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MODELING AND SIMULATION OF PHOTOVOLTAIC COMPONENT OF A POWER SYSTEM

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ABSTRACT

This project presents a modified step-by-step procedure for the simulation of photovoltaic modules with Matlab/ Simulink. One-diode equivalent circuit is employed in order to investigate I-V and P-V characteristics of a typical 45 W solar module (PM045). It is necessary to define a circuit-based simulation model for a PV cell in order to allow the interaction with a power converter. Characteristics of PV cell are affected by irradiation and temperature.

Its results indicated that the created simulation blocks in Simulink/matlab are similar to actual PV modules. By the model, it is allowed to estimate behavior of PV module with respect to changes on irradiance intensity, ambient temperature and the other design parameters of the PV module. All the possible graphs of I-V and P-V are drawn by varying the parameter.

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Chapter 1   **INTRODUCTION**

1.1 INTRODUCTION

Among the renewable energy resources, the energy due to the photovoltaic (PV) effect can be considered the most essential and prerequisite sustainable resource because of the ubiquity, abundance, and sustainability of solar radiant energy.

Regardless of the intermittency of sunlight, solar energy is widely available and is free. Recently, photovoltaic system is recognized to be in the forefront in renewable electric power generation. It can generate direct current electricity without environmental impact and contamination when exposed to solar radiation. Being a semiconductor device, the PV system is static, quiet, free of moving parts, and has little operation and maintenance costs.

PV module represents the fundamental power conversion unit of a PV generator system. The output characteristics of a PV module depend on the solar insolation, the cell temperature and the output voltage of the PV module. Since PV module has nonlinear characteristics, it is necessary to model it for the design and simulation of maximum power point tracking (MPPT) for PV system applications.

Mathematical modeling of PV module is being continuously updated to enable researcher to have a better understanding of its working. In this project, a step-by-step procedure for simulating PV module with subsystem blocks, with user-friendly icons and dialog in the same way as Matlab/ Simulink block libraries is developed.

1.2 NOMENCLATURES

ISC: Short-circuit current

Impp: Current at the maximum-power point

Iph: Light-generated current

ID: Diode current

IS: Diode reverse saturation current

Ish: Current through the shunt resistance

Ir: Irradiation

VOC: Open-circuit voltage

Vmpp: Voltage at the maximum-power point

Pmpp: Power at the maximum-power point

Rs: Series resistance

Rsh: Shunt resistance

q: Electron Charge constant, 1.6 10-19 C

n: emission coefficient, ideality factor (Si = 1.2)

a: diode ideality constant.

k: Boltzmann's constant

T: Cell temperature

NS: Number of cells in series

1.3 Objective

The objective of this project is to develop a computer models to simulate the behavior of a photovoltaic cell, to be able to represent its *IV* and *PV* curves. The model is implemented in Matlab-Simulink. To demonstrate the validity of the model, graphs of*IV* and *PV* curves are plotted. To analyze the operation and the suitability of the model, it is necessary to have precise knowledge of these curves. We found the parameters of the nonlinear I–V equation by adjusting the curve at three points: open circuit, maximum power, and short circuit. The method finds the best I–V equation for the single-diode photovoltaic (PV) model.

Chapter 2   CONSTRUCTION OF PHOTOVOLTAIC CELL

The *photovoltaic solar cell* is made from silicon crystals. Silicon crystal atoms have four electrons in their outermost orbital. These four electrons are shared with neighboring silicon atoms to form full orbitals of eight electrons creating a stable atomic structure.

When sunlight hits the silicon material, electrons are "knocked" from their orbital and become "free electrons". Because the electrons in the silicon crystalline material only become free when exposed to light, it is therefore called a semiconductor. In other words, exposing silicon to light causes its electrons to become mobile or free. But simply exposing a semiconductor to light is not enough to extract an electric current from it, to do that we need to create "positive" and "negative" poles within the silicon allowing electrons and therefore a current to flow in and out of the silicon material.

2.1 **Photovoltaic Solar Cell N-type Semiconductors**

In order for our silicon crystal to conduct electricity, we need to introduce an impurity atom such as Phosphorus (P) into the crystalline structure making it extrinsic (impurities are added). Phosphorus atoms have five outer electrons in their outermost orbital to share with neighboring atoms and are commonly called "Pentavalent" (5-electron) impurities. This allows four out of the five orbital electrons to bond with its neighboring silicon atoms leaving one "free electron" to floating around the doped crystal.

When exposed to sunlight, the electrons freed from the silicon atoms are quickly replaced by the free electrons available from the doped Phosphorus atoms (electron flow). But this action still leaves an extra electron (the freed electron) floating around the doped crystal making it negatively charged. Then a semiconductor material is classed as N-type when it has an excess of electrons thereby creating a negative pole. As each impurity atom "donates" one electron, pentavalent atoms are generally known as "donors".

2.2 Photovoltaic Solar Cell P-Type Semiconductors.

If we go the other way, and introduce a "Trivalent" (3-electron) impurity into the crystalline structure, such as Boron (B), which has only five electrons arranged in three shells around its nucleus with the outermost orbital having only three electrons, the fourth closed bond cannot be formed. Therefore, a complete stable connection is not possible, giving the semiconductor material an abundance of positively charged carriers known as "holes" in the structure of the crystal where electrons are effectively missing.

As there is now a hole in the silicon crystal, a neighboring electron is attracted to it and will try to move into the hole to fill it. However, the electron filling the hole leaves another hole behind it as it moves. This in turn attracts another electron which in turn creates another hole behind it, and so forth giving the appearance that the holes are moving as a positive charge through the semiconductor crystal structure. This movement of holes represents conventional current flow.

The movement of holes results in a shortage of electrons in the silicon turning the entire doped crystal into a positive pole. Therefore, a P-type semiconductor material has more holes than electrons and as each impurity atom generates a hole, trivalent impurities are generally known as "Acceptors" as they are continually "accepting" extra or free electrons.

On their own, both N-type and P-type semiconductor materials are electrically neutral, but when these two semiconductor materials are first brought together some of the free electrons move across the junction to fill up the holes in the P-type material producing negative ions, but because the electrons have moved they leave behind positive ions on the negative N-side and the holes move across the junction in the opposite direction into the region where there are large numbers of free electrons. This movement of electrons and holes across the junction is known as diffusion.

This process continues until the number of electrons which have crossed the junction have a large enough electrical charge to repel or prevent any more carriers from crossing the junction. Eventually a state of equilibrium (electrically neutral situation) will occur producing a "PotentialBarrier" zone around the area of the junction as the donor atoms repel the holes and the acceptor atoms repel the electrons. Since no free charge carriers can rest in a position where there is a potential barrier it is therefore "depleted" of any free mobile carriers, and this area around the junction is now called the Depletion Layer.

The significance of this built-in potential is that it opposes both the flow of holes and electrons across the junction and is why it is called the potential barrier. Sunlight is electromagnetic radiation consisting of very small units of light energy called photons. When a photon in the form of sunlight hits or strikes the PN-junction of the solar cells semiconductor material, the energy from the photon dislodges or knocks lose any free electrons within this PN-junction as they become excited by the photons energy. This results in the electrons being released and able to move freely across the depletion layer leaving in its place a hole or a positive charge.

In the P-type material, these free electrons easily cross through the depletion layer and into the N-type material, but this movement of electrons is one-way, as the electrons are not able to cross the depletion layer back into the

P-type material. As a result, an excess of free electrons builds up in the N-type semiconductor material creating an electrical current within the solar cell and will continue indefinitely as long as there is exposure to sunlight.

As positive and negative sides of the junction are now created, the photovoltaic solar cell acts as a type of battery producing both a voltage and a DC current. Small wires or metal ribs are connected to both the P-type and N-type semiconductor materials to harness this newly created energy producing solar power in the form of a DC current flow as shown below
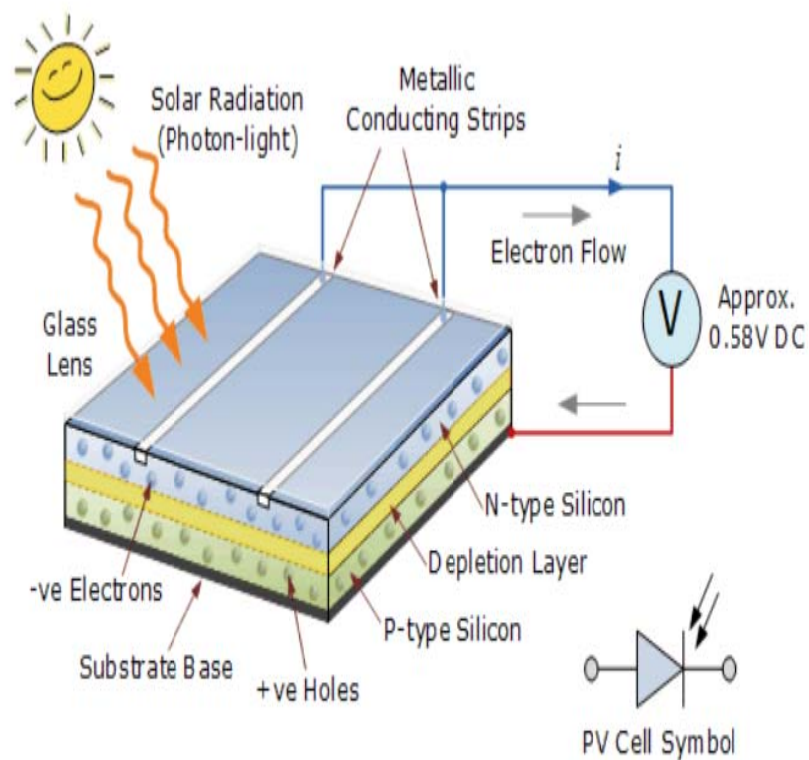

Figure 2.1

Chapter 3   **SOLAR POWER FROM THE SUN.**

The silicon wafer of the photovoltaic solar cell facing the sun consist of the electrical contacts and is coated with an anti-reflective coating that helps absorb the sunlight efficiently. The electrical contacts provide the connection between the semiconductor material and the external electrical load, such as a light bulb or battery. When sunlight shines on a PV cell, photons of light strike the surface of semiconductor material and liberate electrons from the materials atom structure. Certain doping chemicals are added to the semiconductors composition to help to establish a path of the freed electrons.

This creates a flow of electrons forming an electrical current which starts to flow over the surface of the photovoltaic solar cell. Metallic strips are placed across the surface of the photovoltaic cell to collect these electrons which forms the positive connection. The back of the PV cell, the side away from the incoming sunlight consists of a layer of aluminium or molybdenum metal which forms the negative connection to the cell. Then a photovoltaic solar cell has two electrical connections, one positive, on the top, and one negative, at the bottom.

The type of solar power produced by a photovoltaic solar cell is called direct current or DC the same as from a battery. Most photovoltaic solar cells produce a "no load" open circuit voltage (nothing connected to it) of about 0.5 to 0.6 volts when there is no external circuit connected. This output voltage (V_{OUT}) depends very much on the load current (I) demands of the PV cell. For example on very cloudy or dull day the current demand would be low and so the cell could provide the full output voltage, V_{OUT} but at a reduced output current. But as the current demand of the load increases a brighter light (solar radiation) is needed at the junction to maintain a full output voltage, Vout.

However, there is a physical limit to the maximum current that a single photovoltaic solar cell can provide no matter how intense or bright the suns radiation is. This is called the *maximum deliverable current* and is symbolized as I_{MAX}. The I_{MAX} value of a single photovoltaic solar cell depends upon the size or surface area of the cell (especially the PN-junction), the amount of direct sunlight hitting the cell, its efficiency of converting this solar power into a current and of course the type of semiconductor material that the cell is manufactured from either silicon, gallium arsenide, cadmium sulphide, cadmium telluride etc.

Most commercially available photovoltaic solar cells have solar power ratings which indicate the maximum deliverable solar power, P_{MAX} that the cell can provide in watts and is equal to the product of the cell voltage V multiplied by the maximum cell current I and is given as:

$$P_{MAX} = V_{OUT} \times I_{MAX}$$

3.1 **How photovoltaic Work.**

Photovoltaics is the direct conversion of light into electricity at the atomic level. Some materials exhibit a property known as the photoelectric effect that causes them to absorb photons of light and release electrons. When these free electrons are captured, an electric current results that can be used as electricity.

The photoelectric effect was first noted by a French physicist, Edmund Becquerel, in 1839, who found that certain materials would produce small amounts of electric current when exposed to light. In 1905, Albert Einstein described the nature of light and the photoelectric effect on which photovoltaic technology is based, for which he later won a Nobel Prize in physics. The first photovoltaic module was built by Bell Laboratories in 1954. It was billed as a solar battery and was mostly just a curiosity as it was too expensive to gain widespread use. In the 1960s, the space industry began to make the first serious use of the technology to provide power aboard spacecraft. Through the space programs, the technology advanced, its reliability was established, and the cost began to decline. During the energy crisis in the 1970s, photovoltaic technology gained recognition as a source of power for non-space applications.
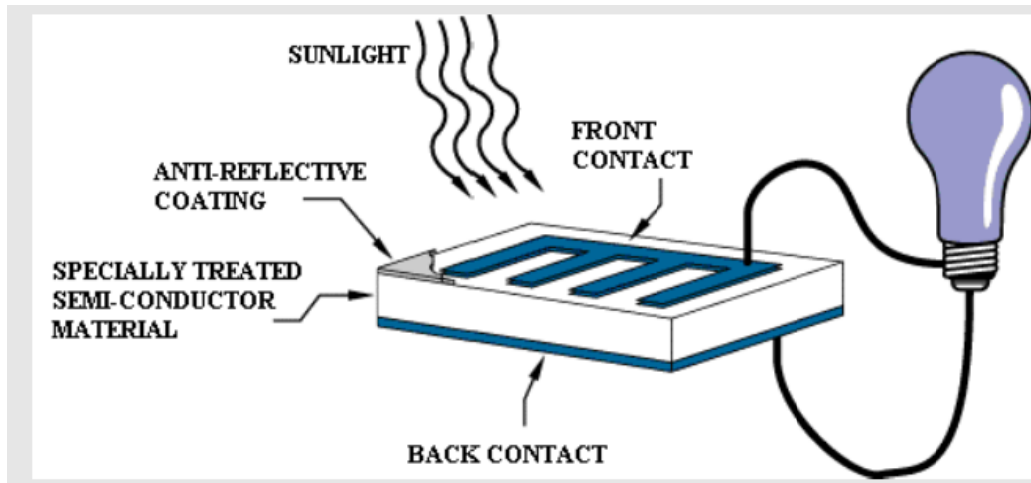
Figure 3.1

Figure 3.1 above illustrates the operation of a basic photovoltaic cell, also called a solar cell. Solar cells are made

of the same kinds of semiconductor materials, such as silicon, used in the microelectronics industry. For solar cells,

a thin semiconductor wafer is specially treated to form an electric field, positive on one side and negative on the

other. When light energy strikes the solar cell, electrons are knocked loose from the atoms in the semiconductor

material. If electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the

electrons can be captured in the form of an electric current -- that is, electricity. This electricity can then be used to

power a load, such as a light or a tool.

A number of solar cells electrically connected to each other and mounted in a support structure or frame is called a

photovoltaic module. Modules are designed to supply electricity at a certain voltage, such as a common 12 volts

system. The current produced is directly dependent on how much light strikes the module.
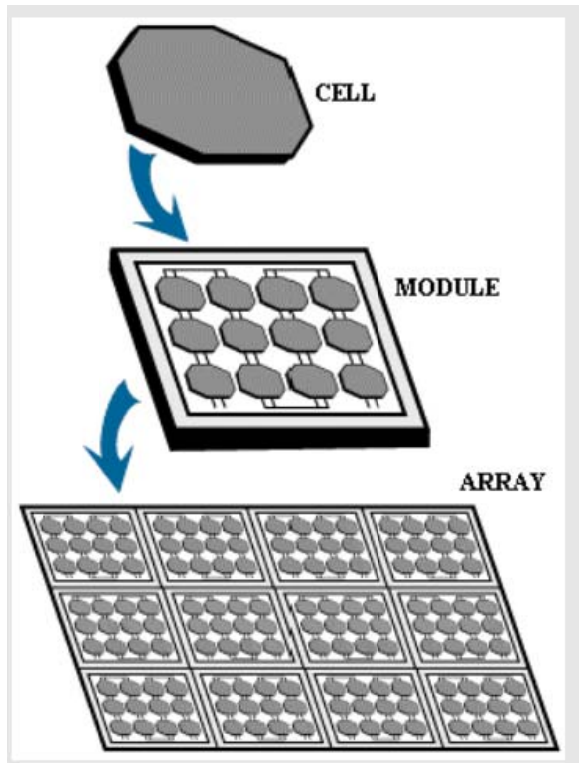
Figure 3.2

Multiple modules can be wired together to form an array. In general, the larger the area of a module or array, the more electricity that will be produced. Photovoltaic modules and arrays produce direct-current (dc) electricity. They can be connected in both series and parallel electrical arrangements to produce any required voltage and current combination.

Today's most common PV devices use a single junction, or interface, to create an electric field within a semiconductor such as a PV cell. In a single-junction PV cell, only photons whose energy is equal to or greater than the band gap of the cell material can free an electron for an electric circuit. In other words, the photovoltaic response of single-junction cells is limited to the portion of the sun's spectrum whose energy is above the band gap of the absorbing material, and lower-energy photons are not used.

One way to get around this limitation is to use two (or more) different cells, with more than one band gap and more than one junction, to generate a voltage. These are referred to as "multifunction" cells (also called "cascade"

or "tandem" cells). Multifunction devices can achieve a higher total conversion efficiency because they can convert more of the energy spectrum of light to electricity.
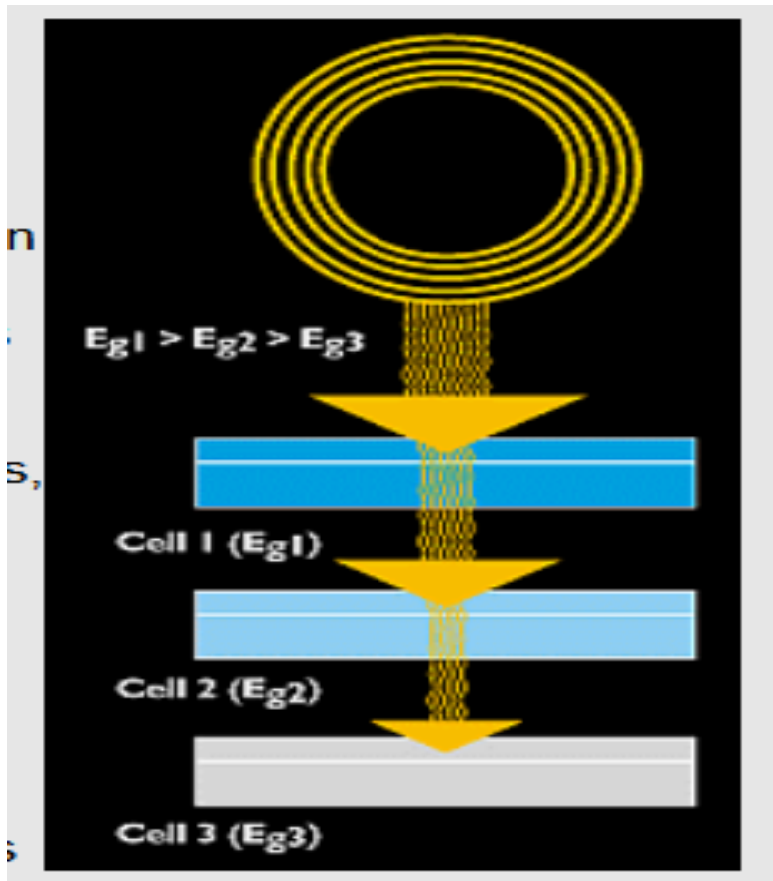

Figure 3.3

Chapter 4   **MATHEMATICAL MODEL FOR A PHOTOVOLTAIC MODULE**

A solar cell is basically a p-n junction fabricated in a thin wafer of semiconductor. The electromagnetic radiation of solar energy can be directly converted to electricity through photovoltaic effect. Being exposed to the sunlight, photons with energy greater than the band-gap energy of the semiconductor creates some electron-hole pairs proportional to the incident irradiation.

4.1 Equivalent Circuit.

The current source Iph represents the cell photocurrent. Rsh and Rs are the intrinsic shunt and series resistances of the cell, respectively. Usually the value of Rsh is very large and that of

Rs is very small, hence they may be neglected to simplify the analysis. PV cells are grouped in larger units called PV modules which are further interconnected in a parallel-series configuration to form PV arrays.
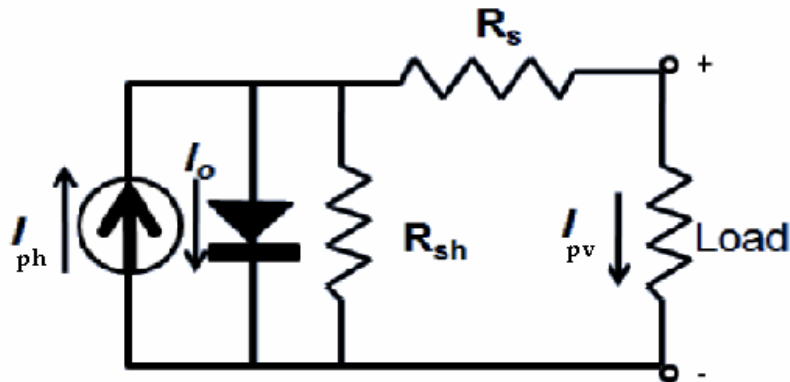

Figure 4.1

4.2 Mathematical Equation for Modeling Photovoltaic Cell.

The photovoltaic can be model mathematically by using equation (1)-(4).

$$I_{rs=} \frac{I_{scr}}{[\exp{(q*V0/(Ns*k*A*T))}]} \dots\dots\dots\dots\dots (1)$$

The Module saturation current I0 varies with the cell temperature which is given by

I0=Irs*[T/Tr]^3*exp[q*Ego*{(1/Tr)*(1/T)}]……(2)

Iph = [Iscr+Ki*(T-298)]*λ/1000………… (3)

The Current of the PV module is

Ipv=Np*Iph-Np*I0*[exp{(q*Vpv+Ipv*Rs)/NsAkT}]…(4)

Where, Vpv=V0, Np=1, Ns=36

In view of that, the current to the load can be given as:

$$I = I_{ph} - I_s(exp^{\frac{q(V+IR_S)}{NKT}} - 1) - \frac{(V+IR_S)}{R_{sh}} \quad (5)$$

Photovoltaic Cells:

Converting Photons to Electrons.

The solar cells that you see on calculators and satellites are also called photovoltaic (PV) cells, which as the name implies (photo meaning "light" and voltaic meaning "electricity"), convert sunlight directly into electricity. A module is a group of cells connected electrically and packaged into a frame (more commonly known as a solar

panel), which can then be grouped into larger solar arrays, like the one operating at Nellis Air Force Base in Nevada.

Photovoltaic cells are made of special materials called semiconductors such as silicon, which is currently used most commonly. Basically, when light strikes the cell, a certain portion of it is absorbed within the semiconductor material. This means that the energy of the absorbed light is transferred to the semiconductor. The energy knocks electrons loose, allowing them to flow freely.

PV cells also all have one or more electric field that acts to force electrons freed by light absorption to flow in a certain direction. This flow of electrons is a current, and by placing metal contacts on the top and bottom of the PV cell, we can draw that current off for external use, say, to power a calculator. This current, together with the cell's voltage (which is a result of its built-in electric field or fields), defines the power (or wattage) that the solar cell can produce.

That's the basic process, but there's really much more to it. On the next page, let's take a deeper look into one example of a PV cell: the single-crystal silicon cell.

4.3 Cell Temperature.

The cell temperature *Tcell*can be very different from the ambient temperature Ta and it depends on the solar irradiation *Ga*, *Ta* and also on the wind speed Ws. Solar irradiation acts on increasing *Tcell*and the wind speed has a cooling effect and lowers *Tcell.* If the PV panels are mounted in the regions with high wind potential, the wind speed must be considered. The forced (wind) convection is large for high wind speeds and the cell temperature function takes the following form:

$$T_{cell} = T_a + \frac{0.32}{(8.91 + \frac{2W_S}{0.67})} G_a * \omega$$

4.4 EFFECT OF VARIATION OF SOLAR IRRADIATION.

The P-V and I-V curves of a solar cell are highly dependent on the solar irradiation values. The solar irradiation as a result of the environmental changes keeps on fluctuating, but control mechanisms are available that can track this change and can alter the working of the solar cell to meet the required load demands. The higher the solar irradiation, the higher would be the solar input to the solar cell and hence power magnitude would increase for the same voltage value. With increase in the solar irradiation the open circuit voltage increases. This is due to the fact that, when more sunlight incidents on to the solar cell, the electrons are supplied with higher excitation energy, thereby increasing the electron mobility and thus more power is generated.

4.5 PV Cell Efficiency versus Cost.

This matrix provides an indication of the relationship between cost and efficiency of photovoltaic material. The most efficient, but also most costly remains the multi-junction material. Therefore, this material is only used in cases where area limitation is the most important factor, for instance in space technology. Otherwise, this material is only used in conjunction with concentrating devices as outlined above.

Note that this picture only shows the relationship between photovoltaic efficiency andcost ofphotovoltaic materialrather than cost of the total system**.** Low efficiency may impact on costs for mounting, wiring and land ownership, as more area needs to be covered for the same rated power. Hence, costs could go up further even when module costs per kWh are the same.
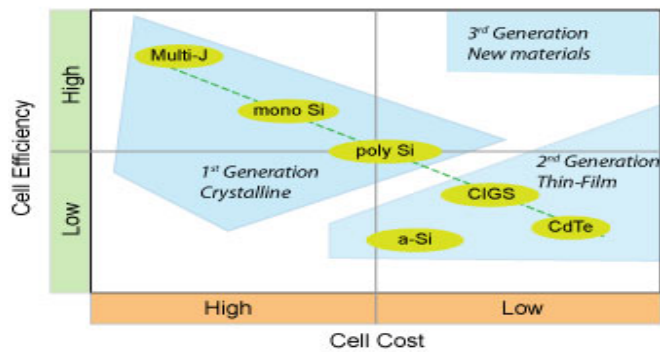
Figure 4.1

4.6 Photocurrent Principle.

With no pollutant emission, Photovoltaic cells convert sunlight directly to electricity. They are basically made up of a PN junction. Figure 1 shows the photocurrent generation principle of PV cells. In fact, when sunlight hits the cell, the photons are absorbed by the semiconductor atoms, freeing electrons from the negative layer. This free electron finds its path through an external circuit toward the positive layer resulting in an electric current from the positive layer to the negative one.
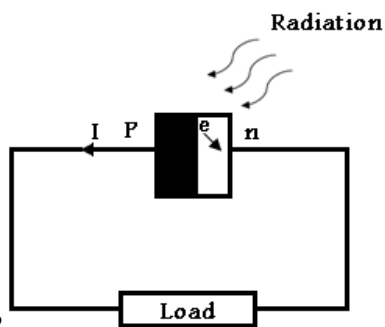

Figure 4.2

Typically, a PV cell generates a voltage around 0.5 to 0.8 volts depending on the semiconductor and the built-up technology. This voltage is low enough as it cannot be of use. Therefore, to get benefit from this technology, tens of PV cells (involving 36 to 72 cells) are connected in series to form a PV module. These modules can be interconnected in series and/or parallel to form a PV panel. In case these modules are connected in series, their voltages are added with the same current. Nevertheless, when they are connected in parallel, their currents are added while the voltage is the same.

4.7 Families of PV Cell.

Three major families of PV cells are monocrystalline technology, polycrystalline technology and thin film technologies. The monocrystalline and polycrystalline technologies are based on microelectronic manufacturing technology and their efficiency is in general between 10% and 15% for monocrystalline and between 9% and 12% for polycrystalline.

For thin film cells, the efficiency is 10% for a-Si, 12% for CuInSe2 and 9% for CdTe. Thus, the monocrystalline cell that has the highest efficiency is the focus of this paper. This paper carried out a Matlab/SIMULINK model of monocrystalline PV cell that made possible the prediction of the PV cell behavior under different varying parameters such as solar radiation, ambient temperature, series resistor, shunt resistor, diode saturation current.

Chapter 5   **MATLAB/SIMULINK BASED MODELLING OF SOLAR PHOTOVOLTAIC CELL.**

5.1 **<u>Software Used</u>**: Matlab/Simulink (Mathlab2012aw)

5.**2   SIMULINK Model of PV Module**.

5.**3 <u>Current-Input PV Module</u>**: This model is well suited for the case when modules are connected in series

and share the same current.

Input: Here, the inputs are;

PV current $IP\ V$ [A]

 Insolation [W/m2]

<u>Output:</u> Here the output are;

PV voltage VPV [V]

PV output power Ppv [W]

5.4 Voltage-Input PV module:

This model is well suited for the case when modules are connected in parallel and share the same voltage.

Inputs: Here the inputs are;

• PV voltage VPV [V]

• Insolation [W/m2]

<u>Outputs:</u> Here the outputs are

• PV current IPV [A]• PV output power Ppv [W]

Chapter 6 STEP BY STEP PROCEDURE FOR SIMULINK MODELING OF PV MODULE.

A model of PV module with moderate complexity that includes the temperature independence of the photocurrent source, the saturation current of the diode, and a series resistance is considered based on the Shockley diode equation. Being illuminated with radiation of sunlight, PV cell converts part of the photovoltaic potential directly into electricity with both I-V and P-V output characteristics.

6.1 Photovoltaic Module:

Module: A group of PV *cells* connected in series and/or parallel and *encapsulated* in an environmentally protective *laminate.*The PV module is the smallest package that produces useful power. The process involvedin manufacturing these modules requires high precision and quality control in order toproduce a reliable product. It is very difficult, and therefore not practical, to make homemademodules.
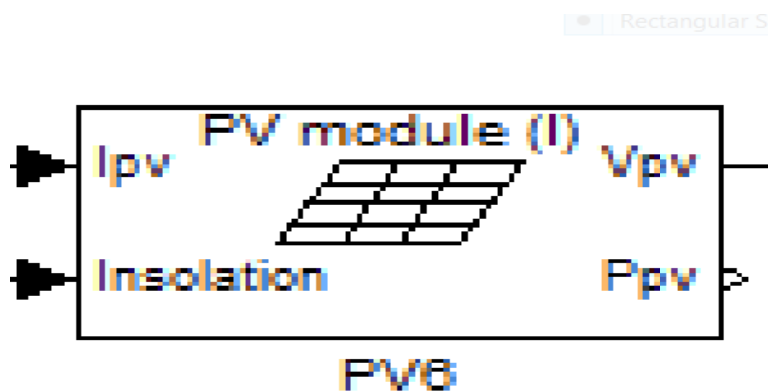

Figure 6.1

6.2 Subsystem:

A subsystem is a hierarchical grouping of blocks encapsulated by a single subsystem.Both PV module

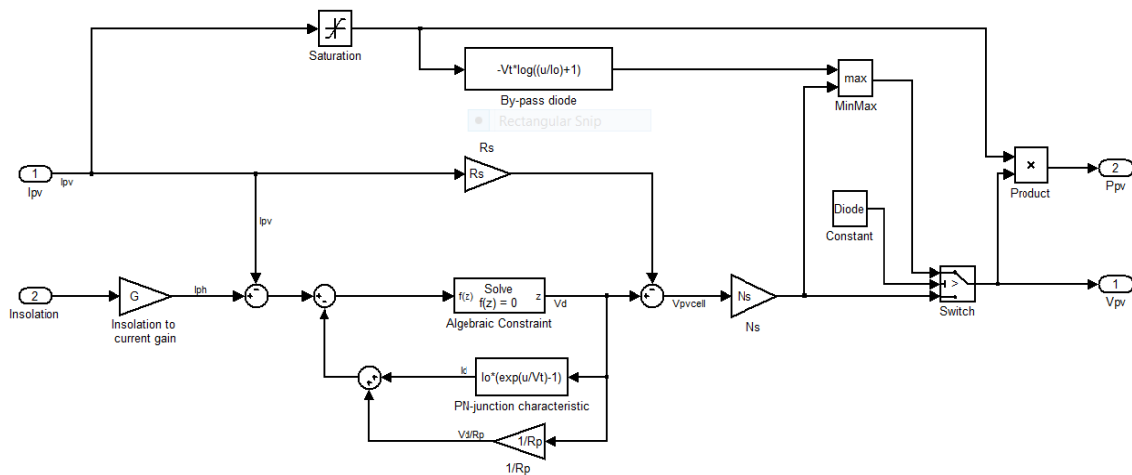models are implemented as masked subsystems in Simulink. The figure below illustrate the subsystem.

Figure 6.2

6.3 Photovoltaic Array.

Array: A group of *panels* that comprises the complete PV generating unit. The total of all the sub-arrays is then

called the complete PV array. The standoff-mounted PV array is the most common type of residential roof-top

installation. It is mounted above and parallel to the roof surface. It is located slightly above the roof for cooling

purposes and is parallel to the roof for aesthetic purposes

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This model contains an external control block permitting an uncomplicated variation of the models' parameters. In this model, 36 PV cell are interconnected in series to form one module. As a result, the module voltage is obtained by multiplying the cell voltage by the cells number while the total module current is the same as the cell's one.In order to get benefit from these developed models, an array of 6 PV modules has been constructed. In fact, these PV modules were interconnected in series and all of them are connected to the external control block as shown in figure 3.
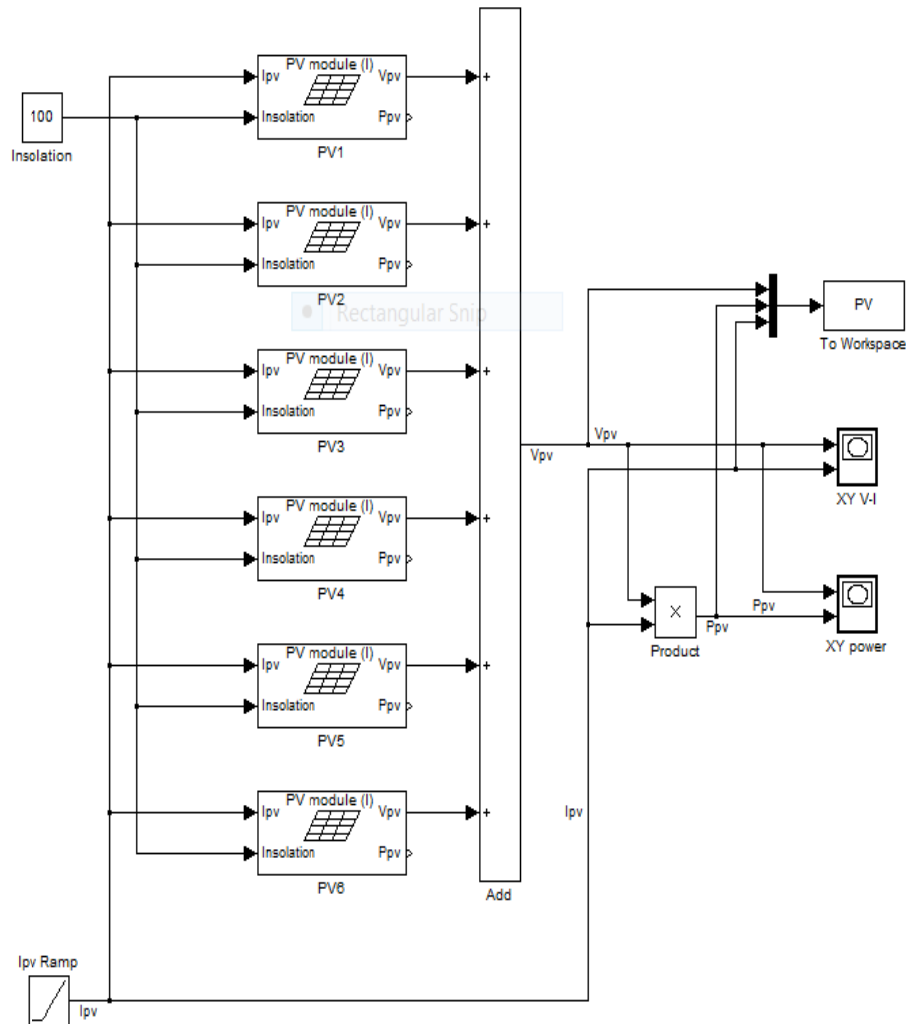

Figure 6.3

6.4 **Photovoltaic Module characteristics**

Current-Voltage Curve: I-U Characteristics.

The I-V equation can only be solved iteratively. Figure4 shows a typical curve using Simulink.
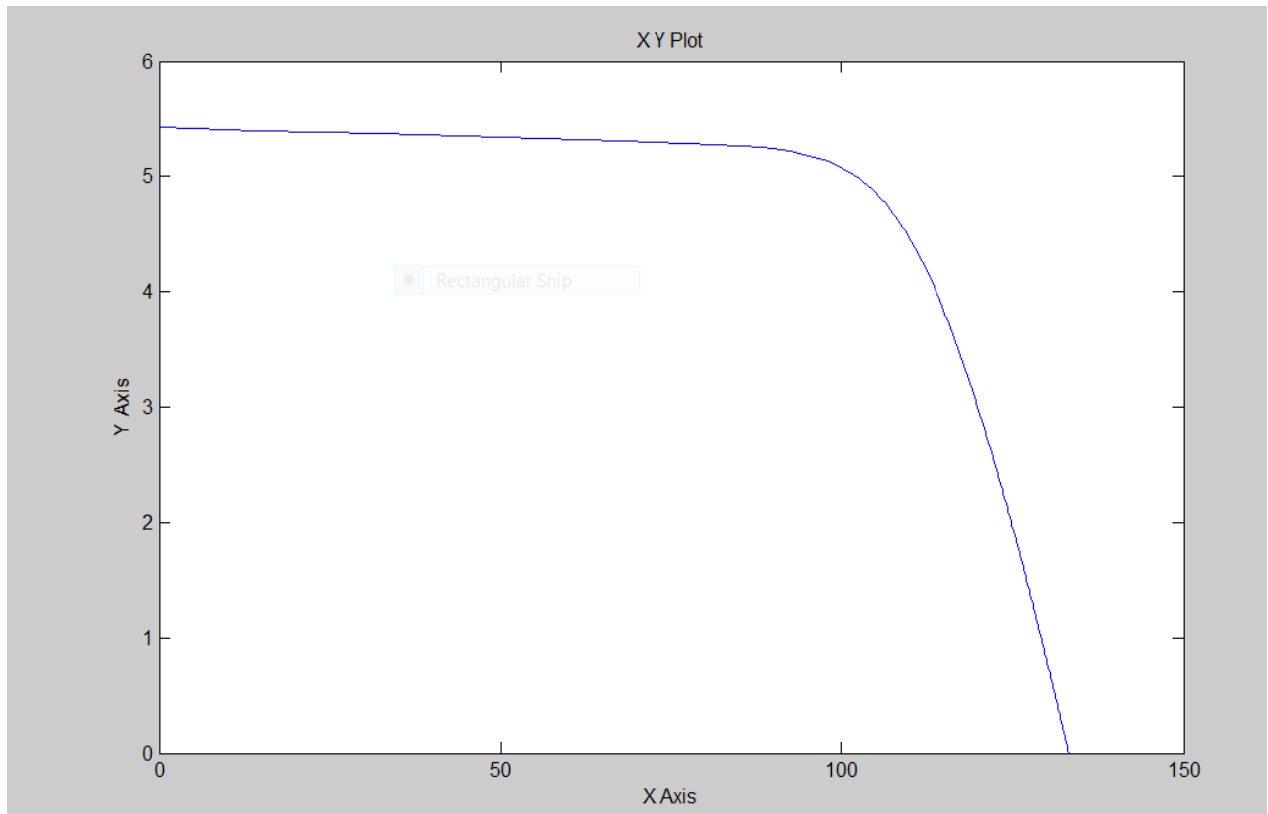

Figure 6.4

6.5 **P-V Curve OF PV MODEL (at 1000w/sq.m):**

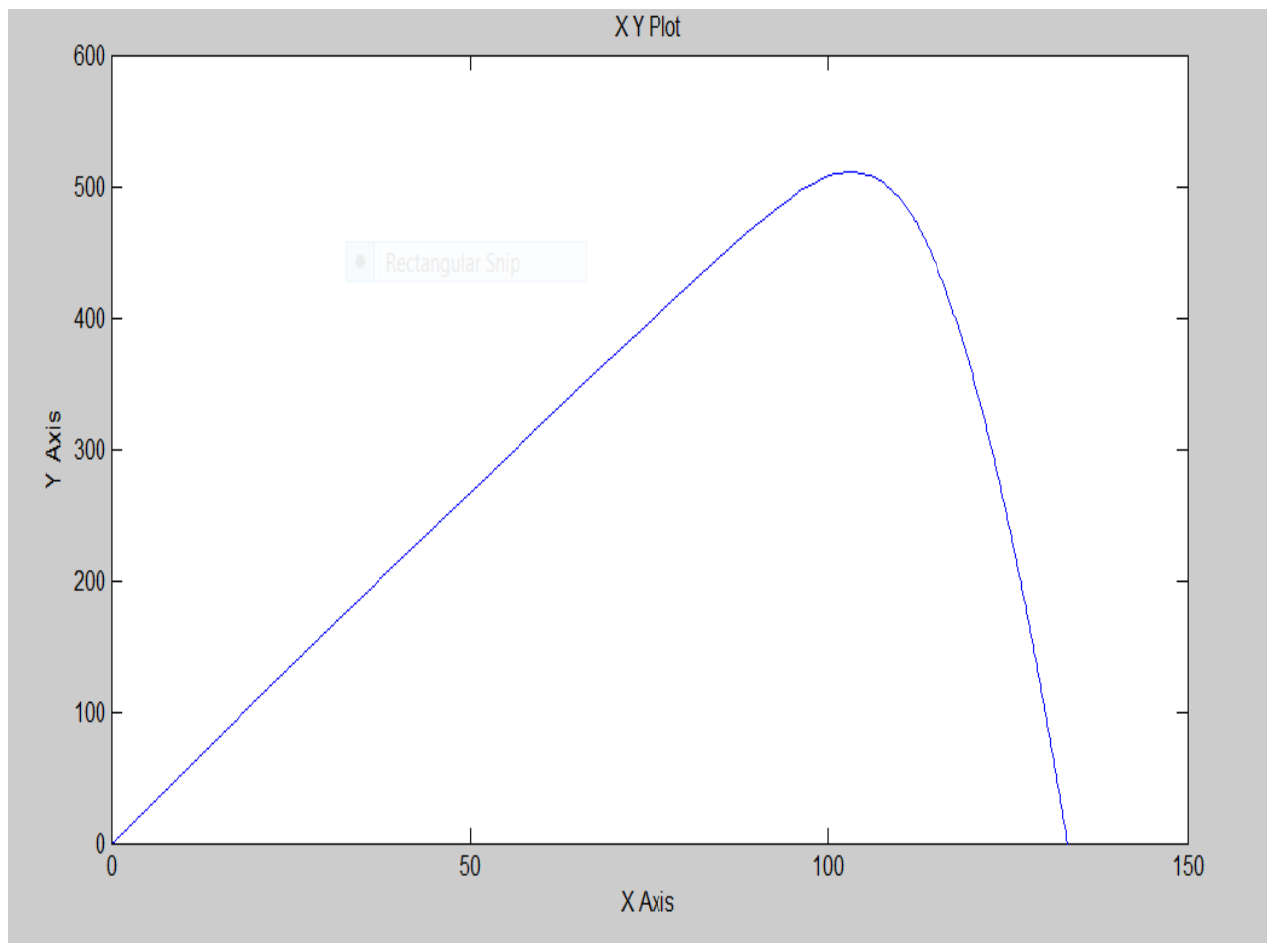Figure5 below shows the power-voltage curve at 1000W/sq.m

Figure 6.6

Chapter 7The I-V output characteristics of PV module with varying irradiation at constant temperature.

The I-V output characteristics of PV module with varying irradiation at constant temperature is shown in the curve below. These curves were generated using matlab code.

7.1 I-V Curves of PV Module Model (at 1000, 800,600,400,200) with varying irradiation

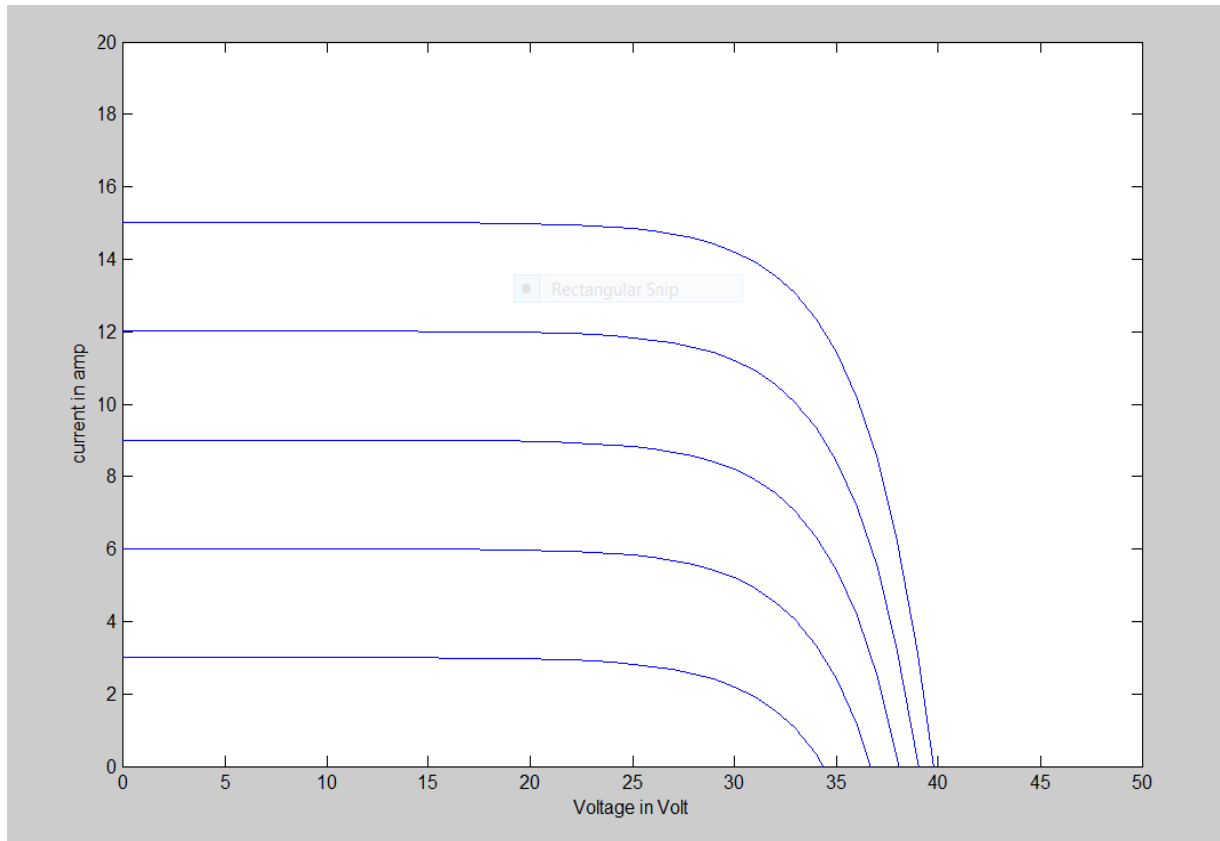Figure 7.2

7.2 P-V characteristics with varying irradiation.

The P-V output characteristics of PV module with varying irradiation at constant temperature is shown in the curve below. These curves were generated using matlab code.
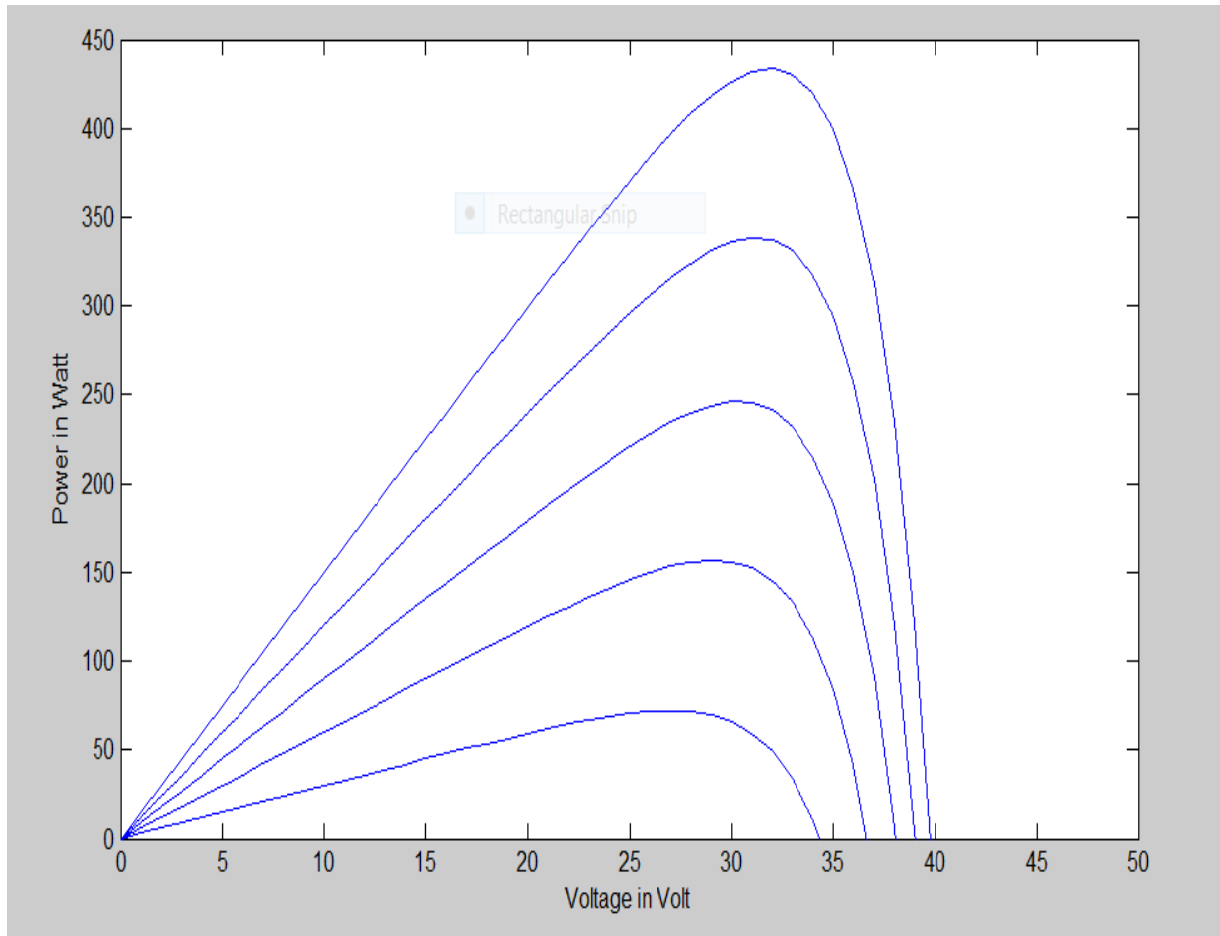

Figure7.3

7.3 Matlab code to plot P-V and I-V.

```
clc

Clear all

Close all

T=28+273;

Tr1=40;            % refrence temp. in degree Fahrenheit

Tr=((Tr1-32))+273;       %reference temp. in kelvin

S=[100 80 60 40 20];        %solar radiation in mW/sq.cm

ki=0.00023; % in A/K

Iscr=3.75;               %SC current at reference temperature in A

Irr=0.000021;           % in A

k=1.38065*10^(-23);              %Boltzmann constant

q=1.6022*10^(-19);              % charge of an electron

A=2.15;

Eg0=1.166;

Alpha=0.473;

Beta=636;

Eg=Eg0-(alpha*T*T)/(T+beta)*q;         %band gap energy of semiconductor used

                                        %cell in joules

Np=4;

Ns=60;
```

```
V0=(0:1:300);

For i=1:5

Iph=(Iscr+ki*(T-Tr))*((S(i))/100);

Irs=Irr*((T/Tr).^3)*exp(q*Eg/(k*A)*((1/Tr)-(1/Tr)));

   I0=Np*Iph-Np*Irs*(exp(q/(k*T*A)*V0./Ns)-1);

   P0=V0.*I0;

figure(1)

plot(V0,I0);

axis([0 50 0 20]);

xlabel('Voltage in Volt');

ylabel('current in amp');

hold on;

figure(2)

plot(V0,P0);

axis([0 50 0 700]);

xlabel('Voltage in Volt');

ylabel('Power in Watt');

hold on;

end.
```

Conclusion

A Matlab/SIMULINK model for the solar PV cell, modules and array was developed and presented in this paper. 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 the solar radiation and cell temperature. The module model was simulated and validated experimentally using the high efficient PVL-124 solar laminate panel.

As a result of the study, one can benefit from this model as a photovoltaic generator in the framework of the Sim-Power-System Matlab/SIMULINK toolbox in the field of solar PV power conversion systems. In addition, such a model would provide a tool to predict the behavior of any solar PV cell, module and array under climate and physical parameters changes.

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