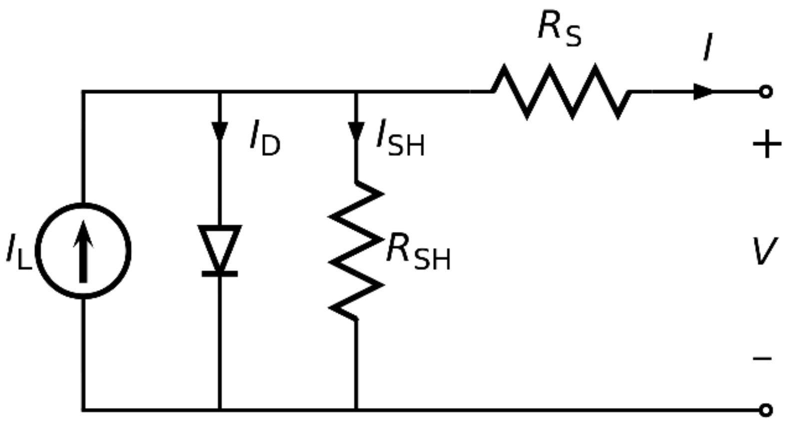

Fig. 4.5: PV cell equivalent circuit.

$$I = Iph - Is\left[\exp\left(\frac{q(V+IRs)}{kTcA}\right) - 1\right] - \frac{V+IRs}{Rsh} \qquad \textbf{(10)}$$

Here,
Iph = photocurrent
Is = reverse saturation current of the diode
q = electron charge
V = voltage across the diode
K = Boltzmann's constant
T = junction temperature
A = ideality factor of the diode
Rs and *Rsh* series and shunt resistors of the cell

Chapter 5- Software Simulation

5.1 MATLAB Code

The MATLAB code for a PV cell model is given below:

```
clc;

clear all;

K=1.38065e-23;  %Boltzmann constant

q=1.6025e-19;    %Charge of electron

Iscn=2.45;          %Nominal SC current

Vocn=21.8;        %Nominal OC voltage

Kv=-0.123;        %Voltage Temperature co-efficient

Ki=0.0032;        %Current Temperature co-efficient

Ns=36;              %No. of series connected cells

T=25+273;       %Operating temperature

Tn=25+273;     %Nominal temperature

Gn=1000;        %Nominal irradiance

a=1.3;             %Diode ideality constant

Eg=1.12;        %Band gap of silicon at 25 degree Celsius

G=1000;        %Actual irradiance

Rs=.221;

Rsh=100;


Vtn=Ns*K*Tn/q;

Ion=Iscn/(exp(Vocn/(a*Vtn))-1);

Io_part=((q*Eg/(a*K))*((1/Tn)-(1/T)));
```

```
Io=Ion*((T/Tn)^3)*exp(Io_part);
Ipvn= Iscn;
Ipv=(G/Gn)*(Ipvn+Ki*(T-Tn));
Vt=Ns*K*T/q;

I=zeros(45,1);
i=1;
I(1,1)=Iscn;

for V=0:0.5:30
    I(i+1)= Ipv- Io*(exp((V+(I(i,1)*Rs))/(a*Vt))-1)-((V+(I(i,1)*Rs))/Rsh);
    V1(i)=V;
    P(i)=V*I(i);
    i=i+1;
end

V1(i)=V1(i-1);
P(i)= P(i-1);
V1=transpose(V1);

subplot(2,1,1)
plot(V1,I,'-.');
subplot(2,1,2)
plot(V1,P,'r')
grid on
```

5.2 Simulink Model

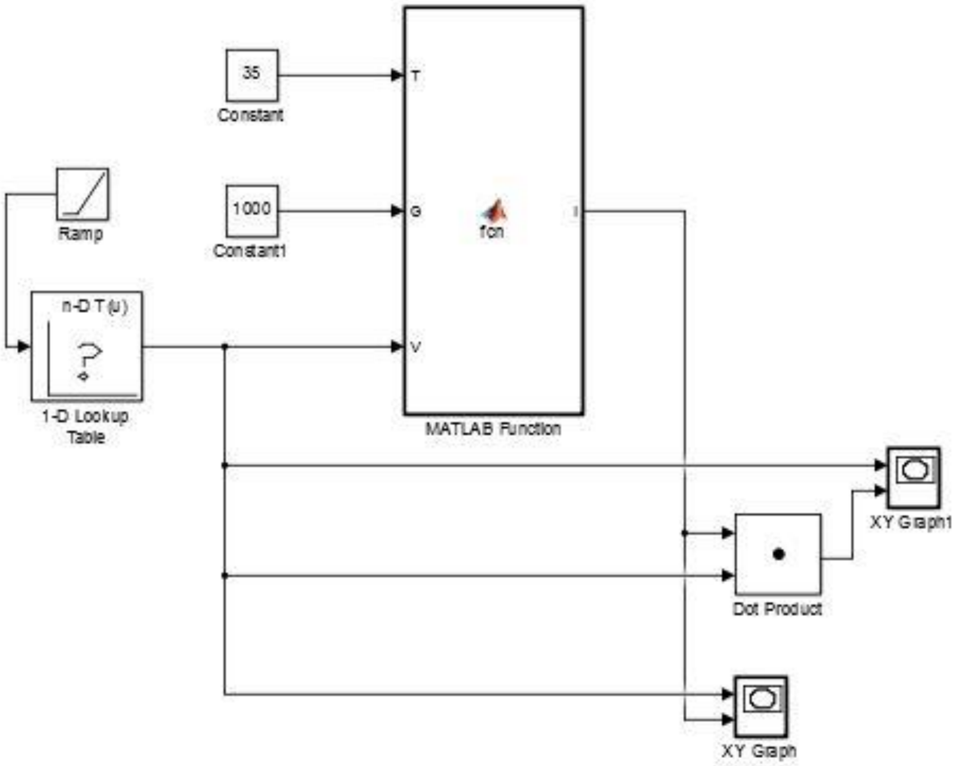

Fig. 5.1: MATLAB/Simulink Based block diagram of PV Cell

Chapter 6- Results & Discussion

6.1 Characteristics Curve

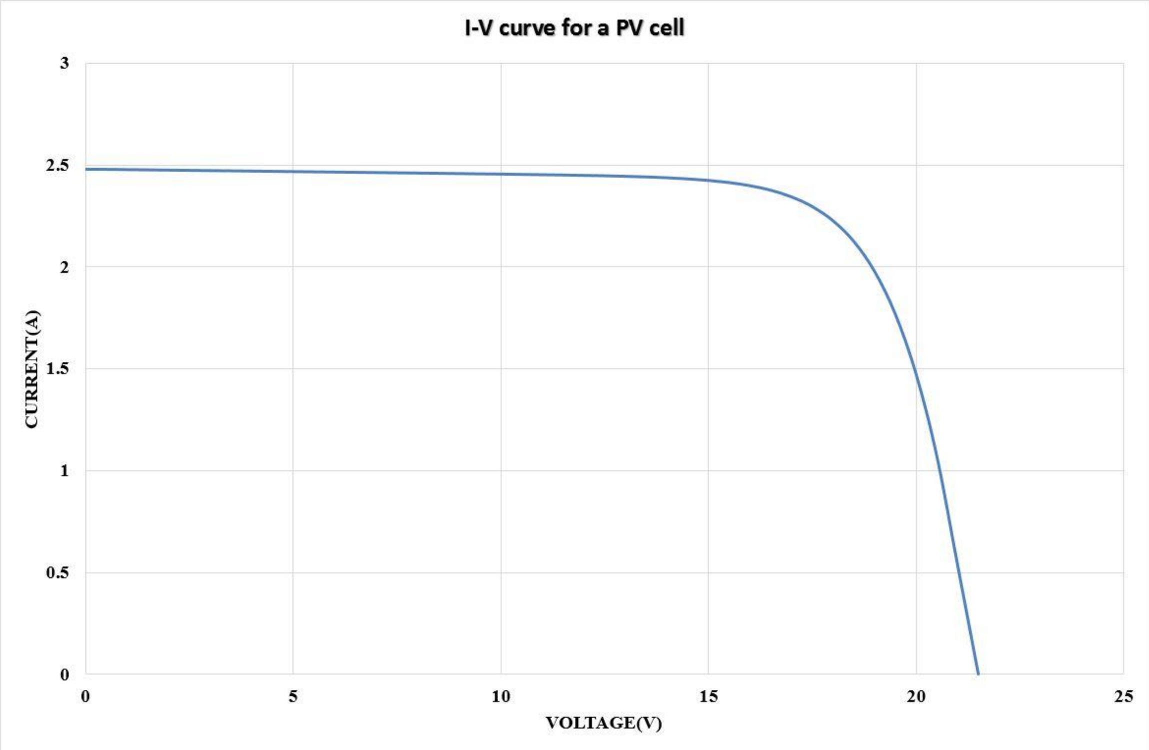

Fig. 6.1: I-V curve for a PV cell

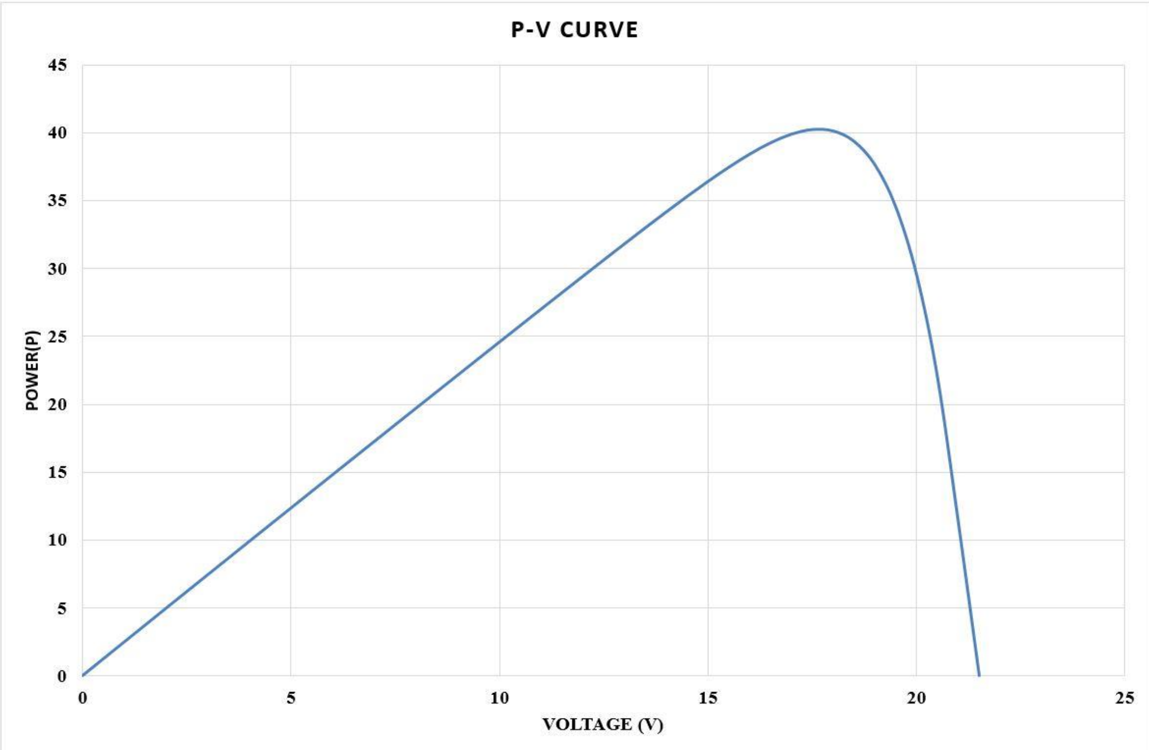

Fig. 6.2: P-V curve for a PV cell

6.2 Effect of varying Solar Irradiance

Our PV cell model includes two subsystems. Among which the PV cell photo current depends on the solar irradiance and operating temperature of the cell according to the following equation [17].

$$\boldsymbol{Iph} = \frac{[\boldsymbol{Isc} + \boldsymbol{Ki}(\boldsymbol{T} - \mathbf{298})]\text{ß}}{\mathbf{1000}}$$

Where Ki =0.0017 A/ºC, the short circuit current temperature co-efficient.

ß is the solar irradiance (W/m²).

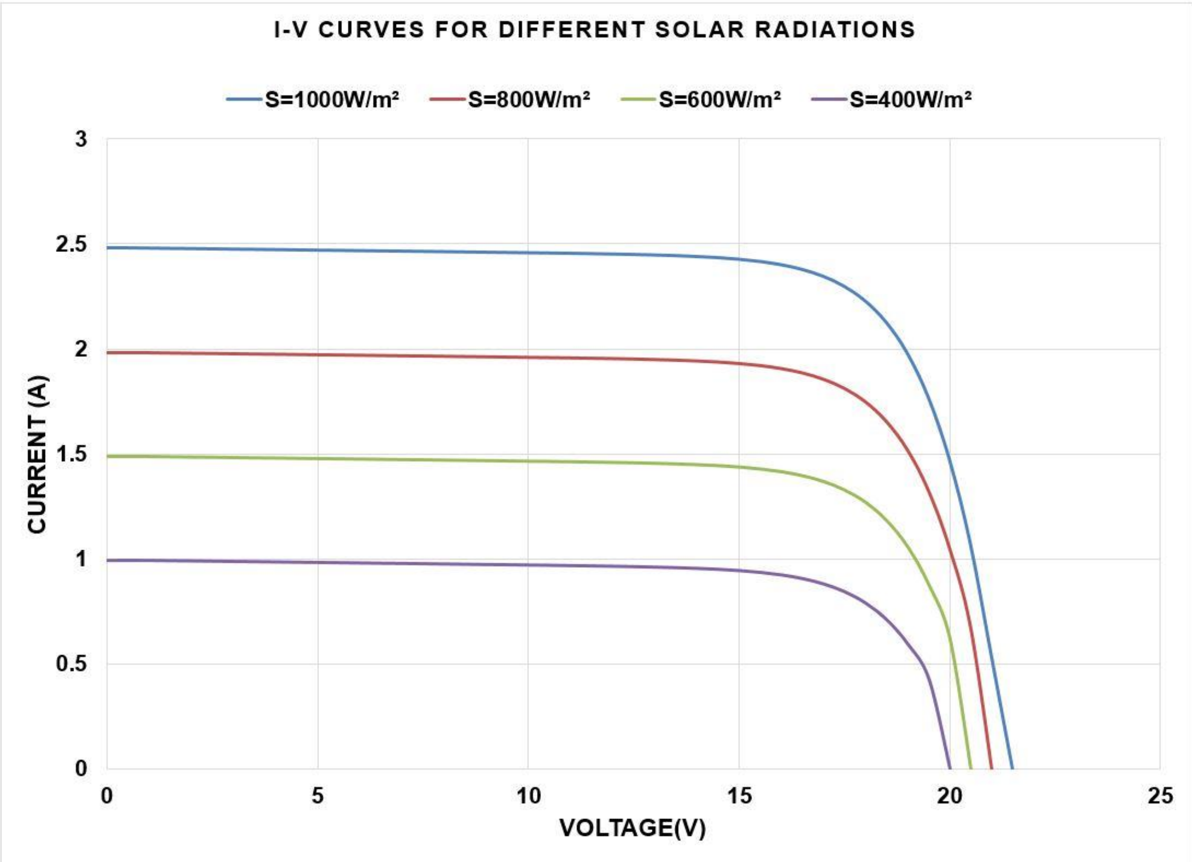

Fig. 6.3: I-V curve for varying solar irradiance

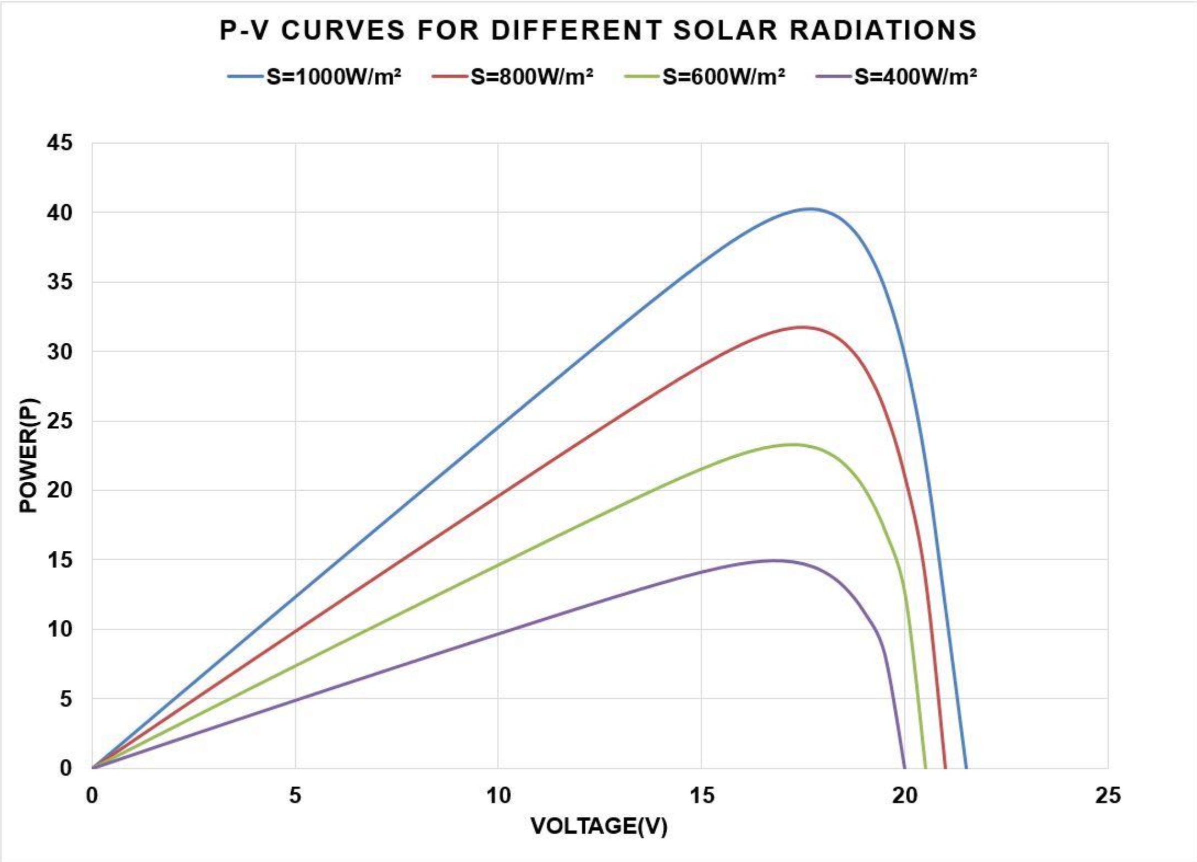

Fig. 6.4: P-V curve for varying solar irradiance

According to the curves shown in fig. 6.3 and fig. 6.4, the PV cell current has a significant dependence on the solar irradiance.

6.3 Effect of cell temperature variation

$$Is(T) = Is\left(\frac{T}{Tnom}\right)^{3} exp\left[\frac{\left(\frac{T}{Tnom} - 1\right)Eg}{NVt}\right]$$

In general, for a given solar radiation, when the cell temperature increases, the open circuit voltage Voc, drops slightly while the short circuit current increases. This behavior is shown in fig. 6.5 and fig. 6.6

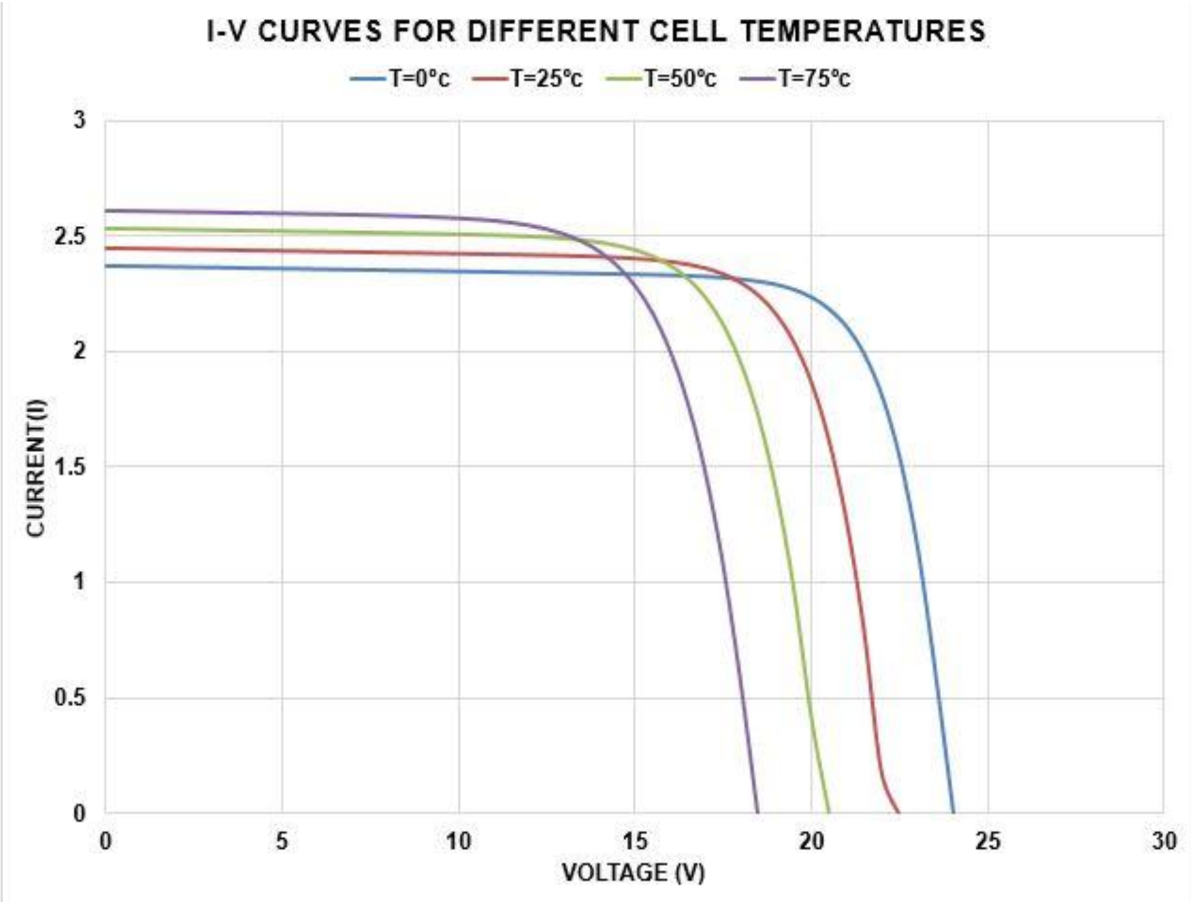

Fig. 6.5: I-V curve for varying cell temperature

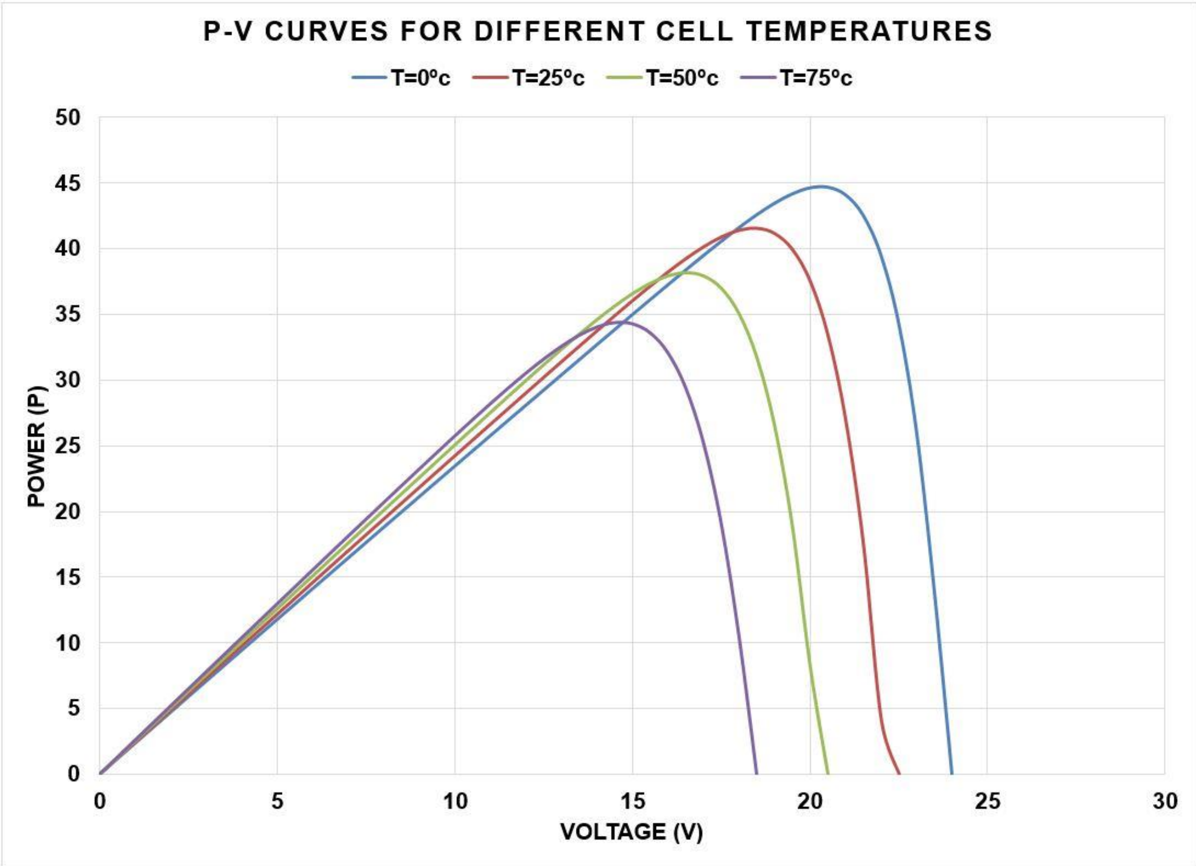

Fig. 6.6: P-V curve for varying cell temperature

6.4 Effect of varying Rs

The series resistance of the PV cell is low and in some cases, it can be neglected [18]. From the simulation we can predict the influences of its variation on the PV cell outputs. As seen in fig. 6.7 and fig. 6.8, the variation of Rs affects the slope angle of the I-V curve resulting in a deviation of the Maximum Power Point (MPP). It is also seen that higher value of Rs reduces the power output of the PV cell.

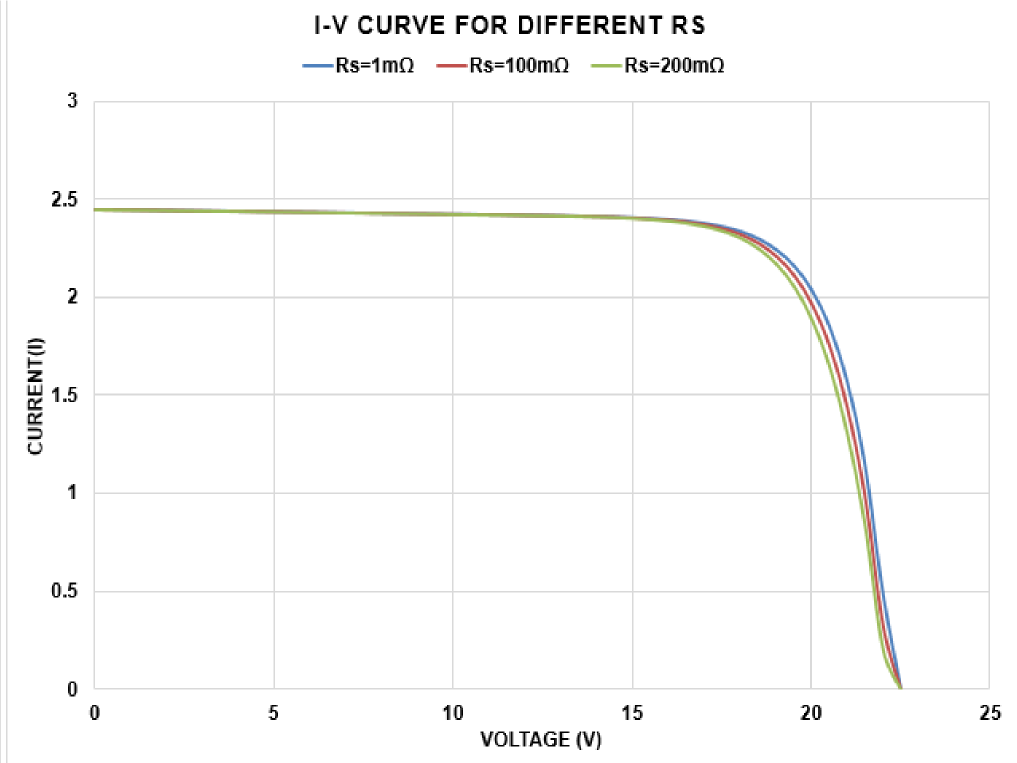

Fig. 6.7: I-V curve for varying Rs

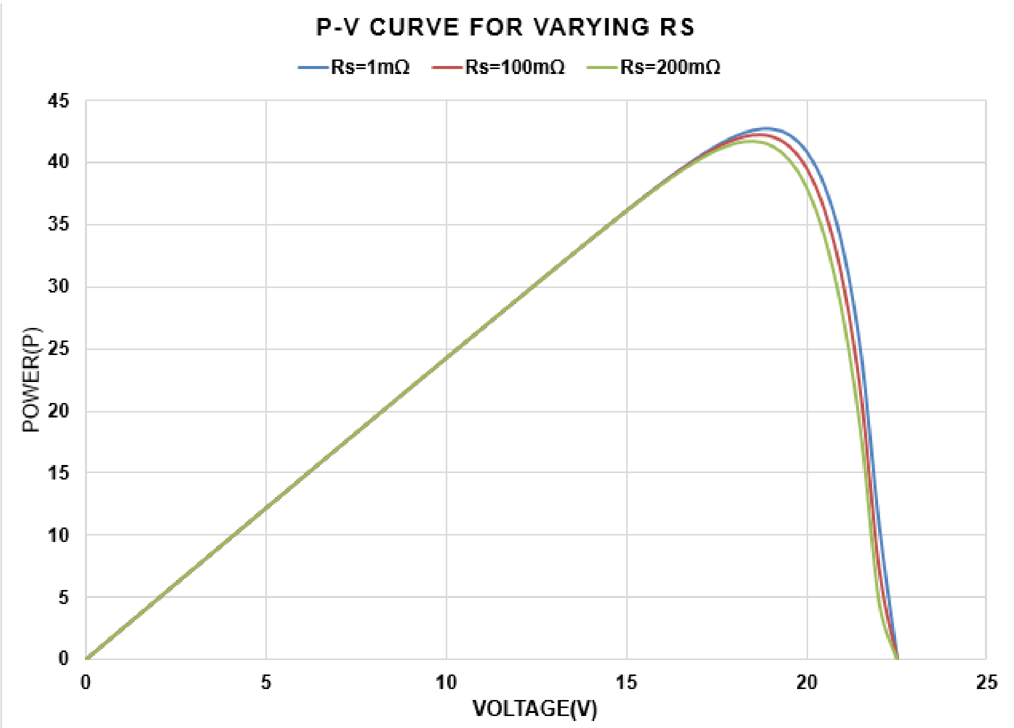

Fig. 6.8: P-V curve for varying Rs

6.5 Effect of varying Rsh

The shunt resistance selection should be as high as possible for better output power and fill factor. For lower shunt resistor, the PV cell current drops more steeply causing higher power loss and lower fill factor. These behavior is shown in fig. 6.9 and fig. 6.10. The fill factor equation is:

$$FF = \frac{Pmax}{Voc * Isc}$$

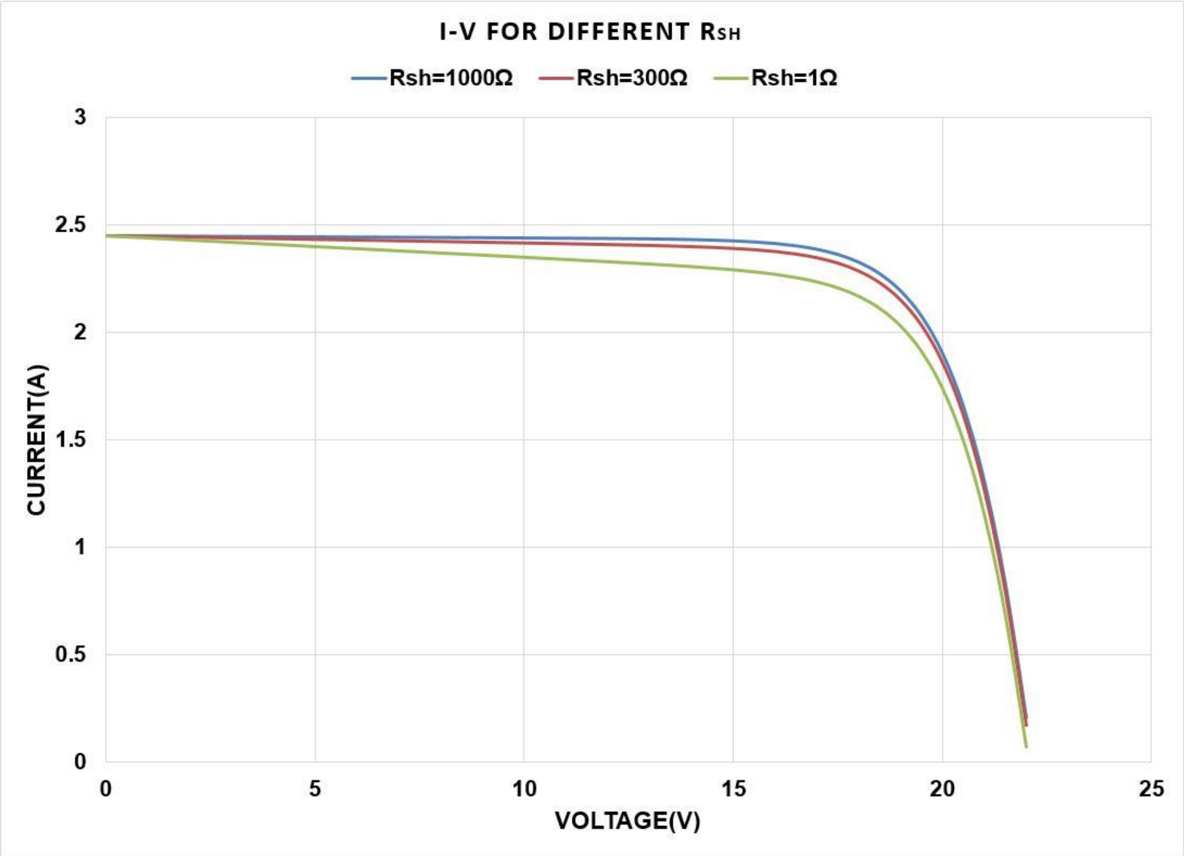

Fig. 6.9: I-V curve for varying Rsh

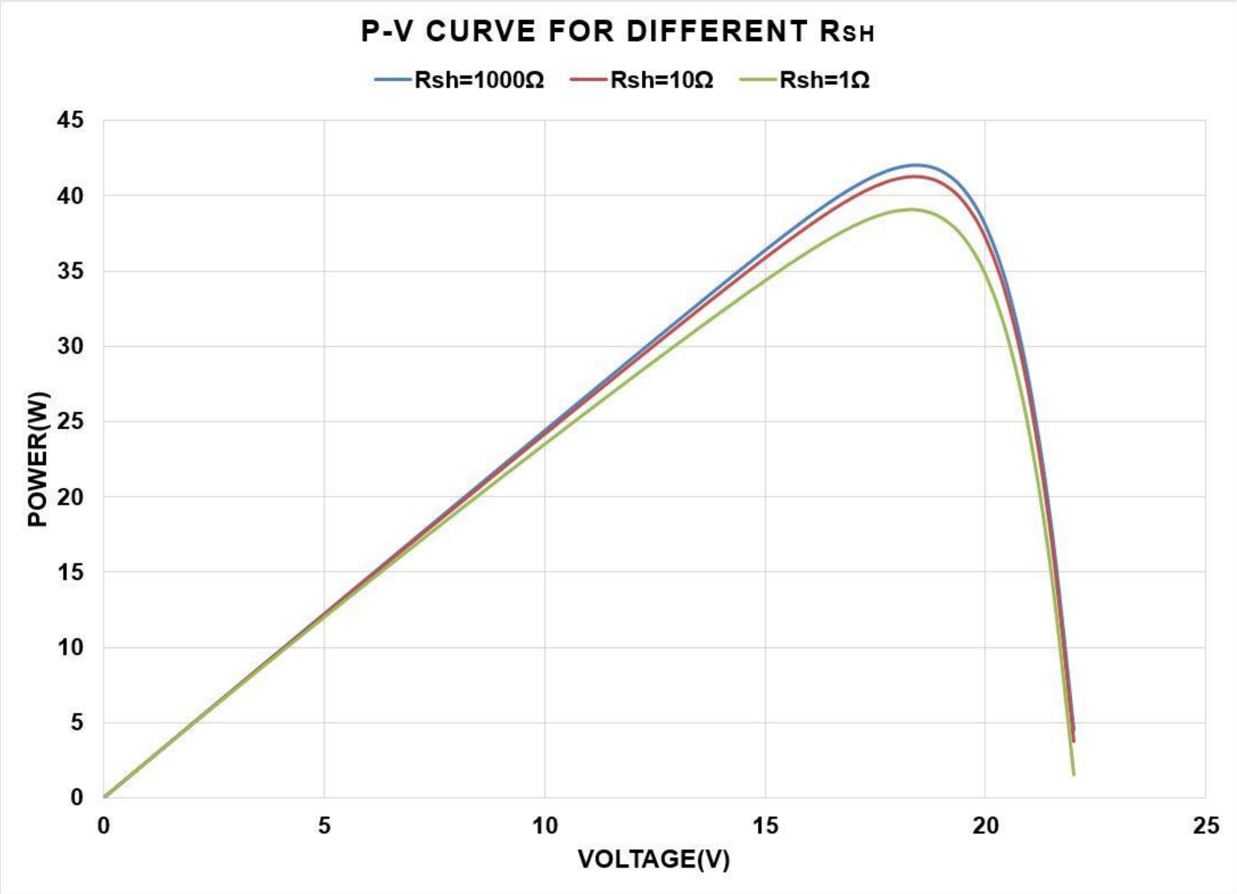

Fig. 6.10: P-V curve for varying Rsh

6.6 Electrical Specification of the test panel

For our simulation purpose we used Tata Solar Gold 40 module using MATLAB/Simulink. The evaluated results are shown in previous figures. The specifications [19] of the test panel is given below:

Tata Solar Gold 40 Series	
Maximum Power	40 W
Voltage at P_{max}	17.8 V
Current at P_{max}	2.22 A
Open Circuit Voltage, V_{oc}	21.8 V
Short Circuit Current, I_{sc}	2.45A

Table 6.1: Electrical Specification of Tata Solar Gold 40 Series

Chapter 7- Summary

7.1 Overview of the Work

In chapter 1, an overview of the research introduction, motivation and outline was presented. This chapter was a gist of the thesis and research that went under in the course of it.

In chapter 2, the basic information are provided. Such as, solar energy, solar cell history, properties of light, the sun, solar radiation etc.

In chapter 3, the basic of semiconductor is discussed. The semiconductor structure, conduction, band gap, doping all are discussed here.

In chapter 4 solar cell structure, light generated current, principle of operation, important quantities, equivalent circuit of PV cell are mentioned.

Chapter 5 is about software simulation. We use MATLAB/Simulink as our platform. The MATLAB code is given as well as Simulink block diagram.

In chapter 6, results and discussion was presented where a detailed analysis was performed about solar cell characteristics. The characteristics curves were presented along with the effects of the various physical and environmental change.

Overall in this thesis the behavior of a solar cell is explained due to the change of various physical and environmental components.

7.2 Future Work

In future we would like to improve the efficiency of photovoltaic cell by suggesting a new cooling system of PV panel. Because we know temperature affects the efficiency of solar cell. The power output decreases with the increase of temperature. So we hope to achieve a much better efficiency by implementing that cooling system design.

7.3 Conclusion

In this thesis paper a MATLAB/Simulink model for the solar PV cell was developed and presented. This model is based on the fundamental circuit equations of a solar PV cell taking into account the effects of physical and environmental parameters such as solar radiation, cell temperature etc.

As a result of this study, one can benefit from this model as photovoltaic generator in the field of solar PV power conversion system. In addition, such a model would provide a tool to predict the behavior of any solar PV cell under climate and physical parameter change.

Bibliography

1. Hassan M. M., Beliveau Y. Modeling of an integrated solar system // Building and Environment. – Elsevier, 2008. – No. 43(5). – P. 804–810.
2. Akpinar A., Kömürcü M. `., Kankal,M., Özölçer `. H., Kaygusuz K. Energy situation and renewables in Turkey and environmental effects of energy use // Renewable and Sustainable Energy Reviews. – Elsevier, 2008. – No. 12(8). – P. 2013–2039.
3. Peter Gevorkian, Sustainable energy systems engineering: the complete green building design resource, p. 498, McGraw-Hill Professional, New York, USA, 2007, ISBN: 978-0071473590.
4. Marius Grundmann, The Physics of Semiconductors: An Introduction Including Nanophysics and Applications, 2nd ed., p. 3, Springer-Verlag, Berlin, Germany, 2010, ISBN: 978-3642138843.
5. K. A. Tsokos, Physics for the IB Diploma, 5th ed., Cambridge University Press, Cambridge, UK, 2008, ISBN: 978-0521708203.
6. Planck M. Distribution of energy in the normal spectrum. Verhandlungen der Deutschen Physikalischen Gesellschaft. 1900; 2:237-245.
7. Einstein A. Generation and transformation of light. Annalen der Physik. 1905; 17.
8. Feynman RP. QED: The Strange Theory of Light and Matter.; 1985.
9. Hanasoge SM, Duvall TL, Sreenivasan KR. From the Cover: Anomalously weak solar convection. Proceedings of the National Academy of Sciences. 2012; 109(30):11928 - 11932.
10. Balčiūnas P., Norkevičius P. Stochastic Nature Electrical Energy Conversion Processes Experimental Research of Wind Micro Power Plant // Electronics and Electrical Engineering. – Kaunas: Technologija, – 2010. – No. 9(105). – P. 57–60.
11. Urjart. (2008) Solar Cell: Basic Principle of Operation. [Online]. Available: http://urjart.wordpress.com/2008/10/05/solar-cell-%E2%80%93-basic-principle-of-operation/
12. Kalogirou S. Solar Energy Engineering: Processes and Systems. – Academic Press, 2009. – 48p.

13. Huan-Liang Tsai, Ci-Siang Tu, Yi-Jie Su, "Development of Generalized Photovoltaic Model Using MATLAB/SIMULINK", Proceedings of the World Congress on Engineering and Computer Science WCECS, San Francisco, USA, 2008.
14. Francisco M, González-Longatt, "Model of Photovoltaic Module in Matlab™", 2do congresoı beroamerı cano de estudıantes de ıngenıeríaeléctrı ca, electrónıca y computacıón pp.1-5, 2005.
15. S. Rustemli, F. Dincer, "Modeling of Photovoltaic Panel and Examining Effects of Temperature in Matlab/Simulink", Electronics and Electrical Engineering, ISSN 1392-1215, no. 3(109), pp. 35-40, 2011.
16. Kinal Kachhiya, Makarand Lokhande, Mukesh Patel, "MATLAB/Simulink Model of Solar PV Module and MPPT Algorithm", Proceedings of the National Conference on Recent Trends in Engineering and Technology, 2011.
17. I.H. Atlas, A.M. Sharaf, "A Photovoltaic Array Simulation Model for Matlab-Simulink GUI Environment", International Conference on Clean Power, pp. 341-345, 2007
18. Savita Nema, R.K. Nema, Gayatri Agnihotri, "MATLAB/Simulink based study of photovoltaic cells / modules / array and their experimental verification", International journal of Energy and Environment, vol.1, No.3, pp.487-500, 2010.
19. Tata Power Solar, Gold Series Module. Available online. Date Accessed: 20.10.2015 http://www.tatapowersolar.com/images/module/downloads/Tata%20Solar%20Gold%20%5BAugust%202014%5D%20%5BScreen%5D.pdf