

**T.C.
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCE**

**A GENERALIZED MODEL OF GRID CONNECTED
PHOTOVOLTAIC SYSTEM
WITH MAXIMUM POWER POINT TRACKING CONTROL**

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**A MASTER OF SCIENCE THESIS
DEPARTMENT OF ELECTRONIC AND COMMUNICATION ENGINEERING
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This paper, which is prepared by Sayema SHAHIDUL has been accepted as a MASTER of SCIENCE THESIS in the department of Electronic and Communication Engineering of The Graduate School of Natural and Applied Sciences by the juries given below on 09.03.2011.

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This thesis work is based on the maximum power point tracking control of a photovoltaic system on MATLAB and simulink environment .

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Sayema Shahidul

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LIST of SYMBOLS

I_s	Short circuit current
V_{oc}	Open circuit voltage
I_{PV}	Photovoltaic output current
V_{PV}	Photovoltaic output voltage
I_{ref}	Reference Voltage
I_d	Diode current
I_0	The reverse saturation current of diode
Q	The electron charge ($1.602 \cdot 10^{-19}$ C)
V_d	The voltage across the diode
K	The Boltzmann's constant ($1.381 \cdot 10^{-23}$ J/K)
R_s	Cell series resistance
R_p	Cell shunt resistance
A	Diode quality factor
G	Irradiance
D	Duty cycle
α_s	Solar azimuth angle
α	Azimuth angle of PV generator
β	Tilt angle of PV generator
γ_s	Solar Incidence or elevation angle
h_s	Solar hour angle
L	Latitude
H_o	Solar irradiance over atmosphere
H	Solar irradiance over a panel surface on earth

LIST of ABBREVIATION

PV	Photovoltaic
MPPT	Maximum Power Point Tracking
AM	Air Mass
KWp	Kilo Watt peak
KWh	Kilo Watt hour
GW	Giga watt
MW	Mega watt
KVA	Kilo Volt Ampere
PWM	Pulse with Modulation

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ABSTRACT

A GENERALIZED MODEL OF GRID CONNECTED PHOTOVOLTAIC SYSTEM WITH MAXIMUM POWER POINT TRACKING CONTROL

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Department of Electronic and Communication Engineering
MSc. Thesis

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This paper takes a look at the simulation model of photovoltaic cell in order to study the electrical behavior of the photovoltaic cell with respect to the changes of environmental parameters such as temperature and solar irradiation level. Maximum power point tracking is the most important issue for the better performance of a photovoltaic system. Taking this in account, this paper also proposes the maximum power point tracking (MPPT) control system for photovoltaic (PV) module using the Perturb and Observe algorithm and the system design of single phase grid connected photovoltaic system. For MATLAB simulation model BP SX 150S photovoltaic module is chosen. Module is made of 72 multi-crystalline silicon solar cells in series and 150W of maximum nominal power. Maximum power point tracking control is implemented over this selected type of module and the effect of variable solar resistance over module performance is also taken into account. Since photovoltaic (PV) energy utilization has increased interest in electrical power applications, it is very much essential to develop a simulation model of the PV system for simulation studies. It is crucial to operate the PV energy conversion

system near the maximum power point to increase the efficiency of the PV system. Because of nonlinear nature of PV system, the current and power of the PV array depends on the array terminal operating voltage. In addition, the maximum power operating point varies with solar irradiance level and temperature. Therefore the tracking control of the maximum power point is most important issue for a successful PV system.

Key Words: Photovoltaic, solar energy system, maximum power point tracking control, simulation.

ÖZET

MAKSİMUM GÜÇ NOKTASI BULUNAN BİR KONTROL SİSTEMİ İLE ÇALIŞAN ŞEBEKEYE BAĞLI BİR FOTOVOLTAİK SYSTEMİN GENEL TASARIMI

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Tez Danışmanı: Prof. Dr. Taner ŞENGÖR

Bu çalışmada, fotovoltaik hücrenin elektronik karakteristiğinin söz konusu fotovoltaik hücrenin simulasyon modeline dayanılarak elektrik devresine gelen güneş ışını ve çevre sıcaklığı ile değişimi incelenmiştir. Maksimum güç izleme bir fotovoltaik sistemin daha iyi performans için en önemli konudur. Bunu dikkate alınarak, bu çalışmada Perturb & Observe algoritma kullanarak fotovoltaik modülün maksimum güç noktası bulunan bir kontrol sistemi tanımlanması ve şebekeye bağlı fotovoltaik sistemin tasarımı amaçlanmıştır. Fotovoltaik modül için MATLAB Simülasyon Modeli BP SX 150S'ı seçilmiştir. Modül, 72 multi-kristal silisyum güneş pilleri (hücre) seri olarak ve maksimum nominal gücü 150W olacak şekilde yapılmıştır. Bu tip modül üzerinde değişken güneş direnç etkisi göz önüne alınarak maksimum güç takibi kontrolü uygulanmıştır. Fotovoltaik enerji kullanımı elektrik güç uygulamalarında artan bir ilgi ve öneme sahip olduğundan simulasyon çalışmaları için PV panel simulasyon modellerinin daha çok geliştirilmesi gerekmektedir. PV sisteminin etkinliğini arttırmak için maksimum güç noktasına yakın PV enerji dönüştürme sistemi oluşturulmalıdır. PV sisteminin doğrusal olmayan davranışlarından dolayı PV sisteminin gücü ve akımı,

düzenine sonundaki çalışma voltajına bağlıdır. Maksimum güç uygulama noktası güneşin sıcaklığına ve ışınma seviyesine göre değişmektedir. Bu nedenle PV sisteminin başarılı olması maksimum güç noktasının kontrol izi uygulanması ile olanaklıdır.

Anahtar Kelimeler: Fotovoltaik, güneş enerji sistemi, maksimum güç noktası kontrol, simulasyon

INTRODUCTION

1.1 Global Energy Demand

The energy demand is increasing day by day for this reason the need for renewable sources those will not harm the environment are of prime importance. The main driver of the energy demand is the economic growth. According to International Energy Outlook 2010 reference, world energy consumption increases by 1.4 percent per year. In 1990 the amount of energy consumption was 355 quadrillion Btu which became 495 quadrillion Btu in 2007 [1]. According to the reference this amount will be 739 quadrillion Btu in 2035 (Table 1.1).

Table 1.1 Global energy consumption over different years according to International Energy Outlook 2010 reference .

Year	Energy consumption in quadrillion Btu	Year	Energy consumption in quadrillion Btu
1990	355	2015	355
1995	375	2020	590
2000	406	2030	687
2007	495	2035	739

According to the increase of the energy demand, the rising of global fossil fuel use will be noticeable. This increase of usage in the fossil fuels will drive up the energy related

CO₂ emissions. Yet majority of the energy requirements is satisfied by fossil fuels but the use of photovoltaic systems could help in supplying the energy demands for the betterment of environment.

1.2 Aim of this Thesis

This paper deals with the modeling of photovoltaic module and proposes the identification of maximum power point tracking (MPPT) control for photovoltaic (PV) module using the Perturb-Observe algorithm to increase the efficiency and an estimated design of grid connected PV system

PHYSICS OF PHOTOVOLTAIC SYSTEM

Photovoltaic (PV) technology is to convert sunlight directly into electricity. The word photovoltaic is a combination of two words. The word “photo” means light and “voltaic,” electricity. A photovoltaic (PV) cell is also known as solar cell. It is a semiconductor device that generates electricity when light falls on it. Although photovoltaic effect was found in 1839 by the French scientist Edmund Becquerel, it was not fully understandable until the development of quantum theory of light and solid state physics.

Photovoltaic systems are designed with the photovoltaic cells. As a typical photovoltaic cell produces less than 3 watts at approximately 0.5 volt dc for high power application, cells are configured into modules and modules are connected as arrays. Modules may have peak output power ranging from a few watts to more than 300 watts. Typical Photovoltaic array output power is from 100 watts to kilo watts range although megawatt array do exists.

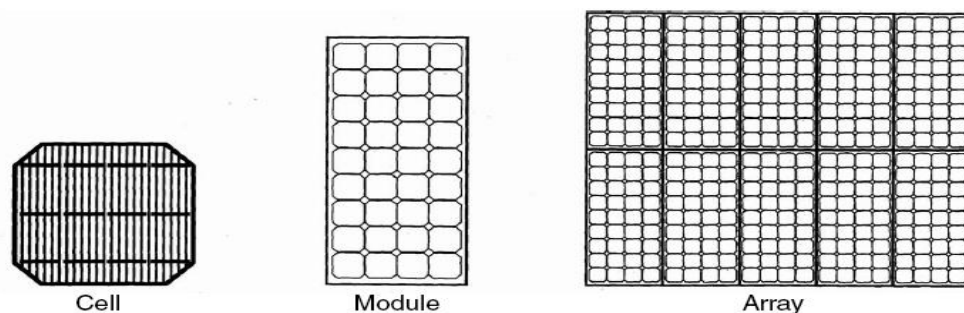


Figure 2.1 PV cell, Module and Array[2].

2.1 Photovoltaic Effect

When light falls on a metal it either been reflected, transmitted or absorbed. The absorption of light is simply the conversion of the energy contained in the incident photon to some other form of energy typically heat. Some materials however have some properties to convert the energy of the incident photons to electricity [3].

When photon energy is absorbed it interacts with atoms of the absorbing material by giving off its energy to an electron in the material. This energy transfer is happened according to the rule of conservation of momentum and conservation of energy. Depending on the energy of the photon an electron may be raised to higher energy state within an atom or it may be liberated from the atom. Free electrons are then capable of moving through the crystal.

2.1.1 Photon Absorption

In photovoltaic energy conversion, we look for to convert solar energy into electricity. This works on the basis of principle of the p-n junction. If a semiconductor material such as silicon (Si) is doped with group 3th or 5th impurities (Ph, Br), the electron hole balance changes as below;

Doped with phosphorous impurity (Excess Holes) P-type

Doped with boron impurity (Excess Electrons) N-type

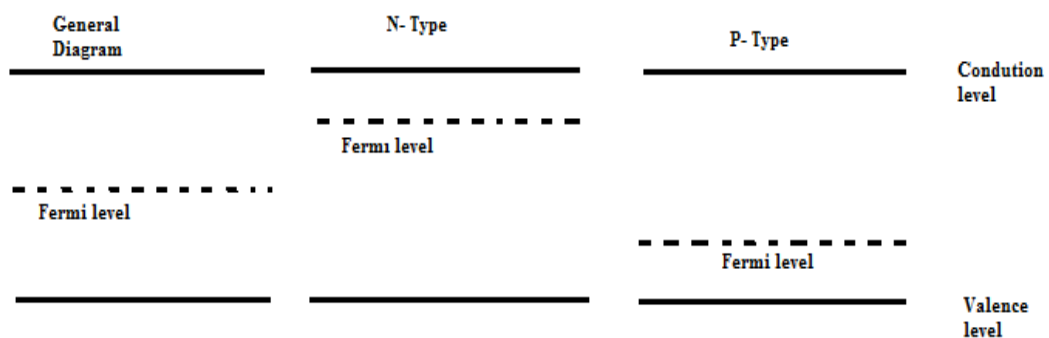


Figure 2.2 Energy band diagram for semi conductor.

The Fermi level usually depicts the actions of such a material, as electrons conduct in the conduction band, while holes conduct in the valance band. This has been shown in the figure (2.2). In the p- type semiconductor, the Fermi level is closer to the valance band, while in the n-type material the Fermi level is closer to the conduction band.

If a p-type semiconductor is joined with an n-type semiconductor, a p-n junction material is formed. Due to the opposite variation experienced in both, the Fermi level becomes equal and balanced in the middle.

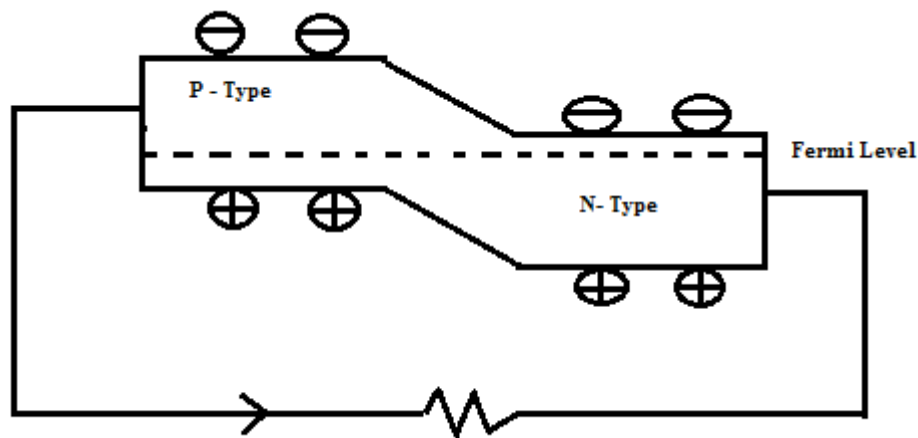


Figure 2.3 p-n junction Band diagram

Due to this phenomenon the electrons find it difficult to go up the band hill and holes find it difficult to go down the band hill, thus making the system act as a diode.

2.1.2 The PV Cell

In a photovoltaic cell, when light is incident on this material and if this light energy is greater than the band gap energy(Fermi level) , electron will absorb this energy and move from their positions, thus making it free and a hole is created in its place. The free moving electrons will flow downhill, while the holes go uphill. This will be the consequence of a large concentration of electrons on the n-side and a large concentration of holes on p-side. These charges can be extracted and made the current flown in the system by connecting it as shown in the figure 2.4.

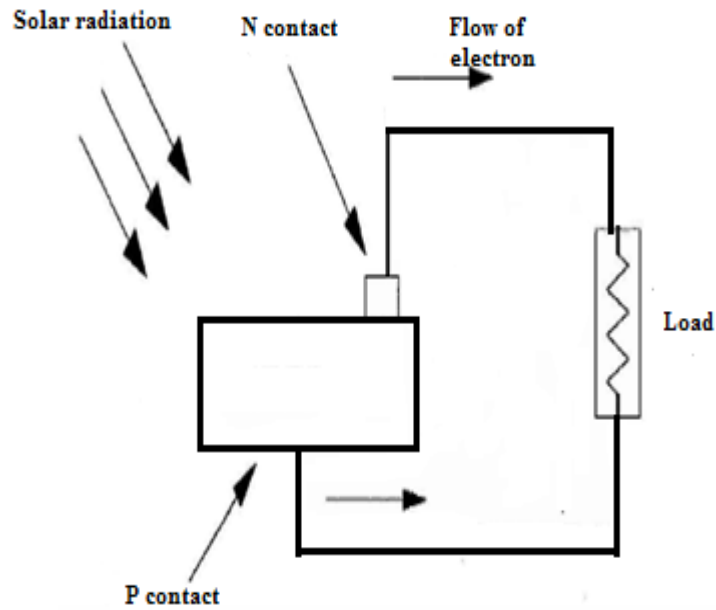


Figure 2.4 PV effect converts the photon energy into voltage across the p-n junction.

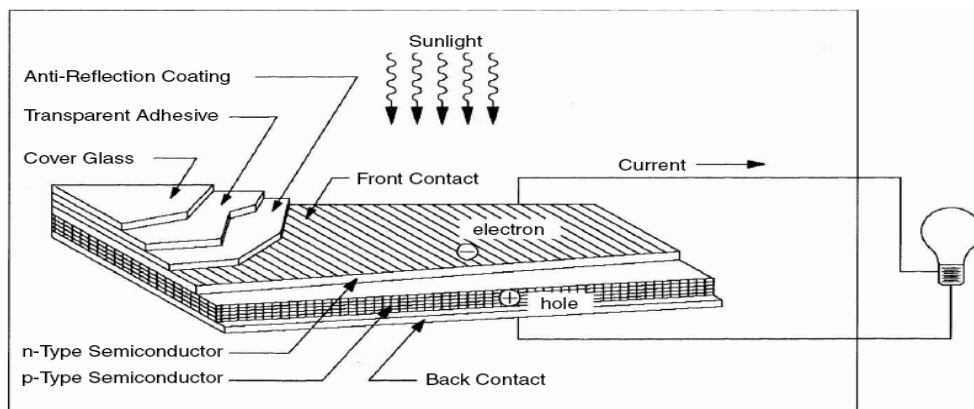


Figure 2.5 Basic construction of PV cell with performance-enhancing features (current collecting silver mesh, antireflective coating, and cover-glass protection)[4].

Metallic wires are provided on both sides of the junction to collect electrical current induced by the photons. A thin conducting mesh of silver fibers placed on the top surface collects the current and lets the light passing through it. In addition to the basic elements, several enhancement features are also included in the construction. For example, the front face of the cell has an antireflective coating to absorb as much light as possible by minimizing the reflection.

The mechanical protection is provided by a cover glass. As long as there is light flowing into the cells, there are electrons flowing out of the cells. The cell never use up its electrons and loose power, like a battery. It is just a converter, changing one kind of energy to other. For every electron that flows out the wire connected, there is another electron flowing into the back from the other return wire. The cell is a part of a circuit, where the same electrons just travel around the same path, getting energy from the sunlight and giving that energy to the load.

CHAPTER 3

PHOTOVOLTIC MODEL

Complete Photovoltaic system consists of two elements. One is a module, which contains solar cells, and the other is the “Balance-of-System” (BoS). The Balance of system mainly consists of electronic components like converter, Inverter, cabling, support structures and, electricity storage and sun trackers.

Two major types of PV systems are available in the market place today:

- Flat plate
- Concentrators.

As the most prevalent type of PV systems, flat plate systems build the PV modules on a rigid and flat surface to capture sunlight. Concentrator systems use lenses to concentrate sunlight on the PV cells and increase the cell power output. Comparing the two systems, flat plate systems are typically less convoluted but needs a larger number of cells while the concentrator systems use smaller areas of cells but require more sophisticated and expensive tracking systems. The concentrator system is unable to focus on diffuse sunlight so this system does not work under cloudy conditions.

3.1 Types of PV cell materials

PV cells are made of semiconductor materials. The major types of materials are crystalline and thin films, which vary from each other according to the efficiency of light absorption and energy conversion, manufacturing technology and cost of production [5].

The type of PV cells are as follows:

a. Crystalline Materials

- Single-crystal silicon
- Polycrystalline silicon
- Gallium Arsenide (GaAs)

b. Thin Film Materials

- Amorphous Silicon (a-Si)
- Cadmium Telluride (CdTe)
- Copper Indium (CuInSe₂, or CIS)

Crystalline silicon has been most commonly used for the PV cells for the past two decades. However, recent progress in the thin-films technology has led many industry experts to believe that thin-films PV cells will ultimately dominate the marketplace.

3.2 PV cell modeling

The use of equivalent circuits makes it achievable to model characteristics of a PV cell. The method is implemented in MATLAB programs for simulations. For modeling a PV module, the same modeling technique is also applicable.

Two key parameters often used to characterize a PV cell and they are

- The Short-circuit current
- The Open circuit voltage

If the terminals of the cell are shorting together, the photon generated current (I_{ph}) will flow out of the cell as a short-circuit current (I_{sc}). Thus, $I_{ph} = I_{sc}$, when there is no connection to the PV cell (open-circuit), the photon generated current is shunted by the internal intrinsic p-n junction diode. This gives the open circuit voltage, V_{oc} . The PV module or cell manufacturers usually provide the values of these parameters in their datasheets [6].

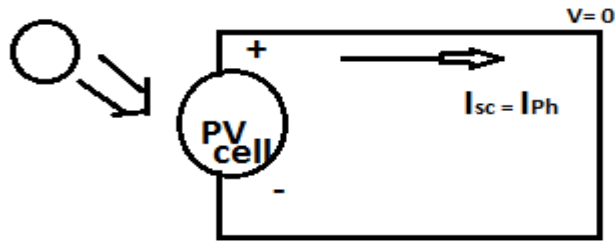


Figure 3.1 Showing a short circuit conduction.

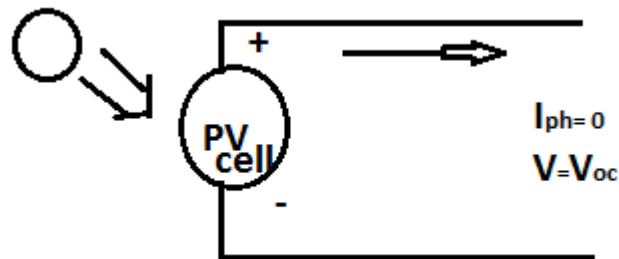


Figure 3.2 Diagram showing open circuit conduction.

PV cells can be modeled as a current source in parallel with a diode. When there is no light present to produce any current, the PV cell behaves like a diode. By applying the Kirchhoff's current law on the equivalent circuit shown in figure 3.3 the output current I of the PV cell is as below, where

$$I = I_{sc} - I_d \quad (3.1)$$

I_{sc} is the short circuit current and I_d is the current shunted through the diode.

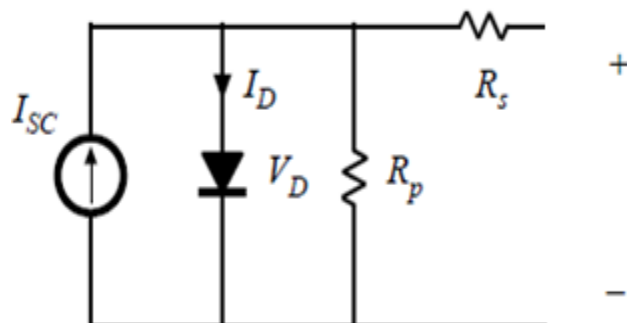


Figure 3.3 Equivalent circuit of PV cell.

The diode current I_d is given by the Shockley diode equation [7]:

$$I_d = I_o (e^{qV_d/kT} - 1) \quad (3.2)$$

Here, T , I_o , q , V_o and K are the junction temperature (Kelvin K), the reverse saturation current of diode, the electron charge (1.602×10^{-19} C), the voltage across the diode and the Boltzmann's constant (1.381×10^{-23} J/K) respectively.

Replacing I_d of the equation (3.1) by the equation (3.2) give the Current –Voltage relationship of the PV cell .

$$I = I_{sc} - I_o (e^{qV/kT} - 1) \quad (3.3)$$

Where V is the voltage across the PV cell, and I is the output current from the cell.

The reverse saturation current of diode (I_o) is invariable under the constant temperature and found by using the open circuit condition.

Let $I = 0$

then by using the equation (3.3),

$$I_{sc} = I_o (e^{qV_{oc}/kT} - 1) \quad (3.4)$$

$$I_o = \frac{I_{sc}}{(e^{qV_{oc}/kT} - 1)} \quad (3.5)$$

The PV cell or module are usually modeled under two categories and they are named as follows

- The Single Exponential Model
- The Double Exponential Model.

The single exponential circuit model is shown in Figure 3.4. The current is expressed in terms of voltage and other parameters as shown in Equation (3.7). Although this model

is widely used but according to the simulation and testing of photovoltaic modules the double exponential model (Figure 3.5) is more accurate [8].

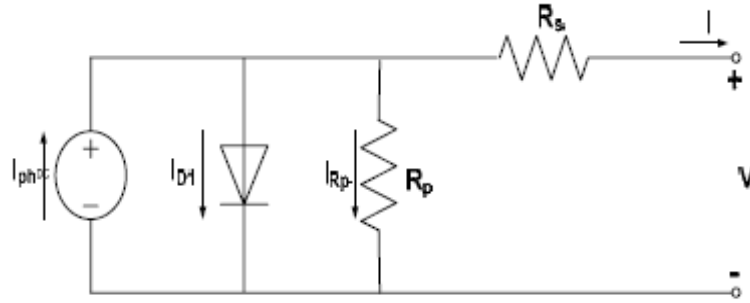


Figure 3.4 The single exponential model of photovoltaic cell [28].

$$I = I_{ph} - I_o \left\{ \exp \left[\frac{q(V + IR_s)}{AkT} \right] - 1 \right\} - \frac{V + IR_s}{R_p} \quad (3.6)$$

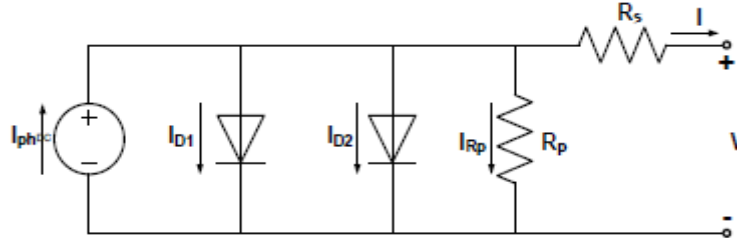


Figure 3.5 The double exponential model of photovoltaic cell.

$$I = I_{sc} - I_{o1} \left[e^{q \left(\frac{V + IR_s}{kT} \right)} - 1 \right] - I_{o2} \left[e^{q \left(\frac{V + IR_s}{2kT} \right)} - 1 \right] - \left(\frac{V + IR_s}{R_p} \right) \quad (3.7)$$

Where I_{ph} , I_{o1} , I_{o2} , R_s , R_p and A are the photo generated current , the saturation current 1, the saturation current , the cell series resistance , the cell shunt resistance and the diode quality factor respectively.

If the diode D1 and D2 are combined the above equation can be rewrite as follows

$$I = I_{sc} - I_o \left[e^{q \left(\frac{V + IR_s}{nkT} \right)} - 1 \right] - \left(\frac{V + IR_s}{R_p} \right) \quad (3.8)$$

Here n is known as the ideality factor and the value is between one and two .

3.3 Photovoltaic Module Modeling

A single PV cell produces an output voltage less than 1V, about 0.6V for crystalline silicon (Si) cells, thus a number of PV cells are connected in series to achieve a desired output voltage. When series-connected cells are placed in a frame, it is called as a module. Most of commercially available PV modules with crystalline-Si cells have either 36 or 72 series connected cells. A 36-cell module produces a voltage suitable for charging a 12V battery, and like a module with 72-cells is suitable for a 24V battery. Most of the PV systems use to have backup batteries on the other hand today many PV systems do not use batteries; for example, grid-tied systems. When the PV cells are wired together in series, the output current is the same as the single cell, but the output voltage is the sum of each cell voltage [9].

The design of modeling a PV module is similar to modeling a PV cell. The parameters are same, but only a voltage parameter the open-circuit voltage is different and must be divided by the number of cells.

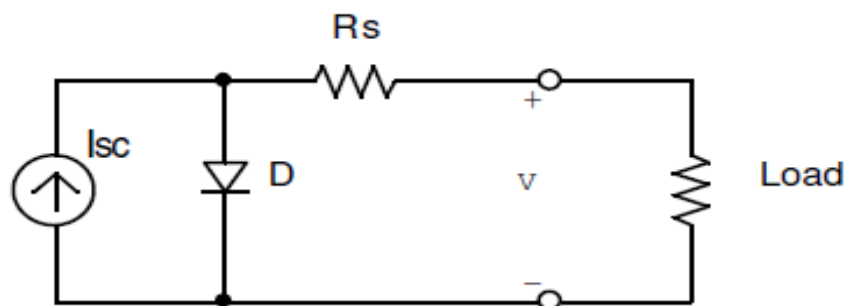


Figure 3.6 Equivalent circuit of PV Module.

Letting R_p is equal to infinity in the equation (3.8) we have

$$I = I_{sc} - I_o \left[e^{\frac{q(V+IR_s)}{nkT}} - 1 \right] \quad (3.9)$$

Here V is the cell voltage .If the module voltage is divided by the number of cells in series then V can be found.

If the temperature dependency of module is considered then we have

$$I_{sc} \Big|_T = I_{sc} \Big|_{T_{ref}} \cdot [1 + a(T - T_{ref})] \quad (3.10)$$

Here a is the temperature coefficient of I_{sc} in percent change per degree temperature also

given in the datasheet.

I_{sc} at T_{ref} is given in the datasheet (measured under irradiance of 1000W/m²),

T_{ref} is the reference temperature of PV cell in Kelvin (K), usually 298K (25oC),

The short-circuit current I_{sc} is proportional to the intensity of irradiance, thus I_{sc} at a given irradiance (G) is

$$I_{sc} \Big|_G = \left(\frac{G}{G_o} \right) I_{sc} \Big|_{G_o} \quad (3.11)$$

The reverse saturation current of diode (I_o) at the reference temperature (T_{ref}) is given by the equation (2.12)

$$I_o = \frac{I_{sc}}{\left(e^{\frac{qV_{oc}}{nkT}} - 1 \right)} \quad (3.12)$$

The reverse saturation current (I_o) is temperature dependant and the I_o at a given temperature (T) is calculated by the following equation

$$I_o \Big|_T = I_o \Big|_{T_{ref}} \cdot \left(\frac{T}{T_{ref}} \right)^{\frac{3}{n}} \cdot e^{\frac{-q.E_g}{n.k} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right)} \quad (3.13)$$

The diode ideality factor (n) is unknown and must be estimated. It takes a value between one and two; the value of $n=1$ for the ideal diode [10].

The value of R_s can be found by differentiating equation (3.9)

$$dI = 0 - I_o \cdot q \left(\frac{dV + R_s \cdot dI}{nkT} \right) \cdot e^{q \left(\frac{V + I \cdot R_s}{nkT} \right)} \quad (3.14)$$

$$R_s = - \frac{dI}{dV} - \frac{nkT/q}{I_o \cdot e^{q \left(\frac{V + I \cdot R_s}{nkT} \right)}} \quad (3.15)$$

The equation (3.9) is a non-linear equation and requires a numerical (solution. It is difficult to solve the equation because the solution of current is recursive as the influence of a series resistance has been included. The Newton-Raphson approximation is chosen as a means of solving this non-linear equation. It is possible to solve the equation (3.9) of I - V characteristics. by simple iterations, the Newton's method has been chosen. The Newton's method derives a solution to the non-linear equation.

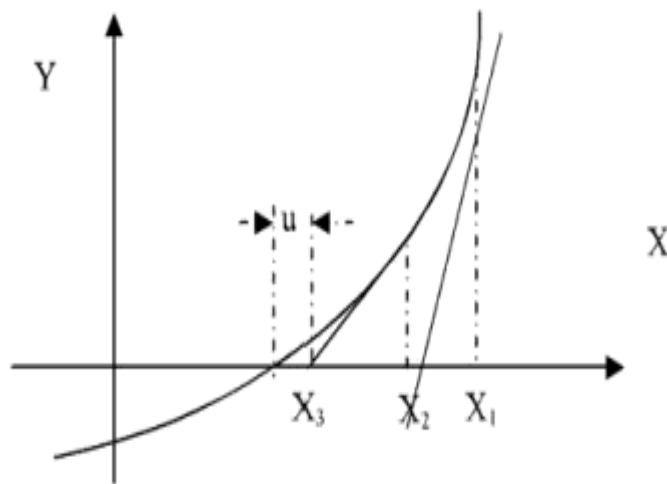


Figure 3.7 Explaining Newton Raphson Method[11].

From the above plot It can be seen that as the continuous tangent is taken from its intercept to the function curve, it tends to closer to the correct value of x, which can be gotten from its interception on X-axis. If X_3 is the final value then u will be the error margin.

From the above plot it can be described that,

$$\begin{aligned}
 X_2 &= X_1 - \frac{f(X_1)}{f'(X_2)}, \\
 X_3 &= X_2 - \frac{f(X_2)}{f'(X_3)} \\
 X_{n+1} &= X_n - \frac{f(X_n)}{f'(X_n)} \tag{3.17}
 \end{aligned}$$

Where $f'(x)$ is the derivative of the function, $f(x)$ and X_n is a present value, and X_{n+1} is a next value.

Considering the plot and the equation above, a step by step procedure can be deduced for evaluating the solution of the non linear equation presented by array of N_s number of cells in series.

Rewriting the equation (2.10) gives the following function:

$$f(I) = I_{sc} - I - I_o \left[e^{q \left(\frac{V+I.R_s}{nkT} \right)} - 1 \right] \tag{3.18}$$

$$f'(I) = -1 - I_o \left(\frac{q.R_s}{nkT} \right) e^{q \left(\frac{V+I_n.R_s}{nkT} \right)} \tag{3.19}$$

By replacing this into the equation (3.17) we have the following equation for the output current

$$I_{n+1} = I_n - \frac{I_{sc} - I_n - I_o \left[e^{q \left(\frac{V + I_n \cdot R_s}{nkT} \right)} - 1 \right]}{-1 - I_o \left(\frac{q \cdot R_s}{nkT} \right) e^{q \left(\frac{V + I_n \cdot R_s}{nkT} \right)}} \quad (3.20)$$

The equation 3.20 is being implemented using MATLAB code, which has been added in the appendix.

Solar cells can be thought as solar batteries. If solar cells are connected in series, then the current remains the same and the voltage increases. On other hand if solar cells are connected in parallel, the voltage remains the same, but the current increases.

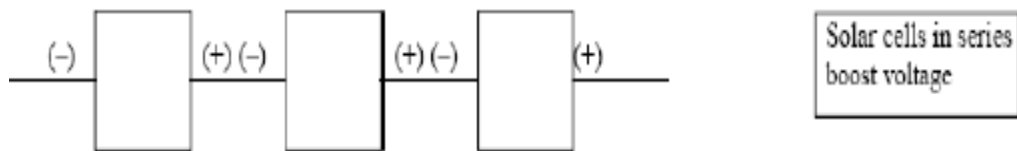


Figure 3.8 series connection of cells.

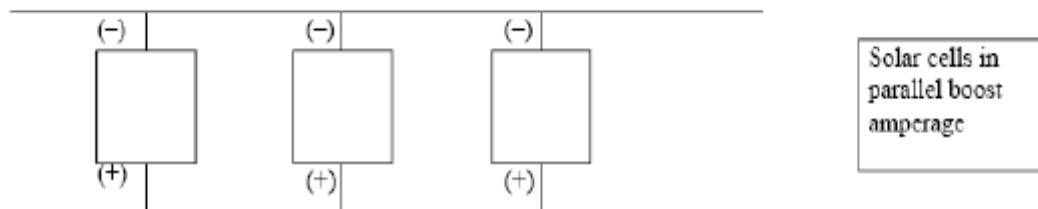


Figure 3.9 parallel connection of cells.

3.4 PV Module Modeling by MATLAB

BP Solar SX 150S PV module has been chosen for MATLAB Simulation Model. Module is made of 72 multi-crystalline silicon solar cells in series and 150w of maximum nominal power. The Data sheet of this PV module is given table 3.1.

Table 3.1 Data sheet of BP Solar BP SX 150S PV module

Electrical Characteristics	
Maximum Power (Pmax)	150W
Voltage at Pmax(Vmp)	34.5V
Current at Pmax(Imp)	4.35V
Open-circuit voltage(Voc)	43.5A
Short-circuit current(Isc)	4.75A
Temperature coefficient of Isc	$0.065 \pm 0.015\%/^{\circ}C$
Temperature coefficient of Voc	$-160 \pm 20mV/^{\circ}C$
Temperature coefficient of power	$-0.5 \pm 0.05\%/^{\circ}C$
NOCT	$47 \pm 2^{\circ}C$

3.4.1 The Standard V-I Characteristic Curve of Photovoltaic Module

A photovoltaic module will produce its maximum current when there is essentially no resistance in the circuit. This would be a short circuit between its positive and negative terminals. This maximum current is called the short circuit current, abbreviated I_{sc} . When the module is shorted, the voltage at the circuit is zero [12].

The I-V characteristic curve of the Module are shown through the following figures

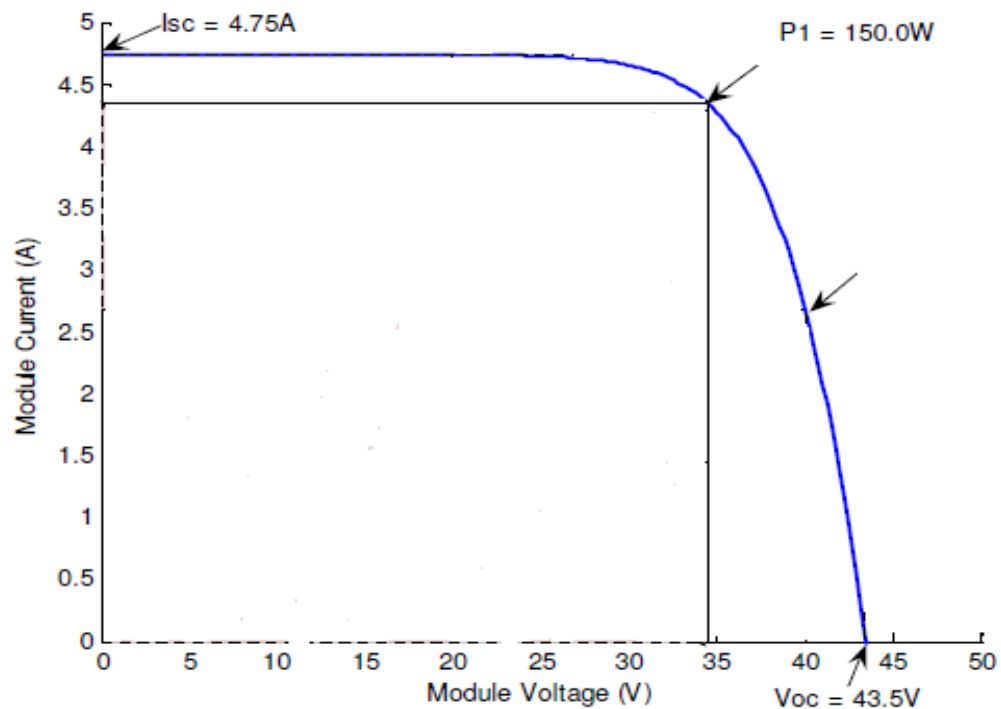


Figure 3.10 I-V characteristic curve.

Conversely, the maximum voltage is produced when there is a break in the circuit. This is called the open circuit voltage, abbreviated V_{oc} . Under this condition the resistance is infinitely high and there is no current, since the circuit is incomplete. Current, expressed in amps, is on the vertical Y-axis. Voltage, in volts, is on the horizontal X-axis as in the figure.

As it can be seen in above figure 3.10, the short circuit current occurs on a point on the curve where the voltage is zero. The open circuit voltage occurs where the current is zero. The power available from a photovoltaic module at any point along the curve is expressed in watts.

At the short circuit current point, the power output is zero, since the voltage is zero. At the open circuit voltage point, the power output is also zero, but this time it is because the current is zero. There is a point on the knee of the curve where the maximum power output is located. At that point the voltage is 34.5 volts, and the current is 4.35 amps. Therefore the maximum power is 150 watts.

The current-voltage (I-V) curve is based on the module being under standard conditions of sunlight (1000w/m^2) and module temperature (25°C). It assumes there is no shading on the module.

Two main factors affect the performance of solar cells. These are

1. Temperature
2. Solar Irradiance

3.4.2 Impact Of Solar Radiation on Characteristic Curve V-I Of Photovoltaic Module

Standard sunlight conditions on a clear day are assumed to be 1000 watts of solar energy per square meter (1000 W/m^2). This is sometimes called one sun, or a peak sun. Less than one sun will reduce the current output of the module by a proportional amount. In the figure 3.11 we can see that the output current of the module at 200w/m^2 is near about 1amp where as at 1000 w/m^2 the output current increased to 4.90 amps. If we look at the voltage changes for variable solar irradiance on 25°C temperature we can find that the difference is very small.

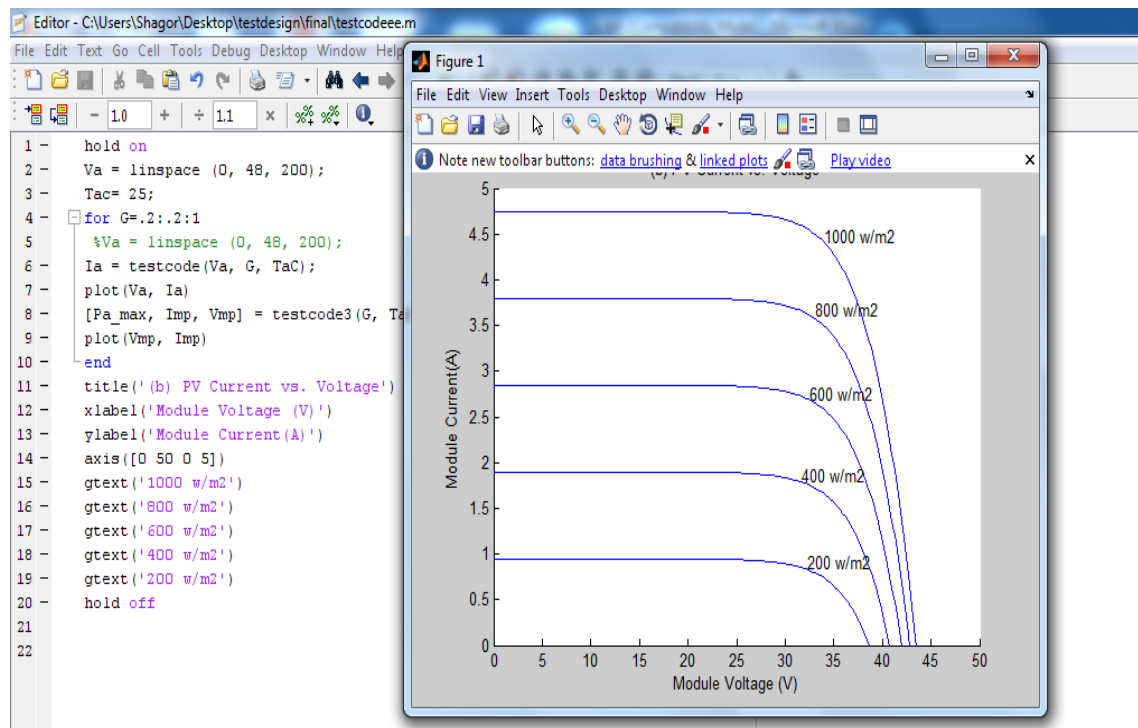


Figure 3.11 The I-V curve of the selected graph at different irradiance at 25°C .

3.4.3 Impact of temperature on V-I characteristic curve of Photovoltaic Module

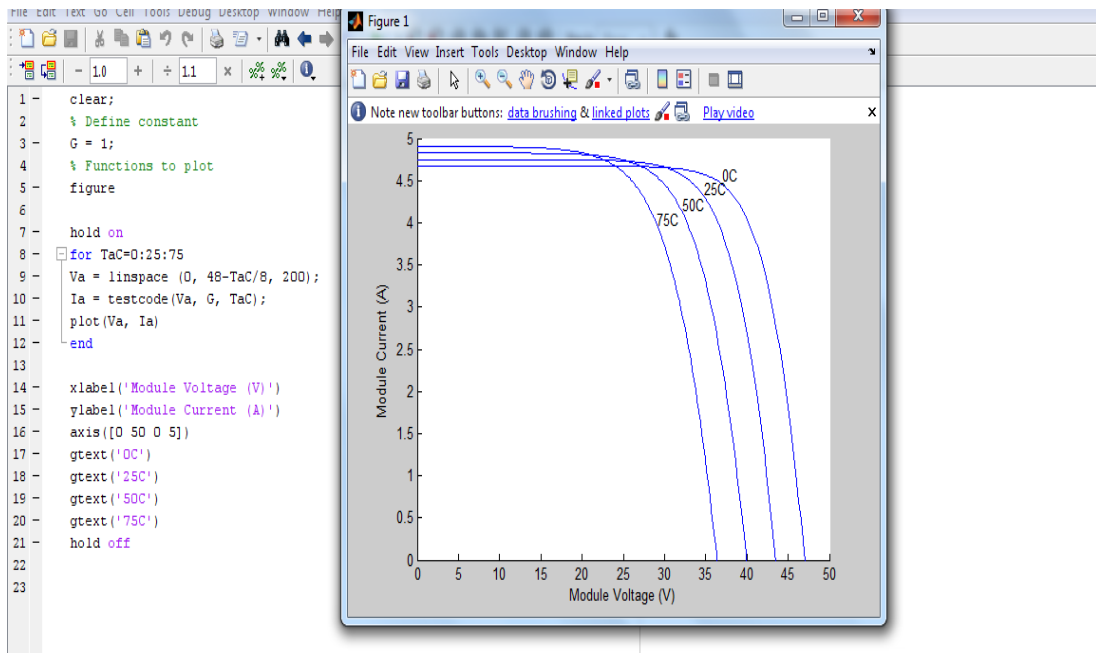


Figure 3.12 The I-V curve of the selected module at different temperature $T= 0^{\circ}, 25^{\circ}, 50^{\circ}, 75^{\circ}\text{C}$ ($G= 1000\text{w/m}^2$).

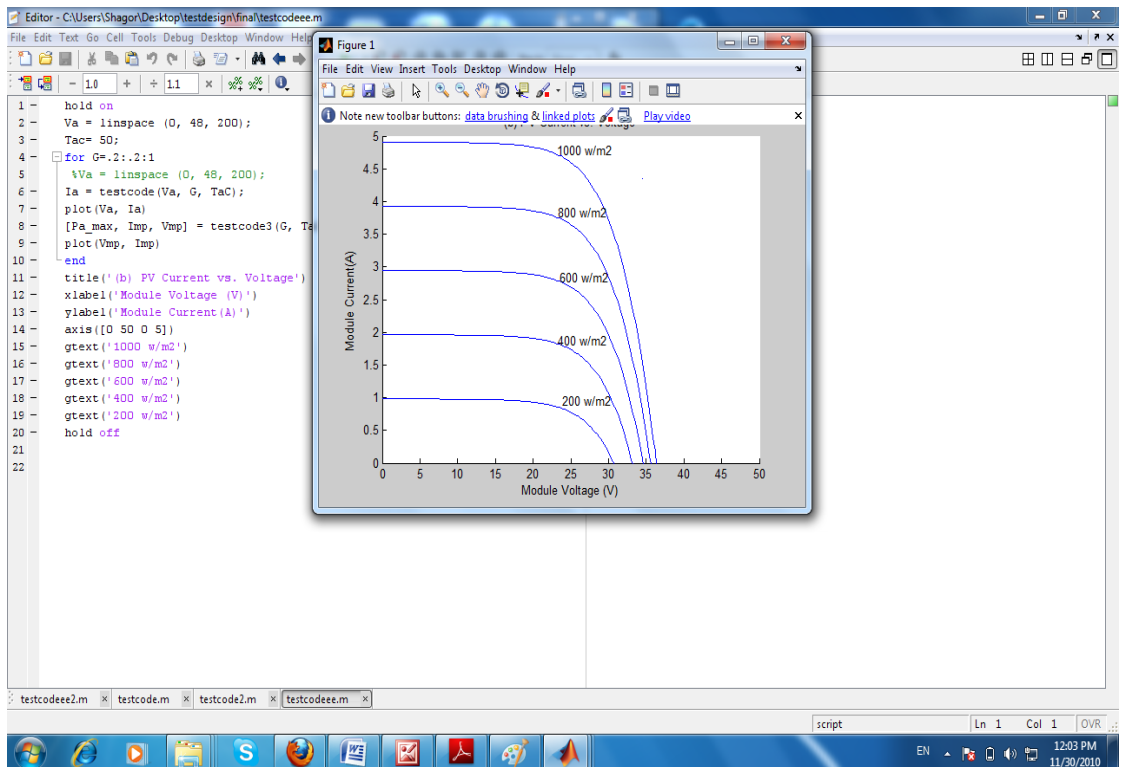


Figure 3.13 The I-V curve of the selected module with varying irradiance (G)/ ($T = 50^{\circ}\text{C}$).

Module temperature affects the output voltage inversely. Higher module temperatures will reduce the voltage by 0.04 to 0.1 volts for every one Celsius degree rise in temperature. Figure 3.12 is the I-V curve of the selected module at different temperature T is 0°, 25°, 50° , 75°C (G= 1000w/m²). Figure 3.13 The I-V curve of the selected module with varying irradiance (G) at T is 50°C.

CHAPTER 4

PV SYSTEM DESIGN

The PV system usually consists of a PV array, that converts solar energy to electrical energy, a DC/DC converter, that converts low dc voltages produced by the PV array to a high dc voltage, an inverter, that converts the high dc voltage to a single or three-phase ac voltage and a digital controller, that controls the system and implement the MPPT algorithm by controlling the current and voltage of the PV array. The MPPT algorithm is vital in increasing the efficiency of the system [12].

There are two types of PV system.

1. Stand alone PV system
2. Grid connected PV system

Stand alone PV system is much more popular than grid connected PV system .Now a days Grid connected PV system getting much more attention.

4.1 Stand Alone PV System

A stand-alone PV system is shown in Figure 3.1 with all necessary components such as PV panels, DC-AC inverter, DC-DC converters, MPPT controller and battery.

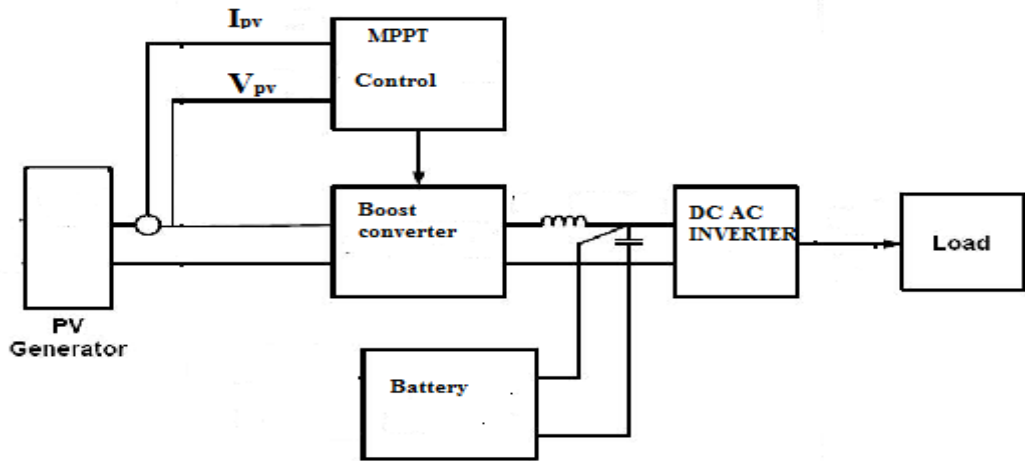


Figure 4.1 Stand alone PV system.

The PV panels are connected in series and parallel combinations to achieve the desired power capacity. DC-AC inverter is used to convert DC input from the PV generator to AC output at certain voltage level and frequency to be used for consumers. By the use of the battery, the excess power generated by the PV system is stored to be used when required. The DC-DC bidirectional converter is boosting the voltage level from the battery side to the higher level of inverter input side or it lowers the voltage from the inverter side to battery input side in order to be able to charge the battery in an appropriate voltage level. The MPPT controller is used to get the maximum power from the PV generator during the operation [13].

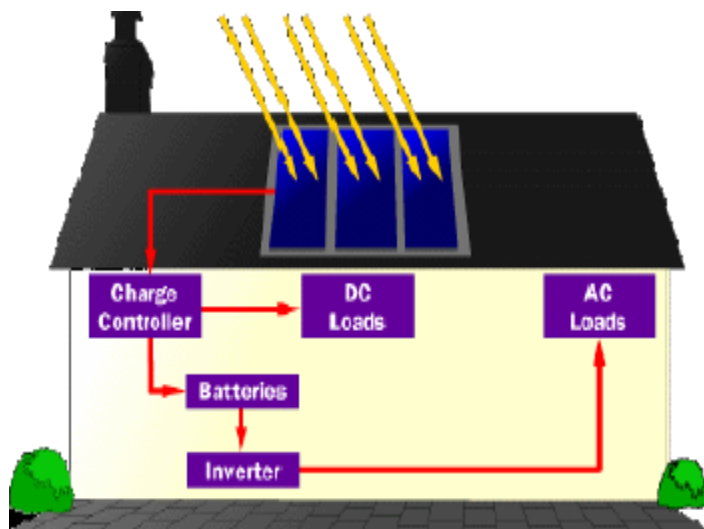


Figure 4.2 Application of stand-alone PV system[14].

4.2 Grid Connected PV System

In a grid-tied solar system, the DC electricity formed by the PV array is usually fed by cables into a PV array combiner box where they are connected together. A cable from this junction box goes to the DC/DC converter which usually steps up the DC output voltage and then DC electricity goes to the grid-tied inverter.

The inverter converts DC to AC, which is either consumed by the building loads and appliances or fed onto the grid. Power from a PV panel is DC while the utility grid requires AC power. The DC power from the PV panel must be converted to AC power of a suitable quality and injected into the grid. This is done using an inverter [15]).

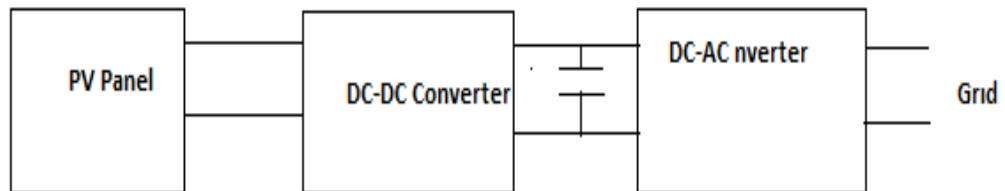


Figure 4.3 Grid connected PV system.

There are two main types of grid connected photovoltaic systems:

1. Grid connected photovoltaic system without battery backup.
2. Grid connected photovoltaic system with battery backup.

The Grid connected photovoltaic system with battery backup is more complicated but it is the only system which also confronts the issue of reliability of the grid supply. Its design is similar to the design of a combination between an uninterruptible power supply (UPS) and a Stand Alone Power System. In a grid connected photovoltaic system with battery backup, the system works as a standalone power system during grid failure to eliminate the use of a fuel generator/plant.

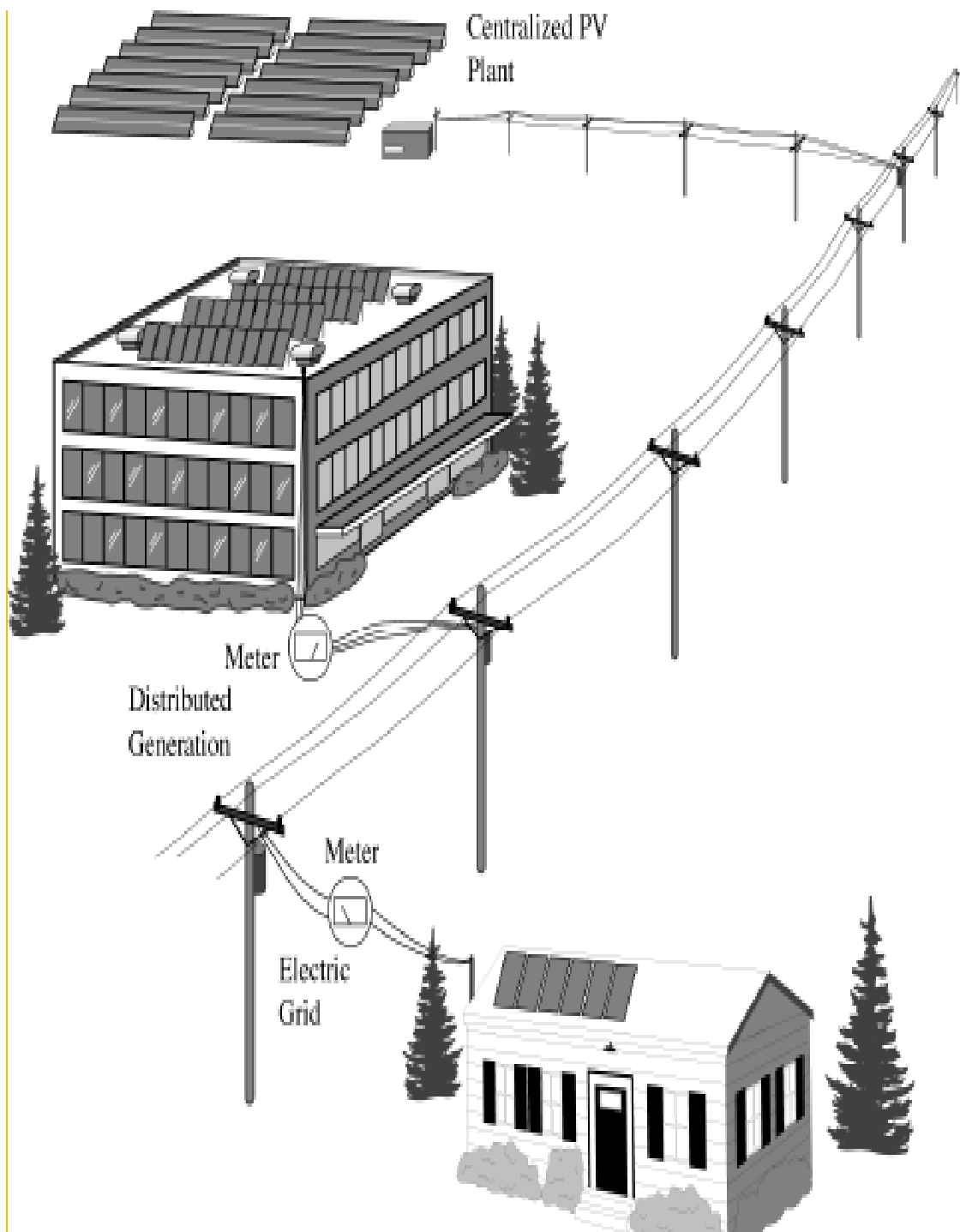


Figure4.4 Schematic diagram of different grid- connected photovoltaic systems [16].

4.3 DC-DC Steps Up Boost Converter

Step up boost up converter steps up the PV voltage. It boosts up the voltage with the change of duty cycle of pulse generator.

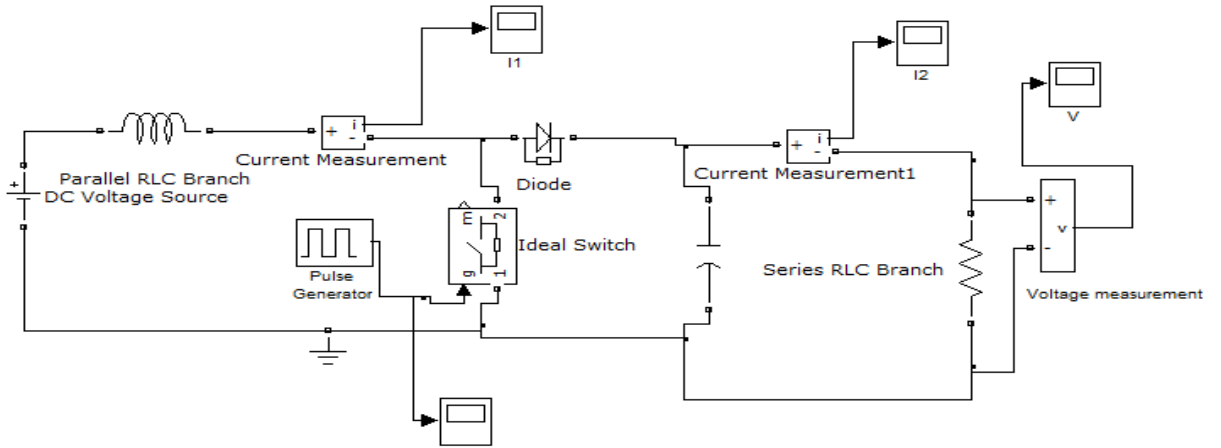


Figure 4.5 Model of boost DC-DC converter.

For the boost converter following equations are considered:

$$\frac{V_0}{V_{in}} = \frac{1}{1-D} \quad (4.1)$$

$$V_0 = V_{in} * \frac{1}{(1-D)} \quad (4.2)$$

$$D = \frac{V_0 - V_{in}}{V_0} \quad (4.3)$$

$$I_0 = I_{in} * (1-D) \quad (4.4)$$

$$P = V_0 * I_0 \quad (5.5)$$

Here,

D , I_{in} , I_o , V_{in} , V_0 and P are the duty cycle, the input current , the output current , the input voltage, the output voltage and the output power respectfully.

For DC-DC step up converter, output voltage increases if duty cycle of pulse modulator (PWM) increases. To step up the input voltage two times higher duty cycle need to be fixed at 0.5.

4.4 Maximum Power Point Tracking

A PV module can produce the power at a point, called an operating point, anywhere on the I-V curve. There is a unique point near knee of the I-V curve, called a maximum power point (MPP) at which the module operates with the maximum efficiency and produces the maximum output power. Figure 3.6 shows the I-V curve of the BP SX 150S PV module simulated with MATLAB model.

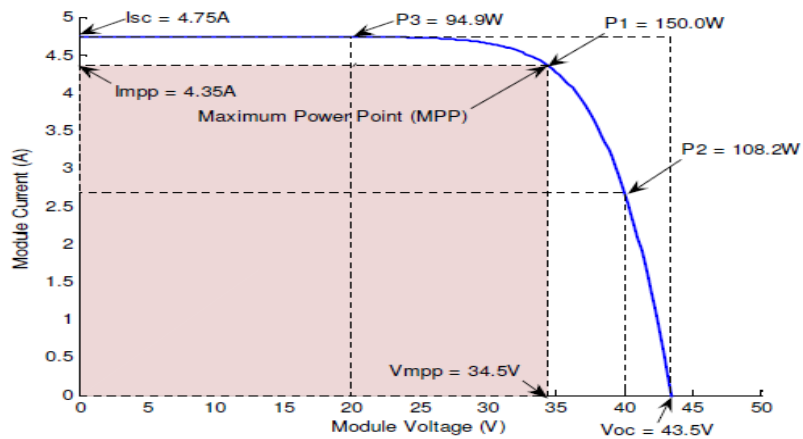


Figure 4.6 simulated I-V curve of BP SX 150S PV module (1KW/m², 25°C).

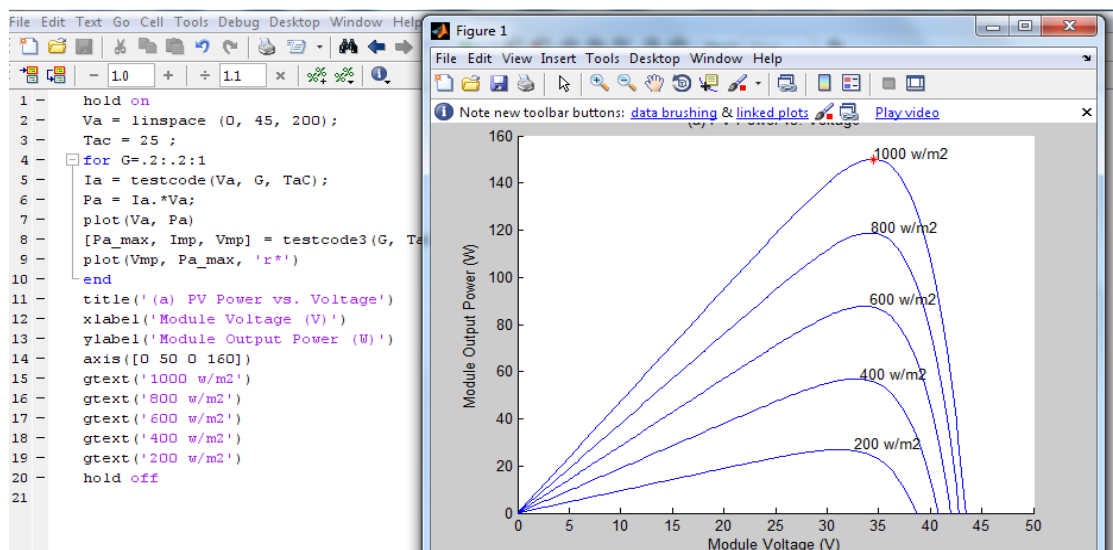


Figure 4.7 power-voltage curve for different irradiance (G).

4.4.1 Maximum Power Point Tracking Algorithm

The Perturb & Observe (P&O) algorithm is widely accepted and usually used in practice because of its simplicity in algorithm and the ease of implementation. It is also known as the hill climbing method. Figure 4.8 shows a output power-voltage curve (P-V curve) of a PV module, at the constant irradiance and the constant module temperature, assuming the PV module is operating at a point which is away from the MPP (point A or B). In this algorithm the operating voltage of the PV module is perturbed by a small increment; therefore, change of power, ΔP , is observed. If the ΔP is positive then it is supposed that it has moved to the operating point closer to the MPP. Thus, further voltage perturbations in the same direction should move the operating point toward the MPP. If the ΔP is negative, the operating point has moved away from the MPP, and the direction of perturbation should be reversed to move back toward the MPP. Figure 3.9 shows the flowchart of this algorithm [17].

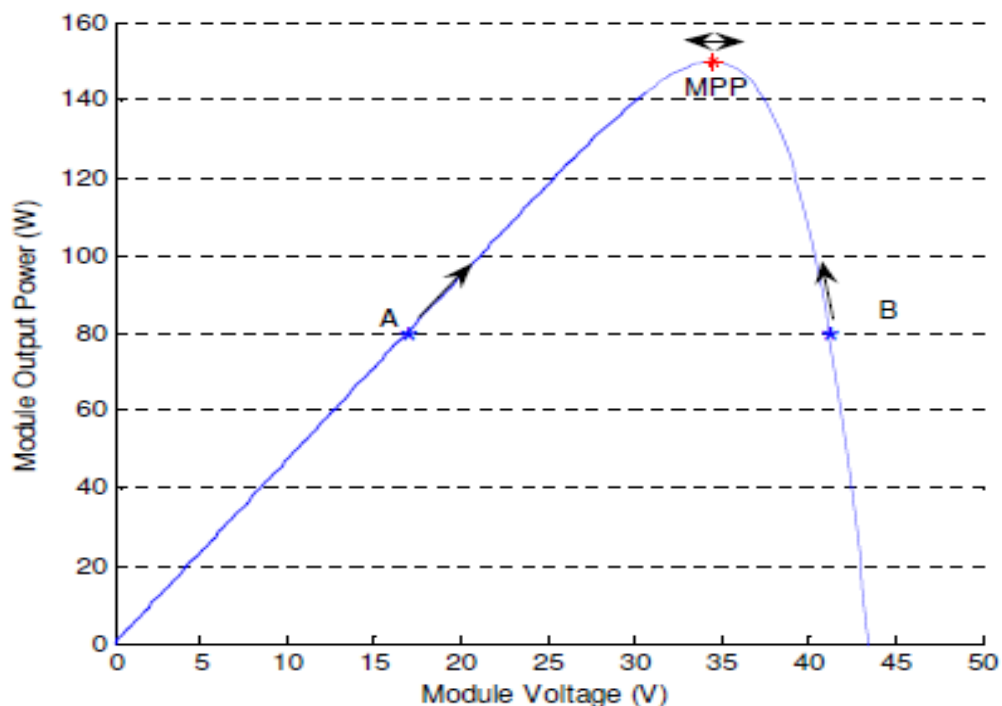


Figure 4.8 Plot of power vs. voltage for BP SX 150S PV module (1KW/m², 25°C).

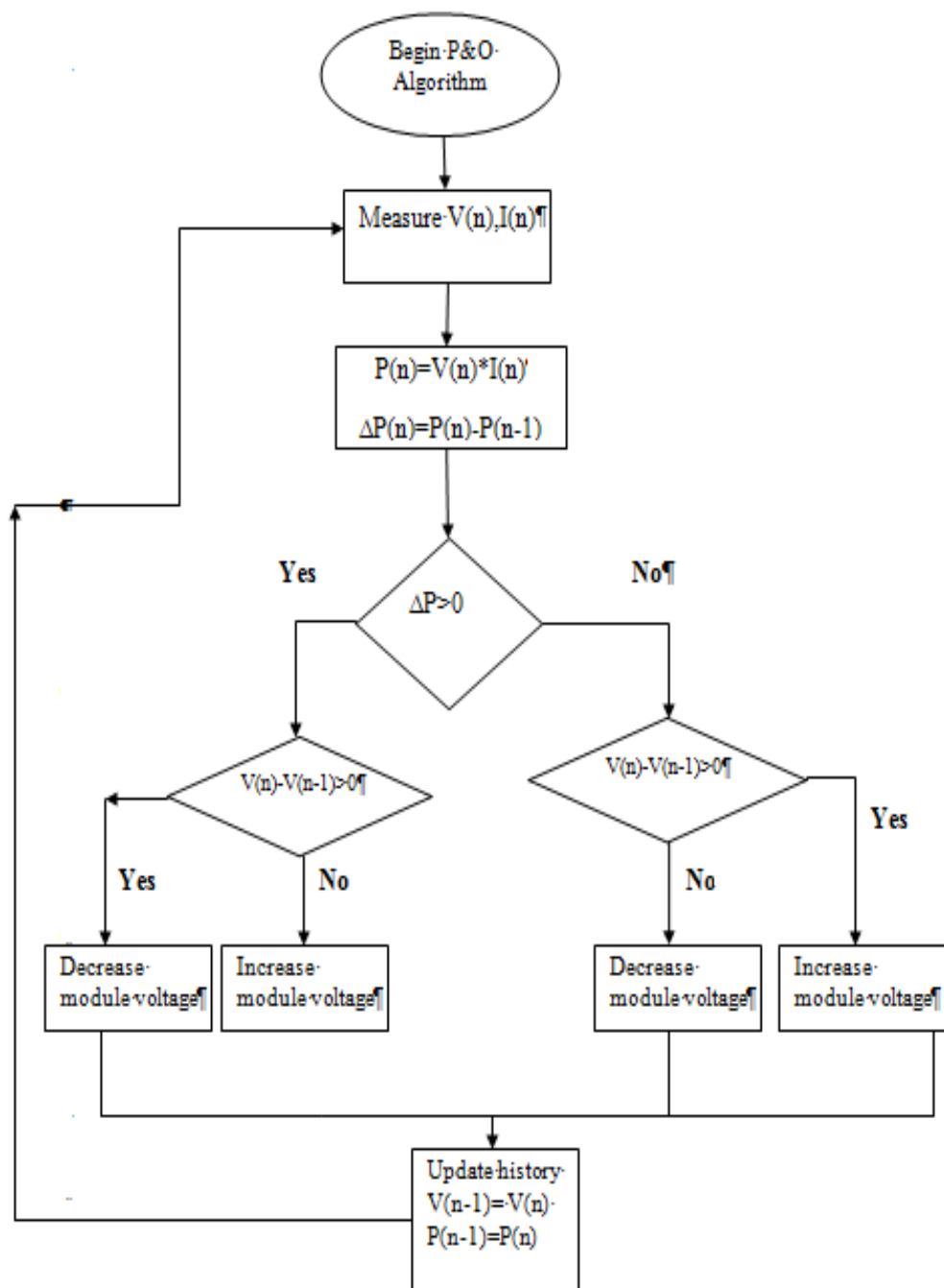


Figure 4.9 Flow chart of P&O algorithm.

4.4.2 MATLAB Implementation Of MPPT Algorithm

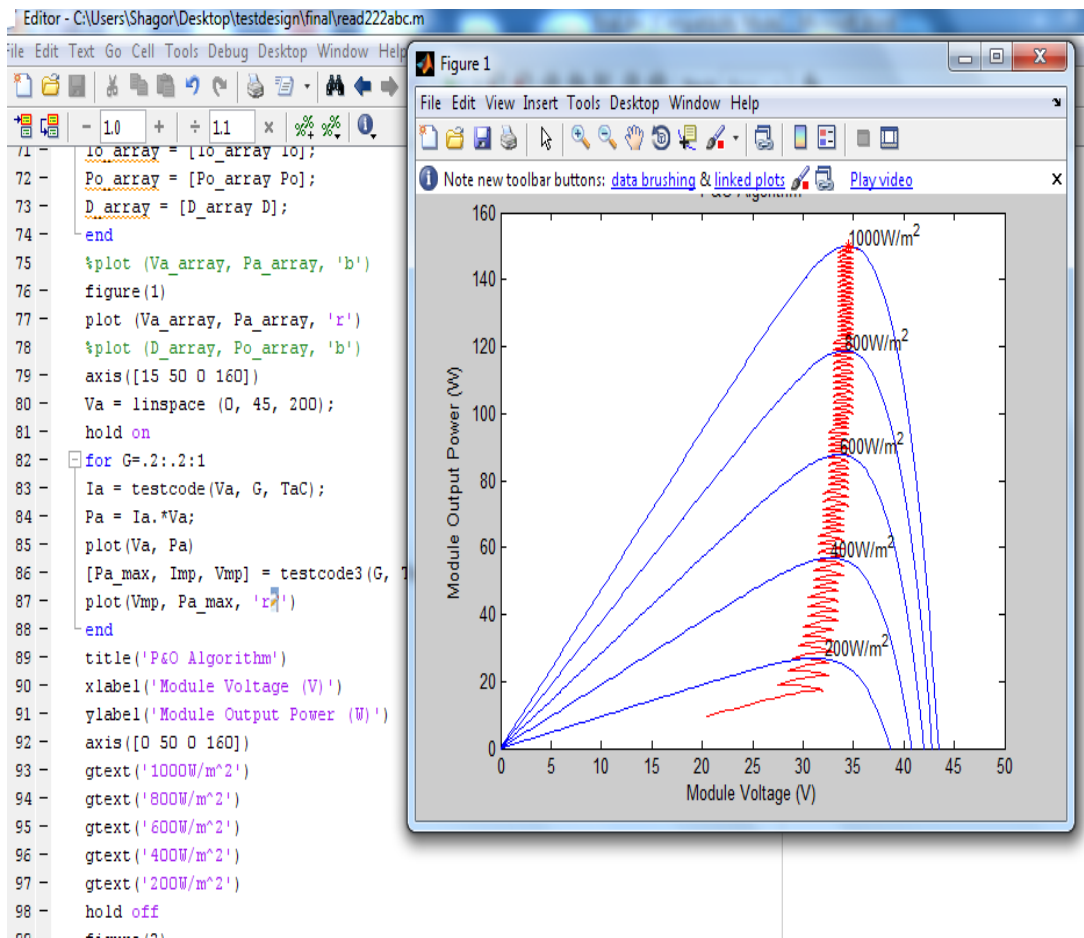


Figure 4.10 MATLAB implementation of MPPT algorithm(25°C) for varying irradiance.

Power vs voltage curve we can be observed from the figure 4.10. Here the out put voltage will fluctuate near the maximum output voltage (34.5V) to get the maximum power with the corresponding irradiance changes (200, 400, 600, 800, 1000 w/m²). The oscillated line shows the maximum power points. PV system is most sensitive to the variation of sudden irradiation fall or rise. System may be completely collapsed on the situation of over or under voltage.

4.4.3 MPPT Control

The main unit of maximum power point control is the DC-DC converter. The figure 4.11 is the MATLAB implementation of converter with the selected module without any control. Simulation has been made under nominal condition. $G=1000\text{w/m}^2$, $T = 25^\circ\text{C}$. The figures tells that the output of the PV module is 33.4 V and the output power of the module is 149.5 W which is the maximum according to the Data sheet. Boost coverter steps up the voltage two times higher which ripples between 62 to 70V.

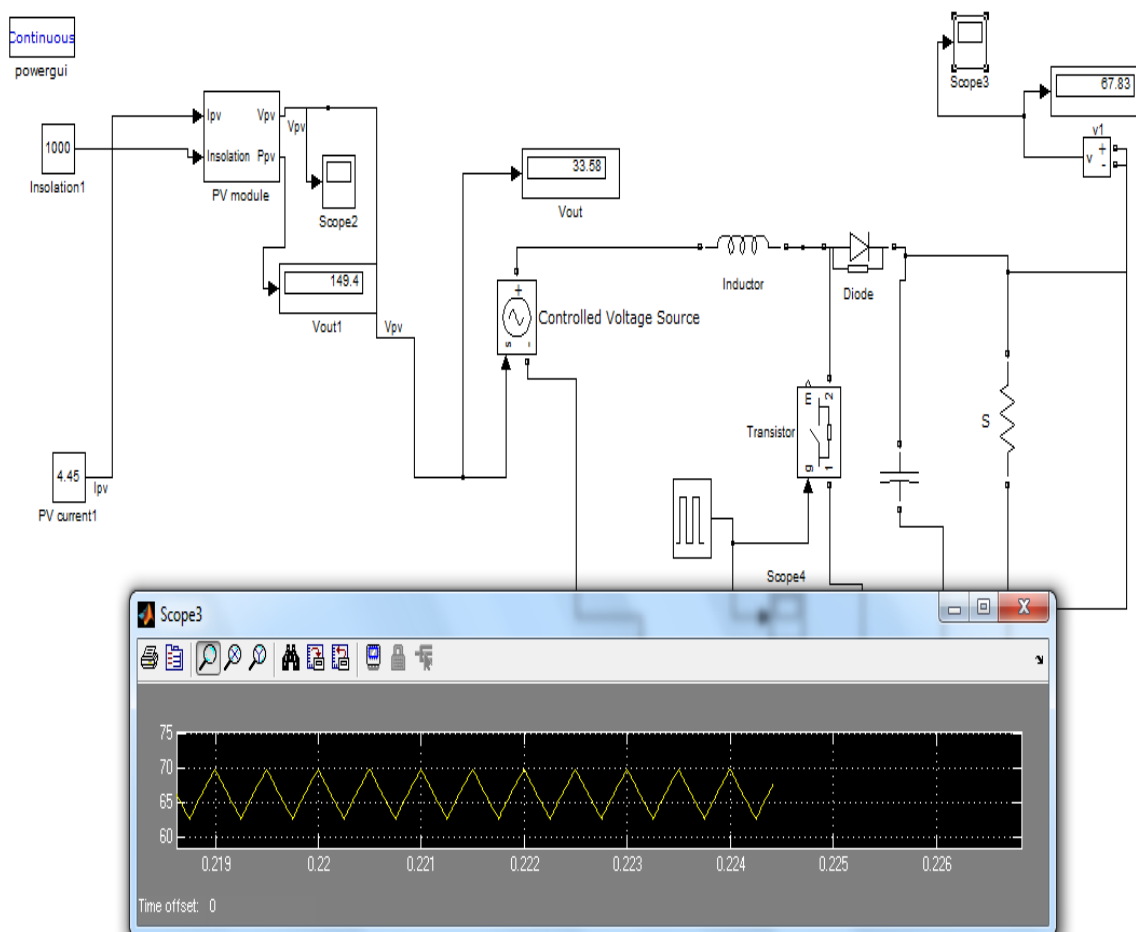


Figure 4.11 Simulation model of Boost converter.

As shown in Figure 4.12, this control method is simpler and uses only one control loop, and it performs the adjustment of duty cycle within the MPP tracking algorithm.

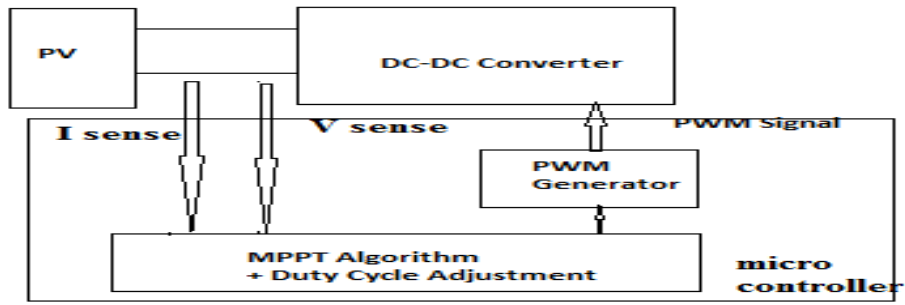


Figure 4.12 MPPT control.

The MATLAB code has been added in the Appendix section. From the following figures we can compare the DC converter input with the controlled output.

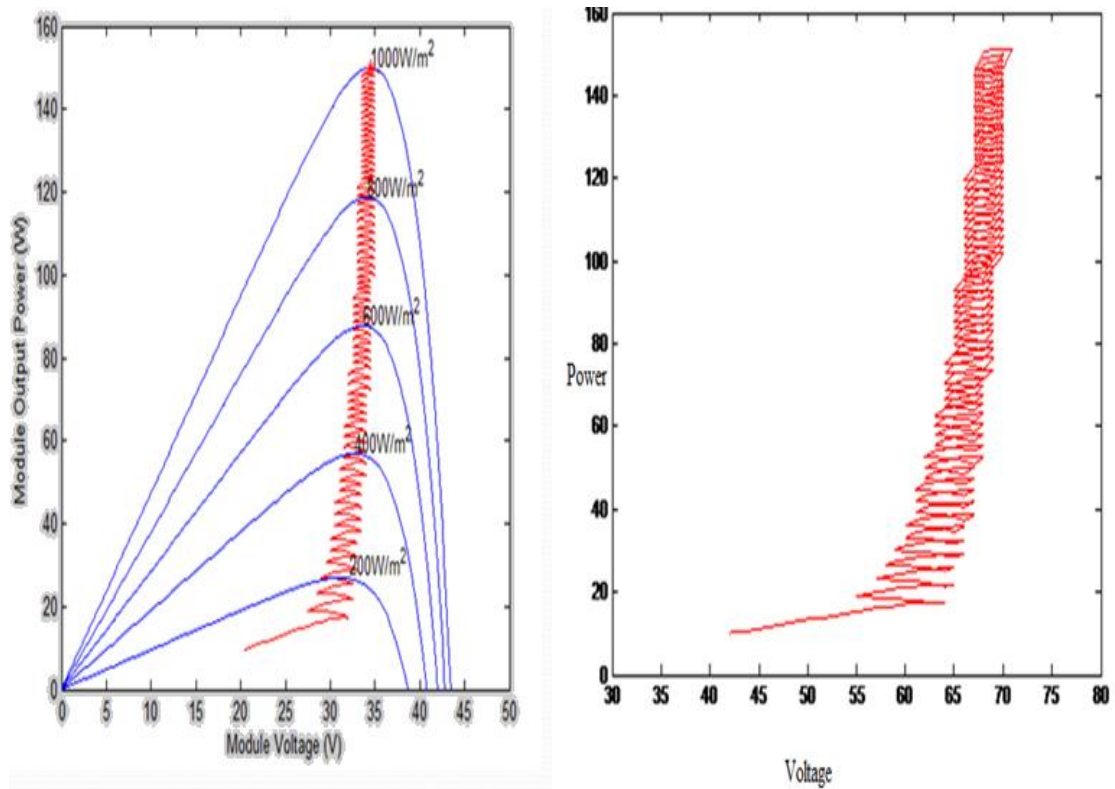


Figure 4.13 The comparison between the module output voltage-power curve (left side) and MPPT controlled DC-DC converter output voltage-power curve (right side).

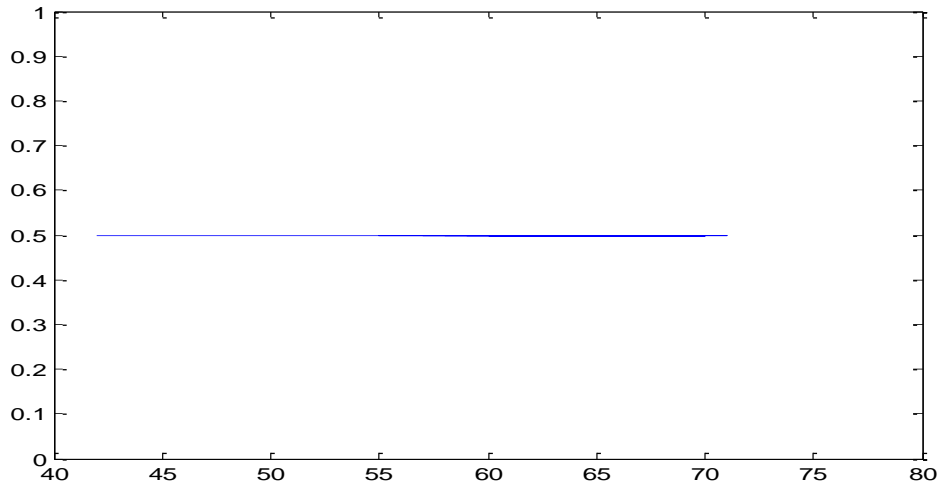


Figure 4.14: Adjusted Duty cycle for desired DC-DC converter out put.

In order to track the Maximum output power point of PV module the P&O algorithm has been used . By using boost converter the voltage has been stepped up two times higher than the PV output voltage. The value of duty cycle of pulse with modulator has increased and be remained constant at 0.5 to fix up the range of converter output voltage within 60-70 V for different solar irradiance (figure 4.13) This is the Maximum output voltage range for the selected PV module for different solar irradiance .

CHAPTER 5

IMPLEMENTATION OF PV SYSTEM

Grid connected PV system is becoming popular day by day. In this paper Grid connected photovoltaic system without battery backup has studied as an example of the implementation of PV system. There are two types of grid connected PV system

- Grid connected Photovoltaic system with battery backup
- Grid connected Photovoltaic system without battery backup

Grid connected PV system consists of following basic components

- PV Array: a number of PV panels connected in series and or in parallel giving a DC output. Orientation and tilt of these panels are important design parameters, as well as shading from surrounding obstructions.
- DC converter: DC converter can step up or step down the DC output voltage of PV Array. DC converter with Maximum Power Point tracker can work to increase the efficiency of PV array.
- Inverter: a power converter that 'inverts' the DC power from the panels into AC power. The characteristics of the output signal should match the voltage, frequency and power quality limits in the supply network.
- Transformer: a transformer can boost up the ac output voltage from inverter when needed. Otherwise transformer less design is also acceptable.
- Load: stands for the network connected appliances that are fed from the inverter, or, alternatively, from the grid.

- Meters: they account for the energy being drawn from or fed into the local supply network.
- Protective device: some protective devices is also installed, like under voltage relay, circuit breakers etc for resisting power flow from utility to PV system.
- Other devices: other devices like AC filter can also be used for better performance.

Tilt angle, which is the angle between the plane of module and the horizontal plane. The optimum array orientation will depend on the latitude of the site, weather conditions and the load to be met. It is generally accepted that, for low latitudes, the maximum annual output is obtained when the array tilt angle is roughly equal to the latitude angle and the array faces to south (in northern hemisphere) or to north (for the southern hemisphere).

5.1 Grid Connected Photovoltaic System with Battery Backup

It is one of the best systems which confront the issue of reliability of the grid supply. Its design is similar to the design of a combination of an Uninterruptible Power Supply (UPS) and a standalone power system. In a grid connected photovoltaic system with battery backup, the system works as a standalone power system during grid failure to eliminate the use of a fuel generator.

Batteries are recognized as the heart of a grid connected photovoltaic system with battery backup. Without proper maintenance, batteries can fail prematurely and shut the whole photovoltaic system down.

5.1.1 Operation of The System

At the start of each day, the solar array charges the battery bank through the charge controller unit (MPPT and boost converter). The inverter will convert the excess solar power into AC power supplying to the load circuit when the battery voltage rises above the float voltage. The inverter will also ensure that the batteries are held at this voltage and this will be directly from the solar power during the day time.

On the AC side, the inverter is both connected to the grid and the loads. If the excess solar power, which is supplied to the load circuit is not enough for its performance, the

grid will supplement it. On the other hand if the solar power output is more than that of required by the loads, then the remaining AC power is fed into the grid. When the grid power fails, the standard protection devices within the inverter will disconnect the inverter from the grid [18].

The system then becomes like a standalone power system and the batteries supply power to the load circuits. When the grid power returns, the inverter will act as a battery charger and it, along with the PV array (if it is during sunshine time) will charge the batteries up to the equalization voltage.

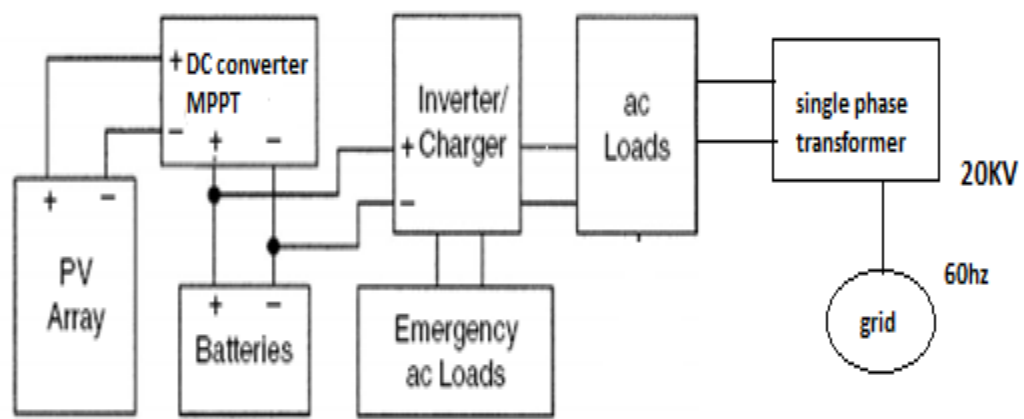


Figure 5.1 Block diagram of Battery backup grid connected system.

The following settings for the charging of the battery are set within the inverter

- Equalization voltage.
- Float voltage.
- Period between equalization.
- How long the equalization voltage is maintained.

5.2 Grid Connected Photovoltaic System without Battery Backup

Electricity is produced by the PV array most efficiently during sunny periods. At night or during cloudy periods, independent power systems use storage batteries to supply electricity needs. The grid acts as the battery and supply electricity to the load when the PV array cannot able to generate electricity.

The power produced by the PV array derives the load during the day time. An inverter converts direct current (DC) produced by the PV array to alternating current (AC) and transformer stepped up the voltage level as need for export to the grid. Grid interactive PV systems can vary substantially in size. There are two meters connected one is called the import meter and the other is called the export meter. Thus the difference between the two meters reading gives the amount of power fed to the grid from solar photovoltaic power plant. So using these meters we can easily determine what amount of energy is fed to the grid from solar power.

5.3 Conditions for Grid Inter Facing

There are some conditions to be satisfied for interfacing or synchronizing the PV system with grid or utility. If properly synchronizing is not made then PV potential cannot be fed to the grid.

The conditions for proper interfacing between two systems are discussed below

- **Phase sequence matching:** phase sequence of PV system with grid should be matched otherwise synchronization is not possible. For a three phase system three phases should be 120° phase apart from each other for both the system.
- **Frequency matching:** frequency of the PV system should be same as grid. Generally grid is of 60 Hz frequency capacity. If PV systems frequency is slightly higher than grid frequency (0.1 to 0.5) synchronization is possible but PV system frequency should not be less than grid frequency.
- **Voltage matching:** Voltage matching is one of the vital points is. Voltage level of both the systems should be the same, otherwise synchronization is not possible.

5.4 Load Assessment

Since the grid connected photovoltaic system it is necessary to undertake a load assessment to determine the amount of energy required when the grid fails. In the following table there is a description of seasonal load [19].

Table 5.1 seasonal use of electric usage of equipment.

Consumer	Power (watt)	Operating hours, daily		Energy used daily	
		Summer	Winter	Summer	Winter
Three lamps in living room	3*12=36 W				
		1	3	36wh	108wh
One lamp in a room	12	0.5	0.5	6wh	6wh
Two lamps	2*7=14	1	1	14wh	6wh
Refrigerator	50	6(effective)	0	360wh	0
TV	50	2	2	100wh	100wh
Water pump	60	1	0.33	60wh	20wh
Total	186w	11.5	6.83	720wh	248wh

5.5 Solar Radiation

Typical solar radiation data are much important as an input in modeling, designing and performance evaluation of solar energy applications. To make a good estimation for energy yields of photovoltaic systems, the angle definitions and solar radiation should be understood perfectly. The angle of the solar radiation to the Earth surface will change with the motion of the sun when sun moves around the earth. In this case the radiation will also change depending on the solar motion .

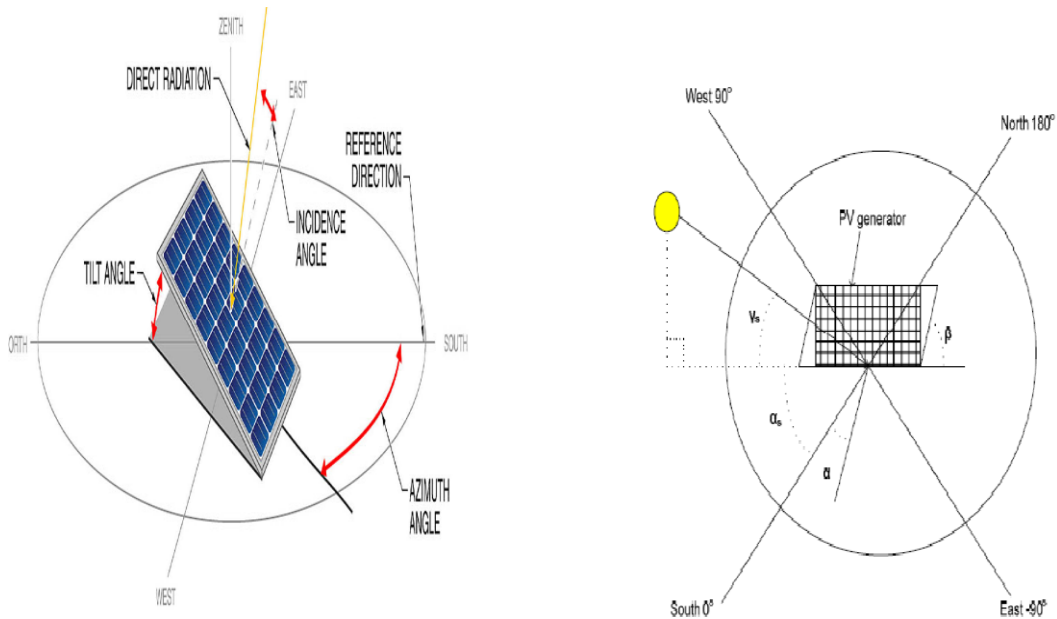


Figure 5.2 The PV panel inclination angle on the Earth's surface under sunshine[20].

Here,

α_s is the solar azimuth angle, α is the Azimuth angle of PV generator, β is the tilt angle of PV generator and γ_s is the solar incidence or elevation angle from the horizon respectively.

The elevation angle of the sun changes every month in the year and every hour in the day while the Earth is rotating,. The air mass (AM) factor determines the total distance where the sunlight has to travel to reach the earth surface. The air mass and elevation angle are inversely proportional. When the solar radiation travels through the atmosphere to reach the Earth's surface, a part of incident energy will be lost by scattering or absorption by air molecules, clouds and particles. The resulting energy flux incident on a unit area perpendicular to the beam outside the Earth's atmosphere is known as a solar constant, i.e. $S=1367\text{W}/\text{m}^2$ [21].

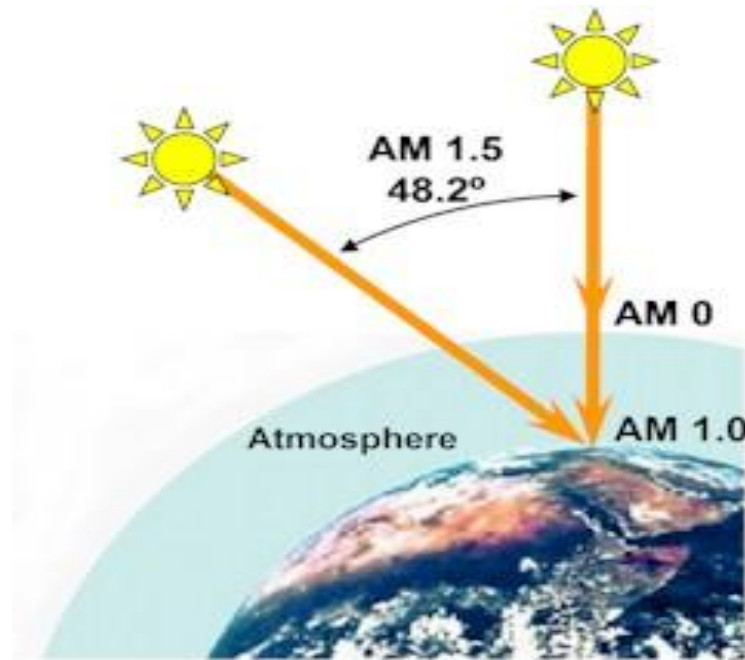


Figure 5.3 Air Mass[22] .

The amount of solar radiation that is absorbed or scattered in the atmosphere depends on how much atmosphere it passes through before reaching Earth's surface. When the sun is at zenith, the amount of atmosphere that the sun's rays have to pass through to reach Earth's surface is at a minimum which can be expressed through Air Mass ($AM = 1.0$) Zenith is the point in the sky directly overhead a particular location.

The zenith angle is the angle between the sun and the zenith. As the zenith angle increases (the sun approaches the horizon), the sun's rays must pass through a greater amount of atmosphere to reach Earth's surface. This reduces the quantity of solar radiation, and also changes its wavelength composition. At this condition the Air Mass will be 1.5.

There are three types of radiation that occur on a surface on earth and they are as follows

- Direct Radiation
- Scattered Radiation
- Reflected or Albedo Radiation

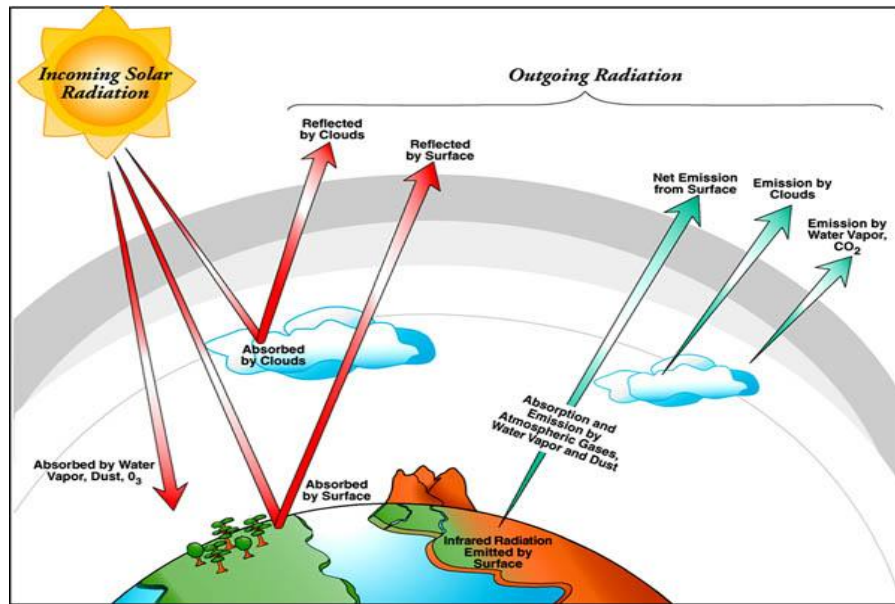


Figure 5.4 Types of radiation[23].

The radiation, which is not reflected or scattered and reaches directly to the surface is called direct radiation or beam radiation. The scattered radiation reaching to the ground surface is called diffuse radiation. The radiation which is the reflection of the radiation reaches to the ground surface and being received by the objects is called reflected radiation. The total radiation is the sum of these different radiation phenomena [24].

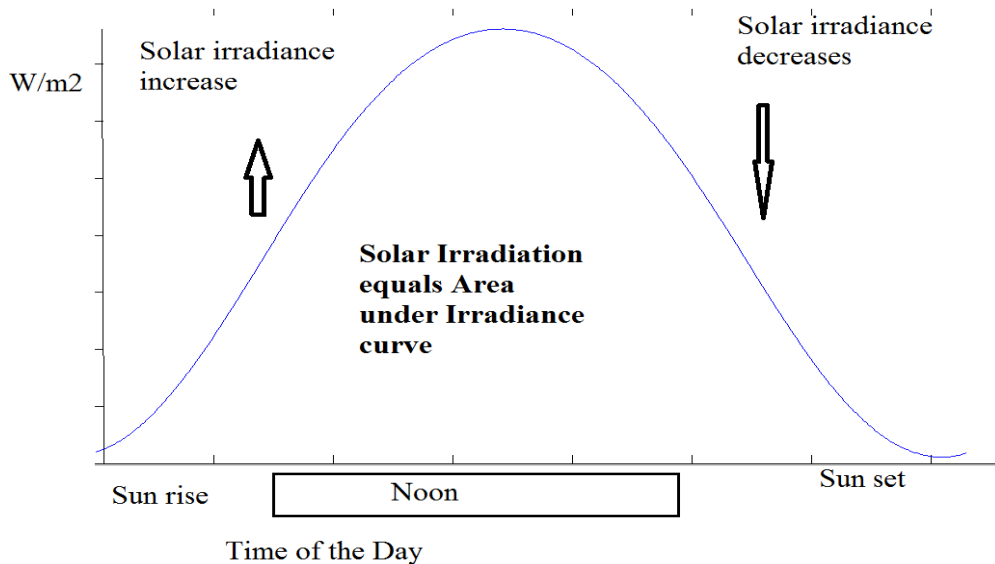


Figure 5.5 Solar irradiance and irradiation.

At the surface of Earth, the magnitude of solar irradiance changes throughout the day. It begins at zero during nighttime, increases as the sun rises, peaks around noon, and decreases as the sun sets. In a plot of solar irradiance versus time, solar irradiation equals the area under the irradiance curve.

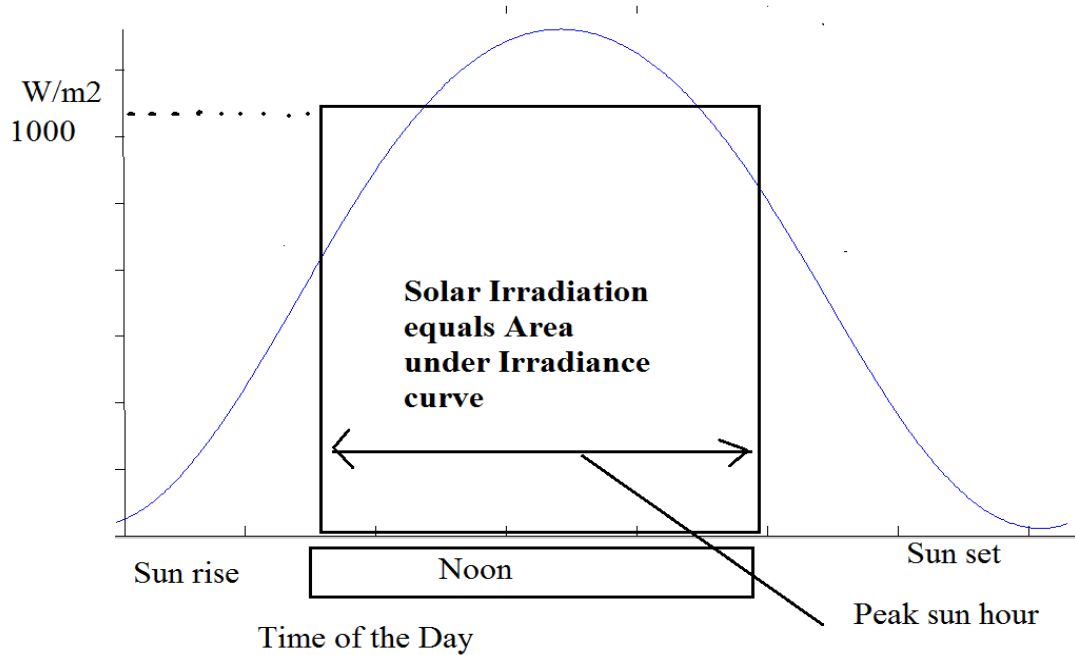


Figure 5.6 Peak sun hour.

Peak sun hours are the number of hours required for total solar irradiation a day to accumulate at peak sun condition. An average day may have only one or two actual hours at peak sun condition, but the total irradiation for a day may be expressed in units of peak sun hours by dividing by 1000 W/m² (peak sun irradiance). For example, a day with an average irradiance of 600 W/m² over 8 hr may only reach peak sun condition for an hour or less around noon. However, the total irradiation of 4800 Wh/m² (600 W/m² × 8 hr = 4800 Wh/m²) is equivalent to 4.8 peak sun hours (4800 Wh/m² ÷ 1000 W/m² = 4.8 peak sun hr).

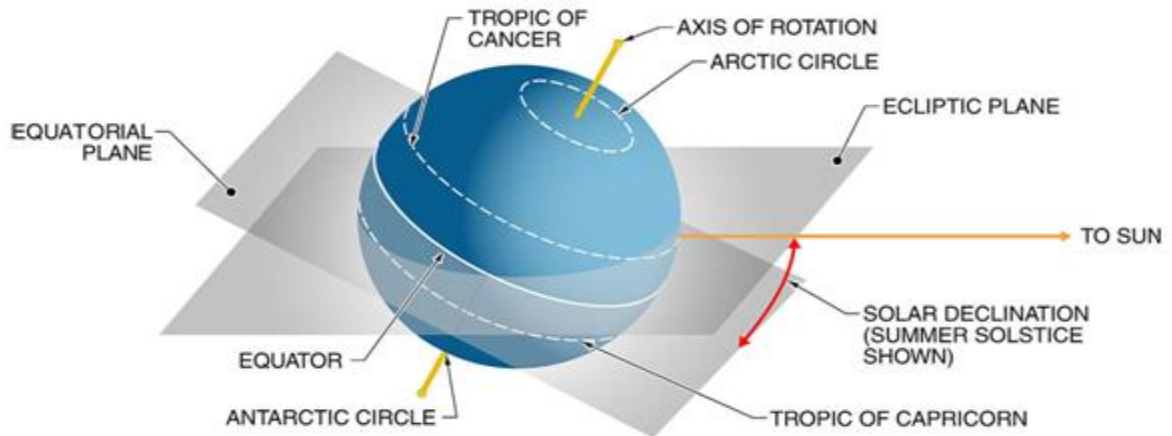


Figure 5.7 Solar declination[25].

The Earth revolves in an elliptical orbit around the sun; the plane of this orbit is elliptical. The Earth completes one cycle travelling around the sun in one year. Solar declination is the angle between the equatorial plane and the rays of the sun. The angle of solar declination changes continuously as Earth orbits the sun, ranging from -23.5° to $+23.5^\circ$ (positive when the Northern Hemisphere is tilted toward the sun). This angle will be zero at 20/21 March and at 22/23 September equinoxes. On these days sun will rise exactly in the east and will set in the west. At summer solstice, 21/22 June, δ will be 23.45° and at winter solstice will be -23.45° .

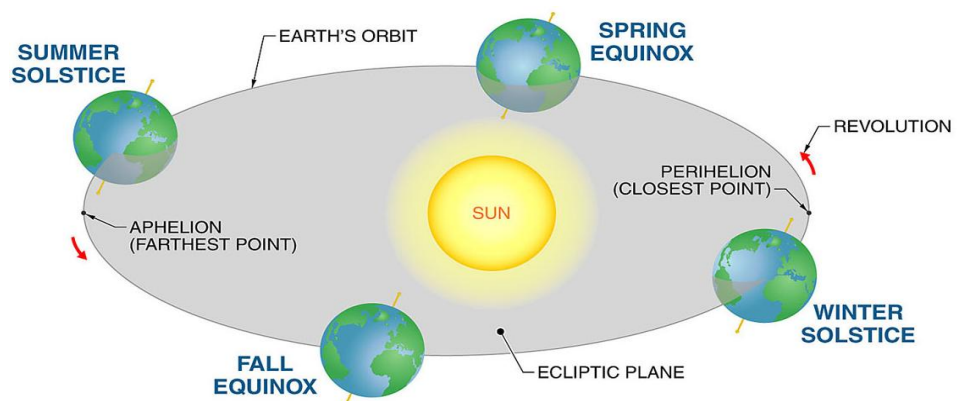


Figure 5.8 Elliptic plane[26].

5.6 Calculation of The Irradiation on An Inclined Surface

The solar radiation data are generally given in the form of global radiation on a horizontal surface. Global daily irradiation is denoted by G. If the PV panels are positioned with an angle on a horizontal surface the total global irradiation received by the PV will change.

The overall formulas to put in the program for calculation of irradiation on an inclined surface are as follows :

Solar declination

$$\delta = 23.45 \sin(360(248+n)/365) \quad (5.1)$$

here , n is the day

Sun hour angle

$$h_s = \cos^{-1}(-\tan L \cdot \tan \delta) \quad (5.2)$$

Here, L is the latitude of a given geographical location on earth.

H_o is the irradiation received over one day by a unit horizontal surface area outside the earth atmosphere.

$$H_o = 24 / \pi \cdot S \cdot (1 + .033 \cos(2 \cdot \pi \cdot 360n / 365)) \cdot (\cos L \cdot \cos \delta \cdot \sin h_s + 2 \cdot \pi \cdot h_s / 360 \cdot \sin L \cdot \sin \delta) \quad (5.3)$$

The clearness index

$$KT = G/H_o \quad (5.4)$$

Here , G is daily solar irradiance data

Diffused radiation

$$D = G(1 - 1.13KT) \quad (5.5)$$

Direct radiation

$$H=G-D \quad (5.6)$$

After H is found for the horizontal surface, the beam or direct irradiation $H(\beta)$ on a south-facing panel inclined at an angle β to the horizontal surface is given by

$$H(\beta) = \frac{\cos(L - \beta) \cos \delta \cdot \sin h' + (\pi / 180) h' \sin(L - S) \sin \delta}{\cos L \cos \delta \sin h_s + (\pi / 180) h_s \sin L \sin \delta} \quad (5.7)$$

$$h' = \min \{h_s, \arccos[-\tan(L - S) \tan \delta]\} \quad (5.8)$$

here, h' is the solar hour angle on Panel surface

Diffused radiation on the panel

$$D(\beta) = \frac{1}{2} \cdot D \cdot (1 - \cos(\beta)) \quad (5.9)$$

Albedo Radiation on the Panel

$$R(\beta) = \frac{1}{2} \cdot H \cdot \rho (1 - \cos(\beta)) \quad (5.10)$$

Total irradiation on the PV panel

$$G(\beta) = H(\beta) + D(\beta) + R(\beta) \quad (5.11)$$

For MATLAB implementation of equation (5.3) to find the irradiation (H_o) received over days on a unit horizontal surface area outside the earth atmosphere, the Batman of Turkey has chosen. The Latitude of this city is $L=37.93^\circ\text{N}$.

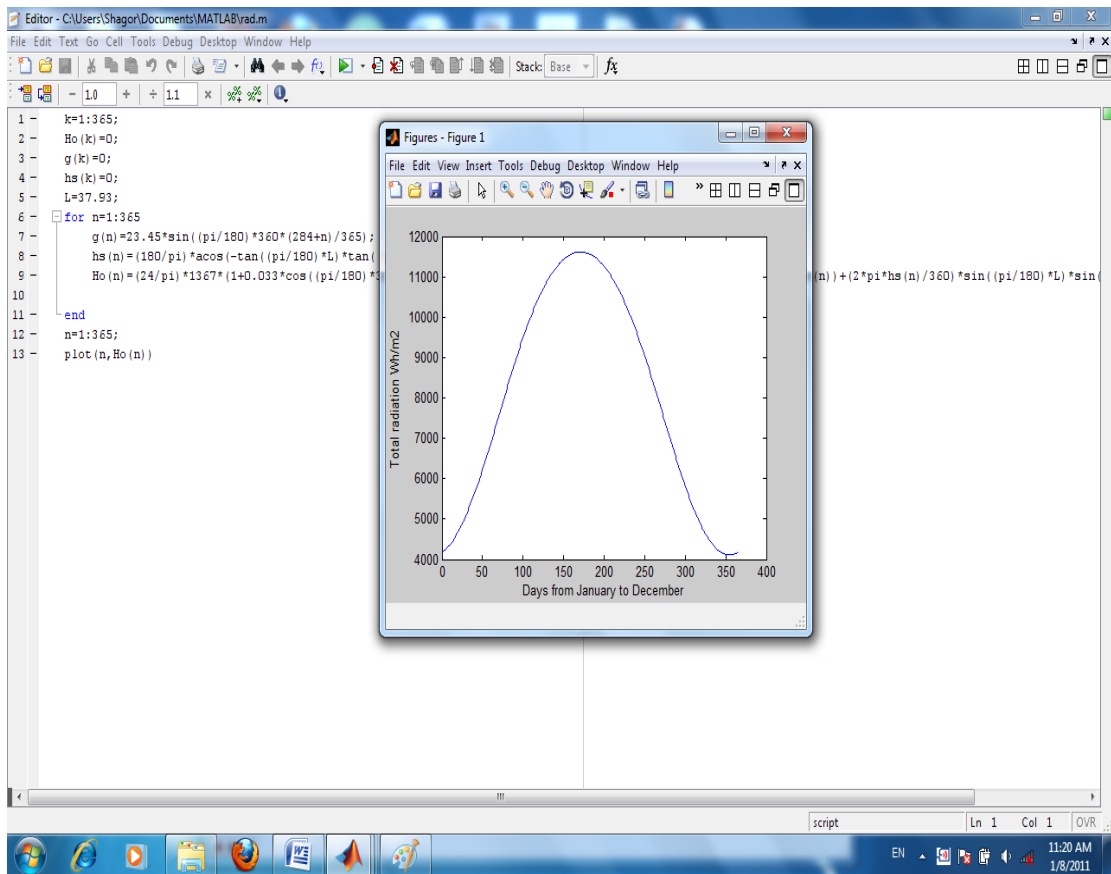


Figure 5.9: Values of the irradiation received over a year by a unit horizontal surface area outside the earth atmosphere at Batman .

Table 5.2 The clearness angle KT.

January	0.383	July	0.661
February	0.390	August	0.650
March	0.431	September	0.602
April	0.498	October	0.499
May	0.562	November	0.415
June	0.619	December	0.372

Table 5.3 Average values of the irradiation received over a year on a unit horizontal surface area outside the earth atmosphere at Batman.

January	4960 Wh/m ²	July	10347 Wh/m ²
February	6897 Wh/m ²	August	9292 Wh/m ²
March	9443 Wh/m ²	September	8754 Wh/m ²
April	10140 Wh/m ²	October	7474 Wh/m ²
May	11103 Wh/m ²	November	5807 Wh/m ²
June	11373 Wh/m ²	December	4838 Wh/m ²

From the figure 5.9 we can get the average value of H_o at different months.

Table 5.4 G is solar irradiance data on a unit surface on earth at horizontal level ($\beta=0^\circ$).

January	1900 Wh/m ²	July	6840 Wh/m ²
February	2690 Wh/m ²	August	6040 Wh/m ²
March	4070 Wh/m ²	September	5270 Wh/m ²
April	5050 Wh/m ²	October	3730 Wh/m ²
May	6240 Wh/m ²	November	2410 Wh/m ²
June	7040 Wh/m ²	December	1800 Wh/m ²

Table 5.5 Diffused radiation.

January	1077 Wh/m ²	July	2658 Wh/m ²
February	1504 Wh/m ²	August	1603 Wh/m ²
March	2087 Wh/m ²	September	1685 Wh/m ²
April	2208 Wh/m ²	October	1626 Wh/m ²
May	2277 Wh/m ²	November	1279 Wh/m ²
June	2736 Wh/m ²	December	1043 Wh/m ²

Table 5.6 Direct radiation on a horizontal unit surface on earth $H=G-D$.

January	823 Wh/m ²	July	4182 Wh/m ²
February	1186 Wh/m ²	August	4437 Wh/m ²
March	1983 Wh/m ²	September	3585 Wh/m ²
April	2842 Wh/m ²	October	2104 Wh/m ²
May	3963 Wh/m ²	November	1131 Wh/m ²
June	4304 Wh/m ²	December	757 Wh/m ²

Using equation (5.7), (5.8), (5.9), (5.10) and (5.11) and data from above given tables , following data table can be get,

Table 5.7 :Average irradiation on a PV Panel on Earth at different tilt angle in Batman for each month at different tilt angle (β).

β	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Aveg. Wh/m ²
0	1900	2690	4070	5050	6240	7040	6840	6040	5270	3730	2410	1800	4232
12	2184	3006	4410	5237	6230	6851	6721	6180	5699	4221	2803	2112	4640
18	2320	3144	4533	5266	6150	6671	6575	6166	5835	4414	2978	2252	4699
24	2425	3253	4616	5252	6015	6433	6367	6095	5915	4570	3110	2371	4702
36	2582	3390	4667	5093	5595	5787	5785	5794	5910	4760	3316	2553	4612
60	2653	3345	4316	4290	4212	3928	4024	4542	5241	4641	3390	2666	3938
70	2570	3159	3129	3677	3320	2807	2935	3671	4600	4333	3270	2595	3400
90	2281	2715	3130	2582	1870	1099	1237	2175	3361	3609	2880	2340	2439

The average irradiation over an unit area or a PV panel on Earth at different tilt angle in Batmat for each month is described in table 5.7. In the table 5.7 the tilt angle of the PV panel β is changing from 0 degree to 90 degree. It is shown that the maximum irradiation has occurred among a total of twelve months at 24 degree of inclination angle and the value is 4702 Wh/m². If the angle of inclination can be changed at every month of the year the yield will be increased, which is very substantial increase of irradiation on PV panel.

5.7 Implementation of Simulation Model

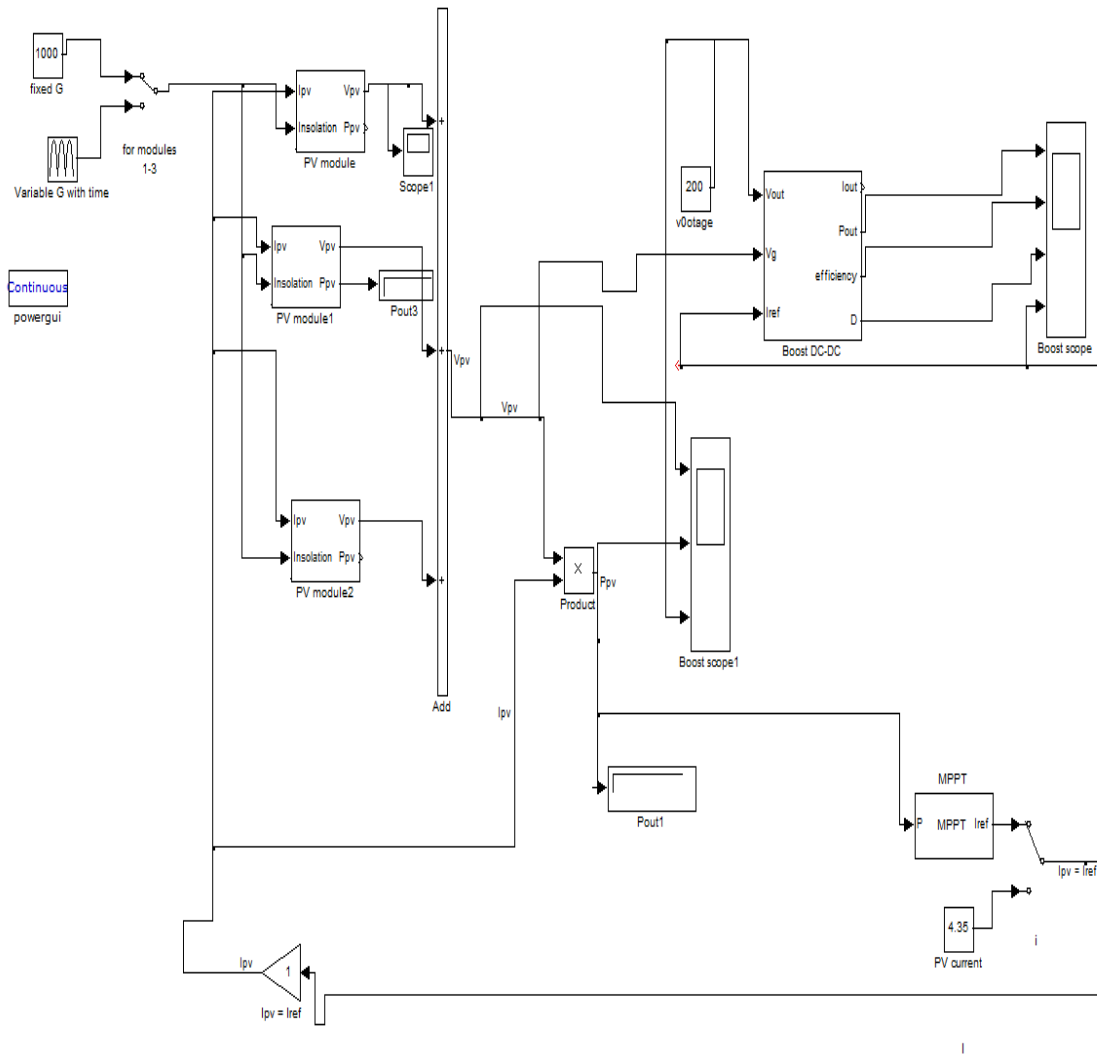


Figure 5.10 MATLAB simulation model to observe the effect of variable irradiance data with the variation of time on PV output power using MPPT algorithm.

From the above simulation model, the effect of variable irradiance data with the variation of time on three series PV module has been observed where Maximum Power Point Tracking algorithm has been used to keep the DC output of DC/DC converter at 200 V. For this reason the duty cycle of the DC/DC converter has been changed with the change of PV output voltage.

Here, previously described P&O algorithm is used for Maximum Power Tracking. The only difference is instead of V_{pv} (PV module voltage) , I_{pv} (PV module current) has been adjusted to I_{ref} (reference current) to get maximum output from PV array at different irradiance level. We can also observe from the following figures that the total output power has changed with different irradiation level.

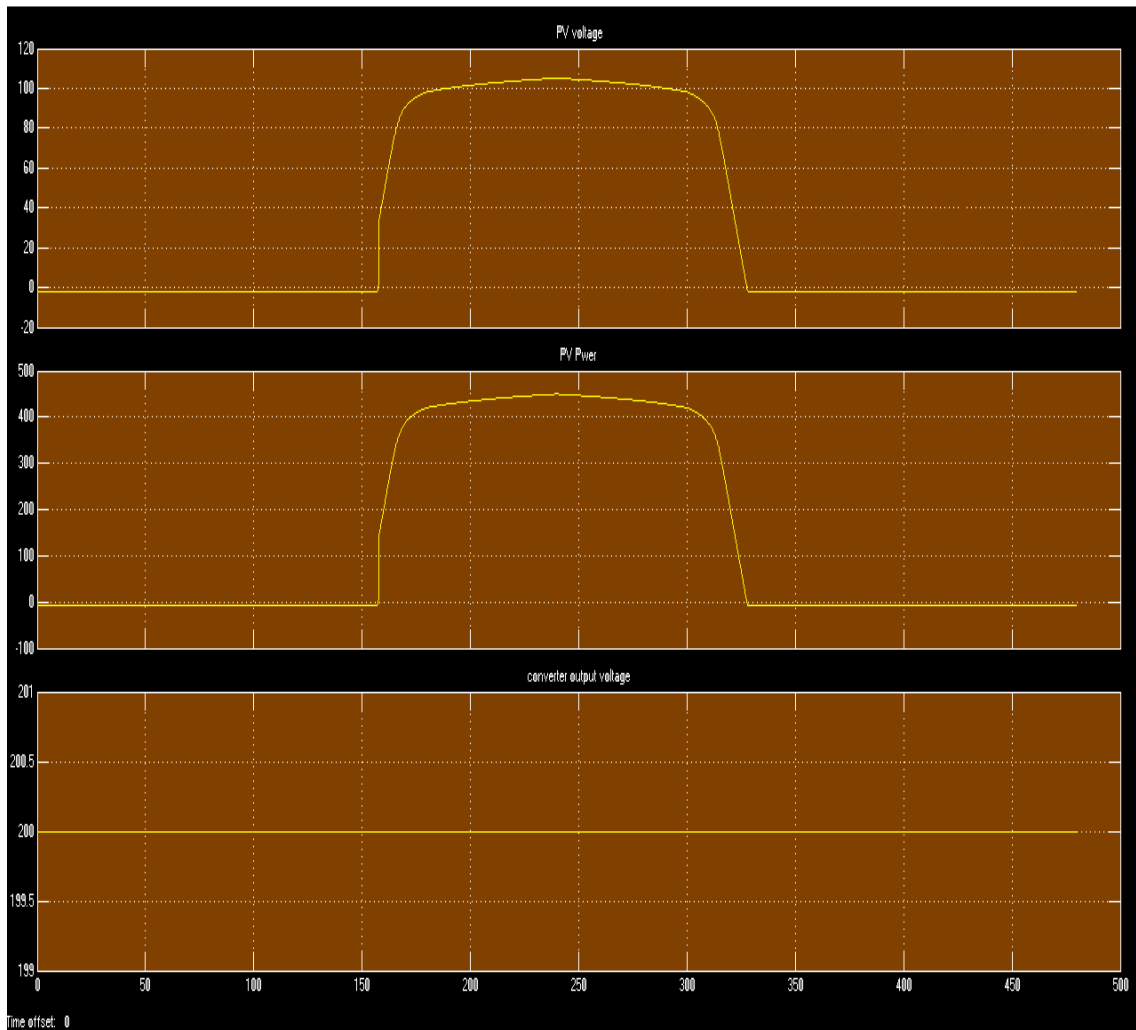


Figure 5.11 Graph of PV voltage (100V), PV Power(450W/m²) and Converter output voltage(200V) at [0 400 850 950 1000 950 850 400 0]W/m²-day.

From the figure (5.11) we can observe the variation of PV output voltage from 0 V to 100V simultaneously PV output power from 0 to 450 w/m² with respect to time. For this whole period DC converter output voltage remains constant at 200 V.

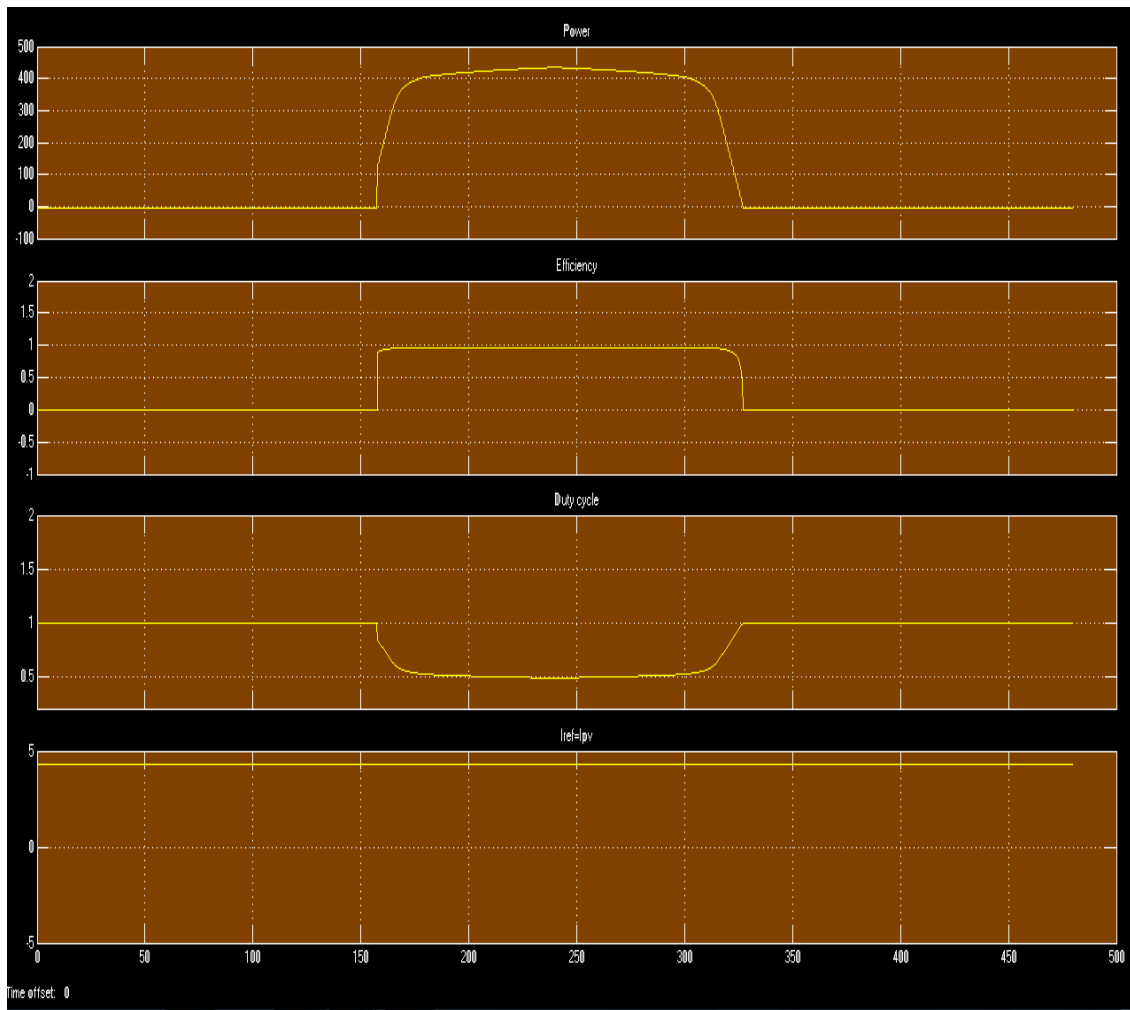


Figure 5.12 Graph of Converter Power, efficiency, Duty cycle, I_{ref} at [0 400 850 950 1000 950 850 400 0]W/m²-day

From figure 5.12 we can observe the variation of converter output power, efficiency and duty cycle with respect to time (over a day) at different solar radiation condition Efficiency increased from 0 to 0.98 at noon time and the duty cycle has been adjusted from 1 to 0.5 to control converter output voltage.

Following figures 5.13 and 5.14 observe the output voltage and output power of module and converter, the change of duty cycle of the converter over a longer day.

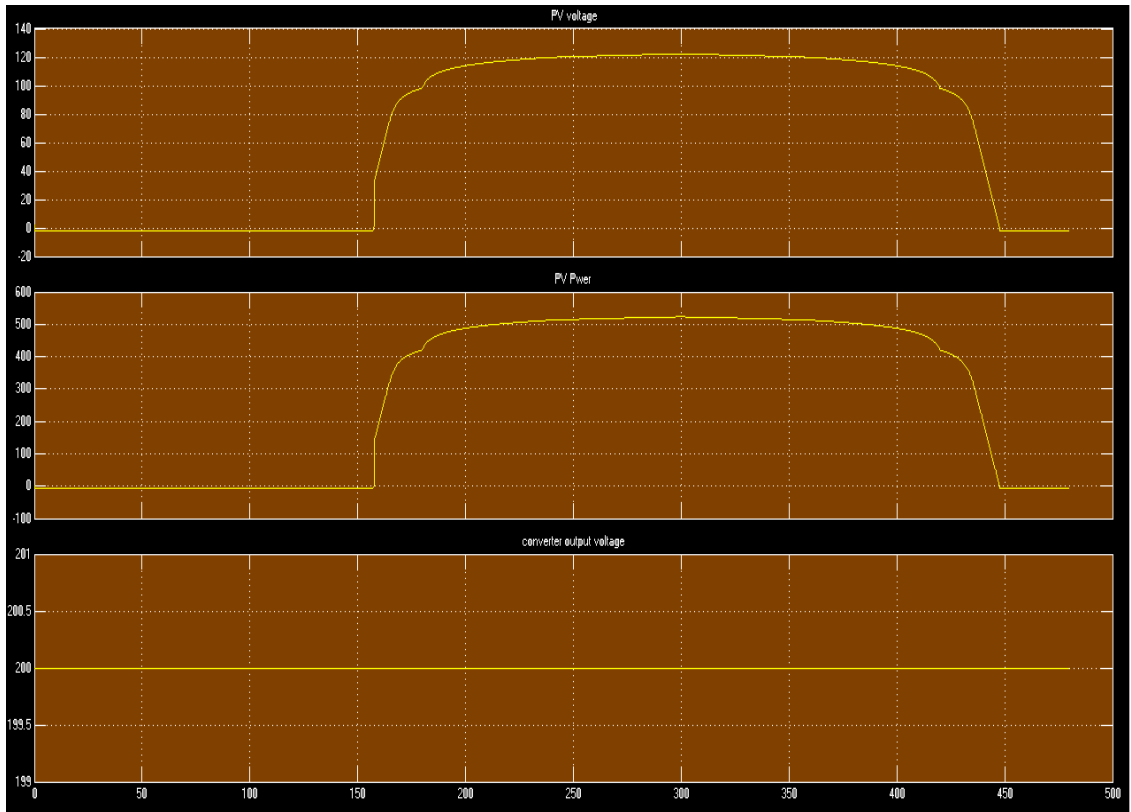


Figure 5.13 Graph of PV voltage, PV Power and Converter output voltage at [0 400 850 1950 4251 1950 850 400 0]W/m²-day.

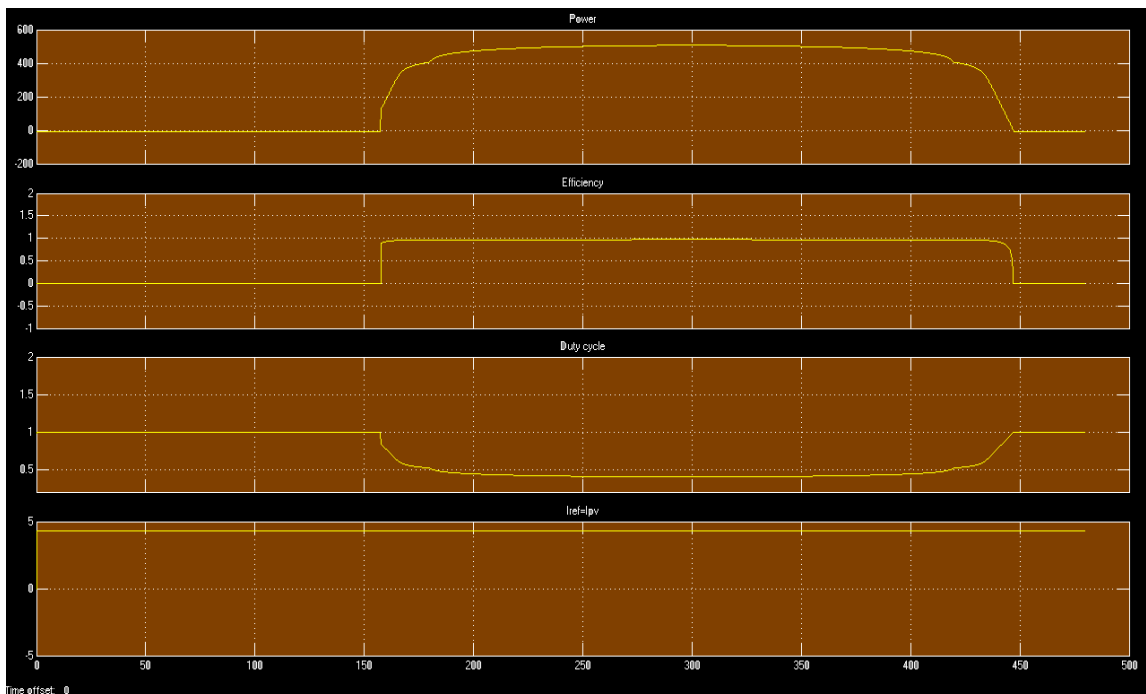


Figure 5.14 Graph of Converter Power , efficiency, Duty cycle, Iref at [0 400 850 1950 2451 1950 850 400 0]W/m²-day.

5.8 Proposed System Design

In the proposed design BP SX 150S PV module is used. Each module (irradiance=1000W/m², T=25oC) capable of producing 150w. From 5.16 we can see that, 3 module is connected in series so the total system is of 150*3= 450W. Per module output voltage is 34.3V, total output voltage is 102.9V .Boost converter is used to step up the voltage up to 189- 204V DC. DC-AC inverter converts the DC voltage into 200V AC. This ac voltage is fed to an ac machine as load. The excess voltage passes to the single phase grid (20KV, f =60 Hz) through a grid tied transformer.

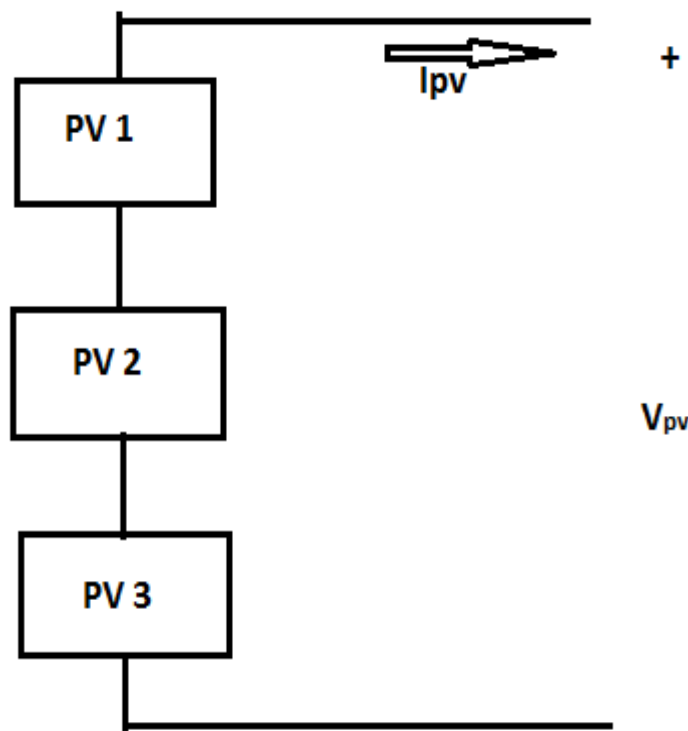


Figure 5.15 Proposed photovoltaic array model.

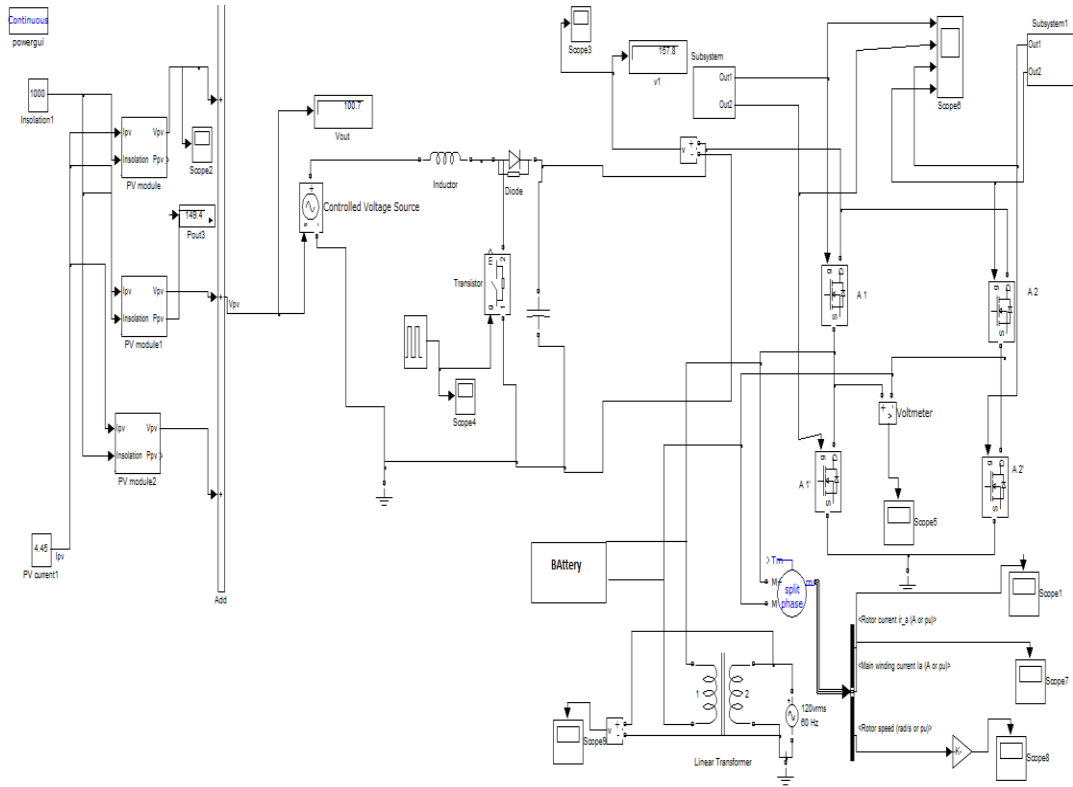


Figure 5.16 Proposed battery backup grid connected system.

Let us take,

P_{mod} as the module output power, H_{tilt} as the average daily irradiation in peak sun hours for the specified tilt angle, N as number of module and E_{array} as energy produced by PV array respectively.

$$\text{So, } E_{array} = P_{mod} * H_{tilt} * N \quad (5.12)$$

$$E_{array} = 150 * 4 * 3 = 1800Wh = 1.8e-3MWh. \quad (5.13)$$

From the above described table 5.1 we can estimate loads according to different seasons,

$$E_{load} (\text{summer}) = 720Wh$$

$$E_{load} (\text{winter}) = 248Wh$$

Let the average daily energy output of the grid connected PV system that is delivered to grid be E_{system} .

$$E_{\text{system}} = E_{\text{array}} * n_{\text{in}} * L - E \quad (5.14)$$

Here, n_{in} is the efficiency of the inverter, L is the losses in the system cabling and E is the energy lost in charging the batteries (battery backup system) respectively.

The energy loss in charging the batteries is actually the energy required to provide for self discharge of the battery bank. After meeting the load the excess power will be fed to the 20KV and 60Hz grid through transformer.

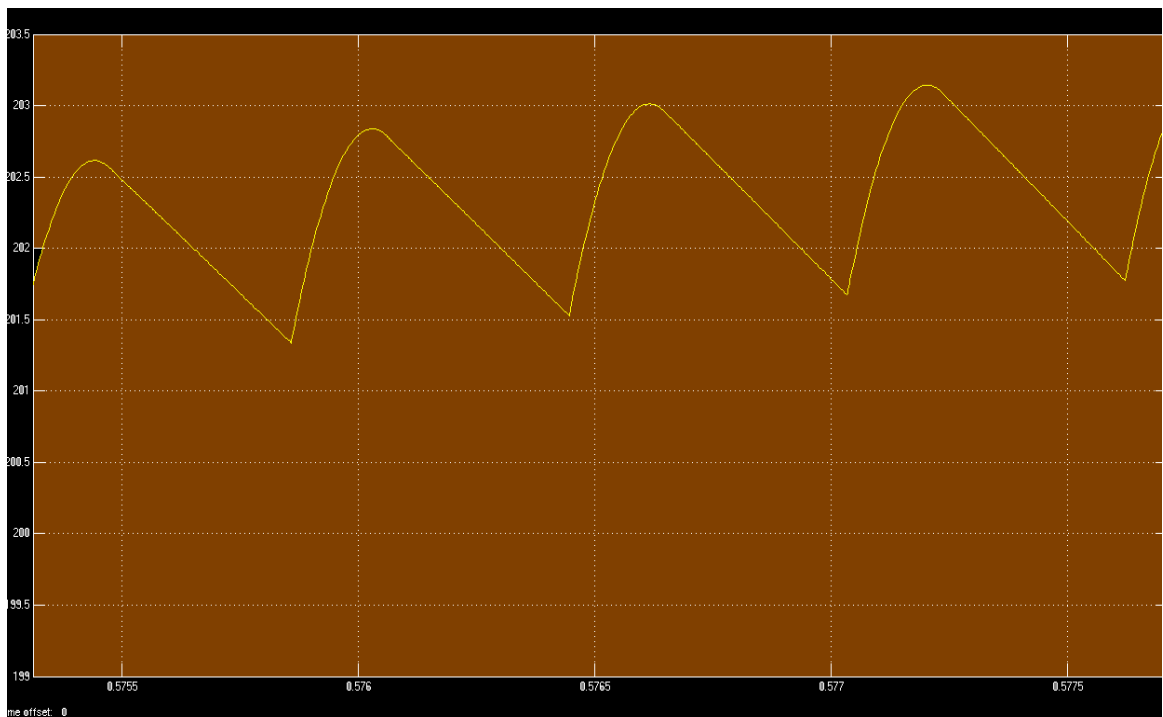


Figure 5.17 DC-DC boost converter output voltage (187-202 V DC).

In our proposed model the output voltage from 3 series module is 102 V. From figure 5.17 it can be observed that DC converter steps up the PV output voltage (102 V) , two times higher which ripples between 187-202 V.

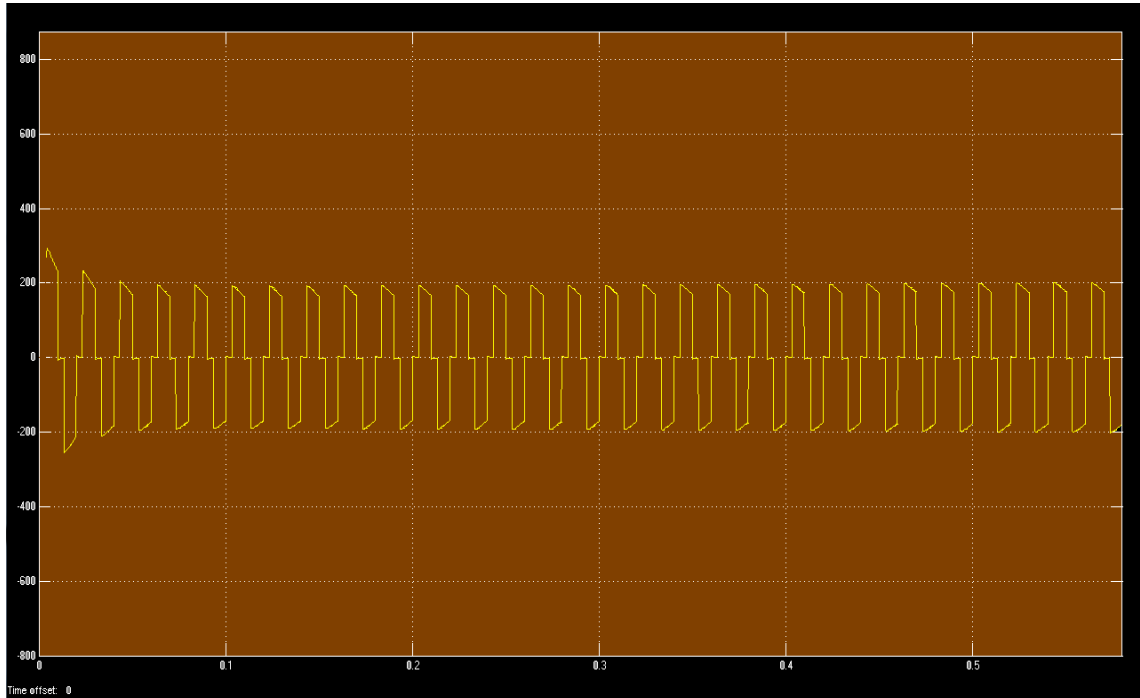


Figure 5.18 Single phase DC- AC Inverter output voltage (200V AC).

Here a modified square wave inverter has been used. From the above figure we can observe the AC output of the inverter in 200V.

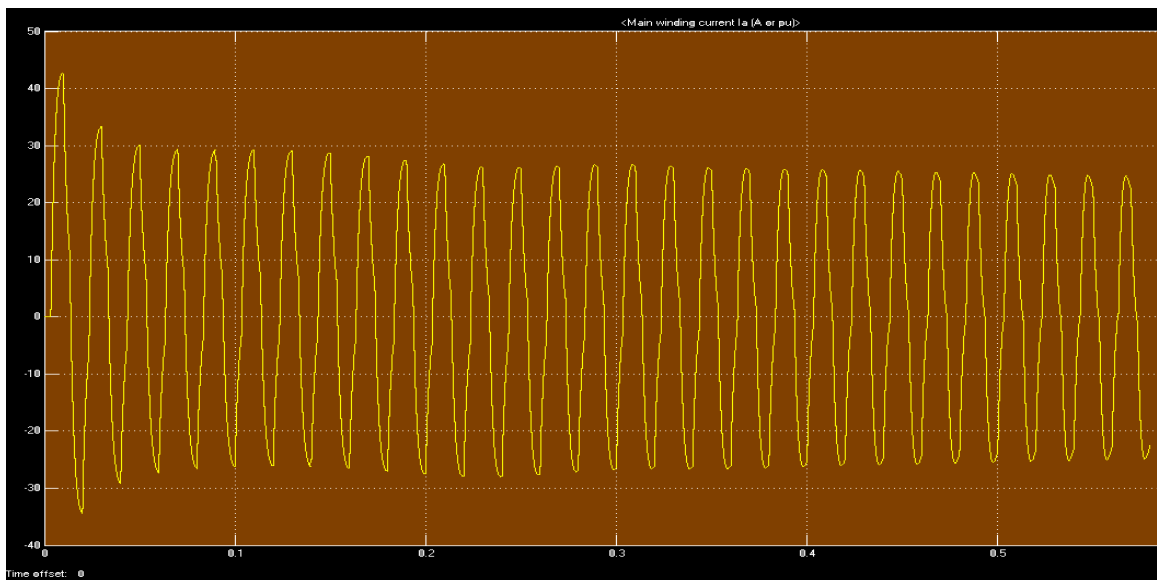


Figure 5.19 Main winding current of machine.

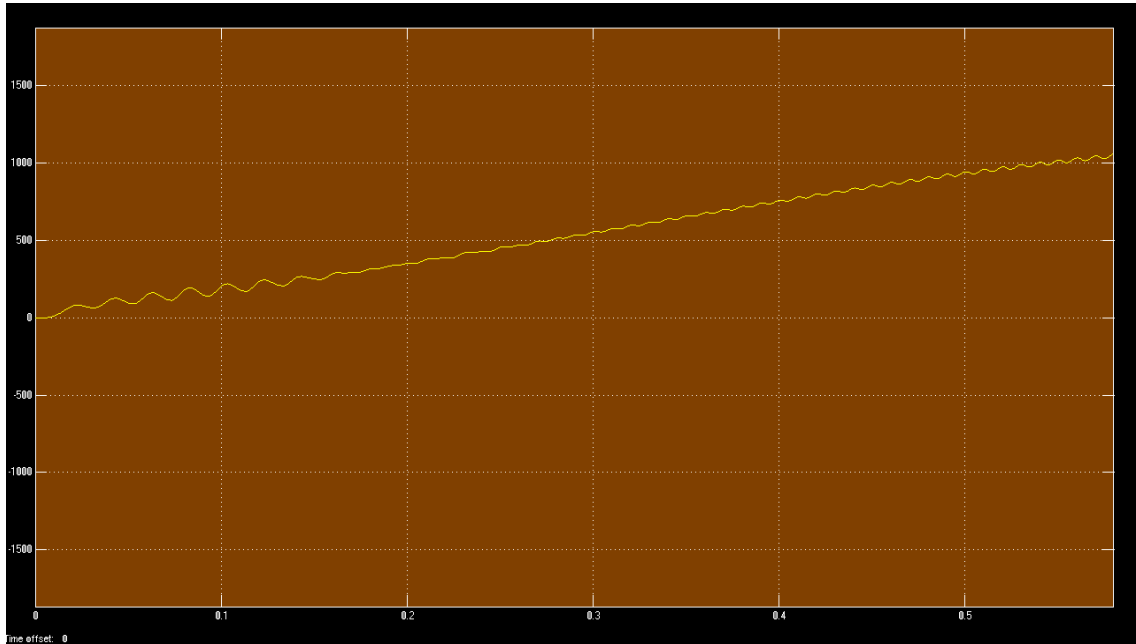


Figure 5.20 Rotor speed (red/ sec).

From the figure 5.19 and 5.20 we can observe the main winding current in ampere and the increasing speed of the induction motor respectively. The excess of electricity produced by the PV system injected to the grid of 20 KV and frequency is 60 Hz.

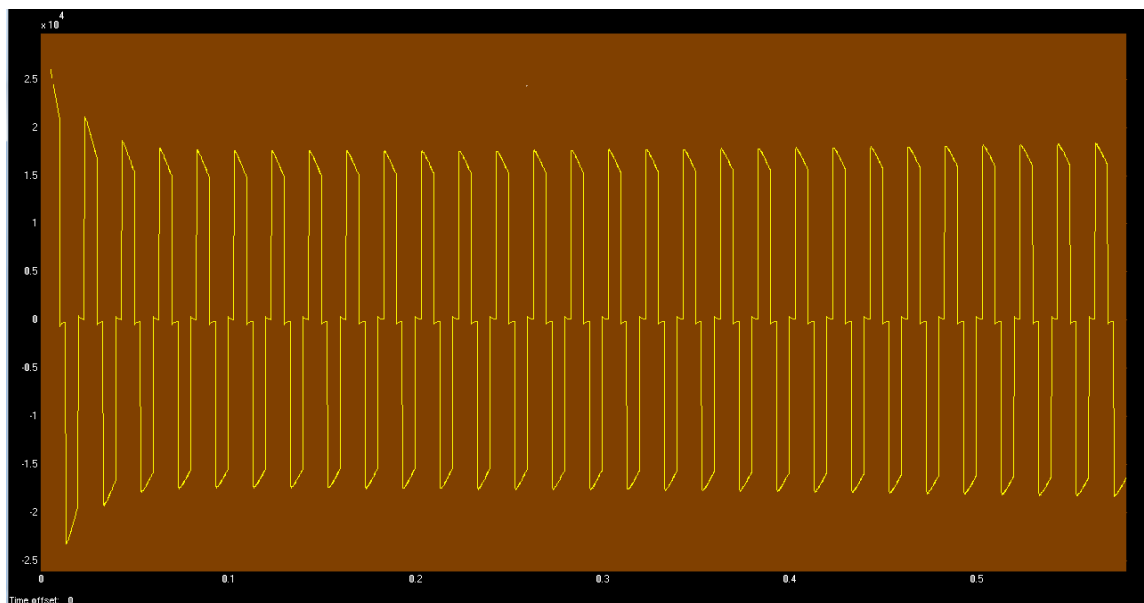


Figure 5.21 Grid connected transformer output voltage 20 KV ($f= 60$ Hz).

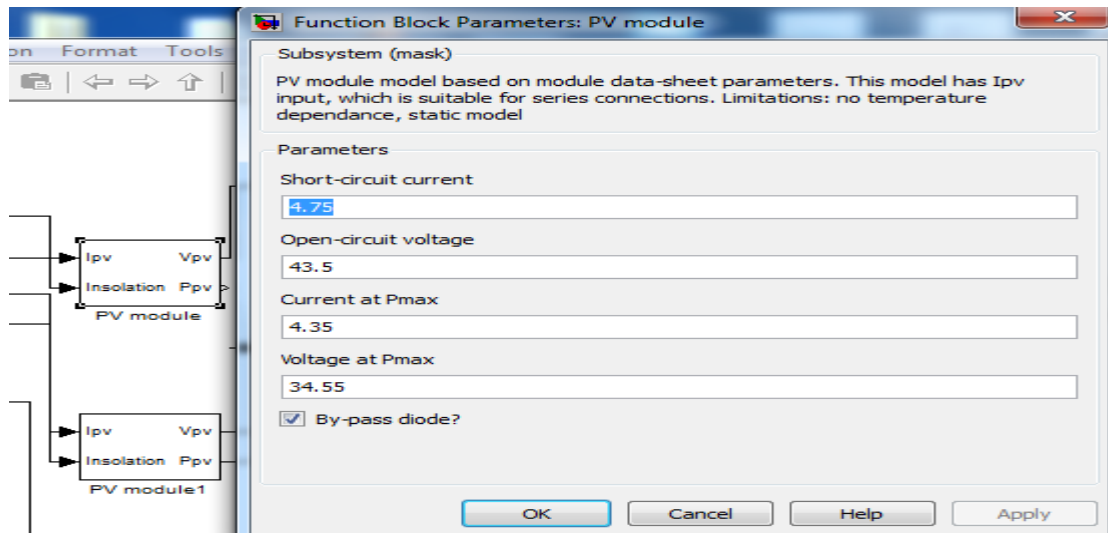


Figure 5.22 Function block parameter of PV module.

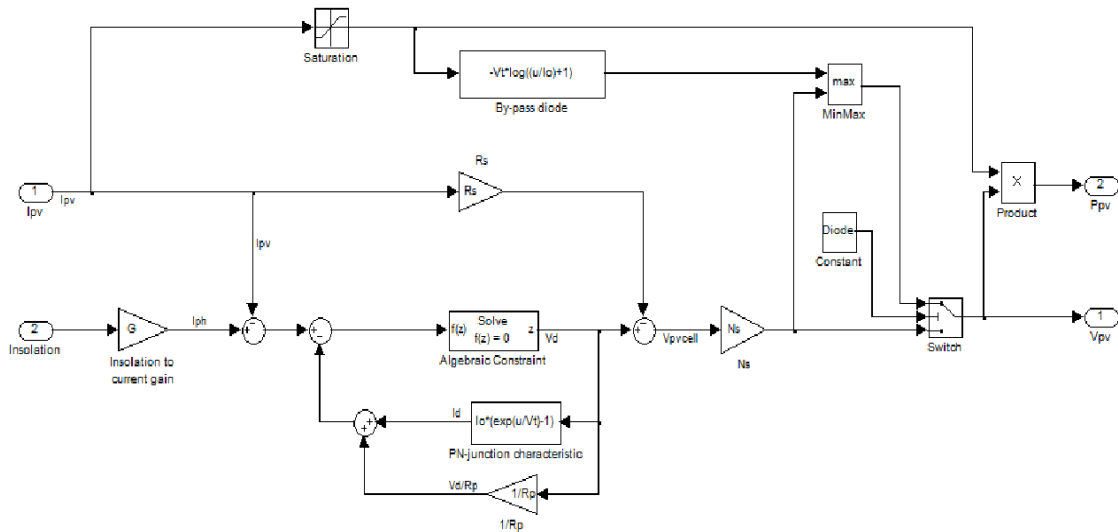


Figure 5.23 Simulation model of PV module (72 cells in series).

Figure 5.23 shows the simulink model of PV module, inside the PV module block. In function block the short circuit current has been fixed to 4.75 amps and open circuit voltage has been fixed to 43.5 V.

CHAPTER 6

CONCLUSION

A PV module electrical model is presented based on the Shockley diode equation. The simple model has a photo-current source, a single diode junction and a series resistance, and it is temperature dependent. Finally the model development was used to show the effect of irradiation level and temperature over PV module. The method of parameter extraction and model evaluation in MATLAB is demonstrated for BP SX 150S photovoltaic module which nominal maximum power is 150W. The result from the MATLAB model shows excellent correspondence to manufacturer's published curves. This model is used to investigate the variation of maximum power point with temperature and irradiation levels. In the projected simulink model perturb and observe algorithm has been used to control the maximum power point at variable solar irradiance condition. Boost maximum power point tracker (MPPT) topologies is made here. The boost converter is used to step up the PV output voltage since it can always track the maximum power point. This paper is the first step to develop a complete solar photovoltaic power electronic conversion system in simulation. The final objective is to develop a general model to simulate the electrical behavior of the PV systems in a grid connected application. Any research has a scope and limitation and it is never a complete compilation of all related topics in the field. This paper only discussed the general model of grid connected PV system. This is the limitation of this paper. The control system of Inverter is not considered here. The synchronization of inverter to the grid is very important issue for grid connected system. This Master's thesis does not include the study of the impact of the designed grid connected PV system on the existing national grid. This section will hope to be covered in the PhD research in future.

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1.MPPT Control

```
clear;

TaC = 25; % Cell temperature (deg C)
deltaD = .3; % Step size for Duty Cycle change
G= .1;
D = .2;
C = 0.5; % ref voltage change (V)
Va = 20.0; % PV voltage
Ia = testcode(Va,G,TaC); % PV current
Pa = Va * Ia; % PV output power
P= 0;
Vo= 0;
Io = 0;
Po= 0 ;
Vref_new = Va + C;
Dref_new= D + deltaD ;
Va_array = [];
Ia_array = [];
Pa_array = [];
Vo_array = [];
Io_array = [];
Po_array = [];
D_array = [];

for G = .1:.001:1
    Va_new = Vref_new;
    D_new = Dref_new;
    Ia_new = testcode(Vref_new,G,TaC);
    Pa_new = Va_new * Ia_new;
    deltaPa = Pa_new - Pa;

    if deltaPa > 0
        if Va_new > Va
            Vref_new = Va_new + C; % Increase Vref
        else
            Vref_new = Va_new - C; % Decrease Vref
        end
    elseif deltaPa < 0
        if Va_new > Va
```

```

        Vref_new = Va_new - C; % Decrease Vref
    else
        Vref_new = Va_new + C; %Increase Vref

        end
    else
        Vref_new = Va_new; % No change

End

Vo_n= Vref_new * 1/(1-D_new);
Io_n= Ia_new * (1-D_new);
P= Vo_n*Io_n ;
deltaPo = P - Po;
if (deltaPo > 0)&&((Io_n> 2.55))
D_new = Dref_new -deltaD; % Decrease duty cycle
else
    D_new= Dref_new;
end

% Update history
Va = Va_new;
Ia= Ia_new;
Pa = Pa_new;
D= D_new;
Vo=Vo_n;
Io=Io_n;
Po=P;

Va_array = [Va_array Va];

Ia_array = [Ia_array Ia];

Pa_array = [Pa_array Pa];

Vo_array = [Vo_array Vo];

Io_array = [Io_array Io];

Po_array = [Po_array Po];

D_array = [D_array D];
End

%plot (Va_array, Pa_array, 'b')
figure(1)

plot (Va_array, Ia_array, 'r')
%plot (D_array, Po_array, 'b')
axis([0 100 0 6])
figure(2)

plot (Vo_array, Io_array, 'r')
axis([0 100 0 3])
figure(3)

```

```

plot (Vo_array, D_array, 'b')
axis([35 80 0 1])
% Store data in arrays for plotend

```

2.Simulink Model of PV Module

```

function Ia = testcode(Va,G,TaC)
% Ia = testcode(Va,G,T)
%Ia = Module operating current (A),
%Va = Module operating voltage (V),

% G = Irradiance (1G = 1000 W/m^2),
% TaC = Module temperature in deg C,

%Va = 50;
%G = 1;
% Tac = 25;
k = 1.381e-23;
q = 1.602e-19;
n = 1.62; % Diode ideality factor (n),
Eg = 1.12; % Band gap energy; 1.12eV (Si), 1.42 (GaAs),

Ns = 72; % of series connected cells ( 72 cells)
TrK = 298; % Reference temperature (25C) in Kelvin
Voc_TrK = 43.5 /Ns; % Voc=open circuit voltage per cell at temp TrK
Isc_TrK = 4.75; % Isc =short circuit current per cell at temp TrK
a = 0.65e-3; % Temperature coefficient of Isc (0.065%/C)

TaK = 273 + TaC; % Module temperature in Kelvin
% Calculate short-circuit current for TaK
Isc = Isc_TrK * (1 + (a * (TaK - TrK)));

Iph = G * Isc;
% Define thermal potential (Vt) at temp TrK
Vt_TrK = n * k * TrK / q;
% Define b = Eg * q/(n*k);
b = Eg * q / (n * k);

Ir_TrK = Isc_TrK / (exp(Voc_TrK / Vt_TrK) -1);
Ir = Ir_TrK * (TaK / TrK)^(3/n) * exp(-b * (1 / TaK -1 / TrK));

dVdI_Voc = -1.0/Ns; % Take dV/dI at Voc from I-V curve of datasheet
Xv = Ir_TrK / Vt_TrK * exp(Voc_TrK / Vt_TrK);
Rs = - dVdI_Voc - 1/Xv;
% Define thermal potential (Vt) at temp Ta
Vt_Ta = n * k * TaK / q;
% Ia = Iph - Ir * (exp((Vc + Ia * Rs) / Vt_Ta) -1)
% f(Ia) = Iph - Ia - Ir * ( exp((Vc + Ia * Rs) / Vt_Ta) -1) = 0
% Solve for Ia by Newton's method: Ia2 = Ia1 - f(Ia1)/f'(Ia1)
Vc= Va/Ns;
Ia=zeros(size(Vc));
for j=1:5;
Ia = Ia - (Iph - Ia - Ir .* ( exp((Vc + Ia .* Rs) ./ Vt_Ta) -1))...
./ (-1 - Ir * (Rs ./ Vt_Ta) .* exp((Vc + Ia .* Rs) ./ Vt_Ta));
end

```


3. Maximum Power Calculation

```
function [Pa_max, Imp, Vmp] = testcode3(G, TaC)

%
% Define variables and initialize
Va = 12;
Pa_max = 0;
TaC = 25 ;
G = 1 ;
% Start process
while Va < 48-TaC/8
Ia = testcode(Va,G,TaC);
Pa_new = Ia * Va;
if Pa_new > Pa_max
Pa_max = Pa_new;
Imp = Ia;
Vmp = Va;
end
Va = Va + .005;
end
```

4. I-V Characteristic of PV Module At Different Temperature

```
clear;
% Define constant
G = 1;
% Functions to plot
figure

hold on
for TaC=0:25:75
Va = linspace (0, 48-TaC/8, 200);
Ia = testcode(Va, G, TaC);
plot(Va, Ia)
end

xlabel('Module Voltage (V)')

ylabel('Module Current (A)')

axis([0 50 0 5])

gtext('0C')
gtext('25C')
gtext('50C')
gtext('75C')
hold off
```

5. Maximum Power at Different Irradiances

```
clear;

TaC = 25; % Cell temperature (deg C)
C = 0.5; % ref voltage change (V)

G = 0.1; % Irradiance (1G = 1000W/m^2)

Va = 20.0; % PV voltage

Ia = testcode(Va,G,TaC); % PV current

Pa = Va * Ia; % PV output power

Vref_new = Va + C; % New reference voltage

% Set up arrays storing data for plots

Va_array = [];
Pa_array = [];

Va = linspace (0, 45, 200);
hold on
for G=.2:.2:1
Ia = testcode(Va, G, TaC);
Pa = Ia.*Va;
plot(Va, Pa)
[Pa_max, Imp, Vmp] = testcode3(G, TaC);
plot(Vmp, Pa_max, 'r*')
end

xlabel('Module Voltage (V)')

ylabel('Module Output Power (W)')

axis([0 50 0 160])
gtext('1000W/m^2')
gtext('800W/m^2')
gtext('600W/m^2')
gtext('400W/m^2')
gtext('200W/m^2')
hold off
```

6. P&O Algorithm

```
clear;

TaC = 25; % Cell temperature (deg C)
C = 0.5; % ref voltage change (V)

G = 0.1; % Irradiance (1G = 1000W/m^2)
Va = 20.0; % PV voltage
Ia = testcode(Va,G,TaC); % PV current
Pa = Va * Ia; % PV output power
Vref_new = Va + C; % New reference voltage
% arrays storing data for plots
Va_array = [];
Pa_array = [];

for G = .1:.0021:1

Va_new = Vref_new;
Ia_new = testcode(Vref_new,G,TaC);
% Calculate new Pa
Pa_new = Va_new * Ia_new;
deltaPa = Pa_new - Pa;
% P&O Algorithm starts here
if deltaPa > 0
if Va_new > Va
Vref_new = Va_new + C; % Increase Vref
else
Vref_new = Va_new - C; % Decrease Vref
end
elseif deltaPa < 0
if Va_new > Va
Vref_new = Va_new - C; % Decrease Vref
else
Vref_new = Va_new + C; %Increase Vref
end
else
Vref_new = Va_new; % No change
end
% Update history
Va = Va_new;
Pa = Pa_new;
% Store data in arrays for plot
Va_array = [Va_array Va];
Pa_array = [Pa_array Pa];
End

% Plot result
figure
plot (Va_array, Pa_array, 'b')
% Overlay with P-I curves and MPP
Va = linspace (0, 45, 200);
hold on
for G=.2:.2:1
```

```
Ia = testcode(Va, G, TaC);
Pa = Ia.*Va;
plot(Va, Pa)
[Pa_max, Imp, Vmp] = testcode3(G, TaC);
plot(Vmp, Pa_max, 'r*')
end
title('P&O Algorithm')
xlabel('Module Voltage (V)')
ylabel('Module Output Power (W)')
axis([0 50 0 160])
%gtext('1000W/m^2')
%gtext('800W/m^2')
%gtext('600W/m^2')
%gtext('400W/m^2')
%gtext('200W/m^2')
hold off
```

PERSONAL INFORMATION

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EDUCATION

Degree	Department	University	Year
Under Graduate	Electrical and Electronic Engineering	American International University-Bangladesh	2007
College	Science	Cant. Public School and College Rangpur	2003