DEVELOPMENT OF PROTOTYPE OF MPPT BASED CHARGE CONTROLLER FOR E-RICKSHAWS

A PROJECT REPORT

Submitted in partial fulfilment of the requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
SOLID STATE ELECTRONIC MATERIALS

Submitted by:
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MAY 2019

DECLARATION BY THE CANDIDATE

We hereby certify that the wok which is presented in this project entitled ***"Development of prototype of MPPT based charge controller for E-Rickshaws"*** in partial fulfillment for the award of the degree of Master of Technology (SSEM) submitted to the Department of Physics, I. I. T. Roorkee is an authentic record of our own work carried out during the period from July 2018 to May 2019 under the guidance of ***Dr. S.P. Singh,*** Professor, Department of Electrical Engineering, I. I. T. Roorkee and ***Dr. Anirban Mitra,*** Associate Professor, Department of Physics, I. I. T. Roorkee.

The matter embodied in this project report to the best of our knowledge has not submitted for the award of any other degree elsewhere.

May 31, 2019

Avinash Kumar (17550001) ……………………

CERTIFICATE

This is to certify that the above declaration is true to the best of my knowledge.

………………… …………………

Dr. Anirban Mitra **Dr. S.P. Singh**

Acknowledgement

We would like to take this opportunity to express our deep gratitude to our advisor and mentor ***Dr. S.P. Singh*, **Professor, Department of Electrical Engineering, I.I.T. Roorkee and ***Dr. Anirban Mitra*, **Associate Professor, Department of Physics, I.I.T. Roorkee for his constant help and support throughout the project. Without his constant monitoring and guidance, it would have been impossible to achieve results. His enthusiasm and ideas have motivated us to work with dedication to this project and thus completing the project and the technical report.

We would also like to pay our sincere thanks to *Mr. Rupak Chakraborty*, Phd. Scholar, Department of Electrical Engineering, I.I.T. Roorkee.

Abstract

This project aims to develop a MPPT (Maximum Power Point Tracking) based charge controller for charging batteries of E-Rickshaws. PV array has non-linear I-V characteristic and output power depends on environmental conditions such as solar irradiation and temperature. There is a unique point on I-V, P-V characteristic curve of PV array, the Maximum Power Point (MPP), where the PV system produces its maximum output power. Location of MPP changes with change in environmental condition. The purpose of MPPT based charge controller is to adjust the operating voltage of the solar panel close to MPP dynamically under changing environmental conditions. Two MPPT algorithms namely the P&O (Perturb and Observe) method and the Incremental Conductance method are implemented. The developed algorithm performs a wide-range search in order to detect rapidly changing weather conditions, and keeps the system continuously operating close to the MPP. The motivation behind this project is to contribute to power for charging of batteries of E-Rickshaws to reduce the dependency for charging on electricity. This solution is cost-effective and will not emit any air pollutants.

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List of symbols used

I_{ph}: Photocurrent (A)

I_s: Diode Saturation Current (A)

q: Electron Charge (1.60217646 × 10^{-19} C)

n: Diode Ideality Factor

k: Boltzmann Constant (1.3806503 × 10^{-23} J/K)

T: Temperature of the p-n Junction (K)

T_{STC}: 25°C

R_s: Series Resistance (Ω)

R_{sh}: Shunt Resistance (Ω)

I_{SC}: Short-Circuit Current (A)

K_i: Short-Circuit Current Coefficient

G: Irradiance on the Surface of the Cell (W/m^2)

G_{STC}: 1000 W/m^2

E_g: The band gap energy of the semiconductor

V_t: Thermal voltage of the cell (V_t= kT/q)

V_{OC}: Open Circuit Voltage

I_{SC}: Short Circuit Current

MPPT: Maximum Power Point Tracking

PWM: Pulse Width Modulation

PV: Photo Voltaic

1. Introduction

1.1 Introduction:

One of the important concerns in the power sector is the day-by-day increasing power demand but the unaccessibility and unavailability of enough resources to feed the power demand using the traditional sources of energy. The constant and unabating use of fossil fuels has caused the fossil fuel stock to be reduced and has significantly affected the environment by gradually enhancing global warming. So, demand has risen up for renewable sources. Renewable or non-traditional sources like wind energy and solar energy are the common sources of energy which are being used in this regard.

Thermal cell technology: In this, sun-rays are focused to heat a boiler to generate steam using parabolic concentrators. Further steps are similar to the thermal power plant where this steam is used to run the turbines.

PV cell technology: A Photovoltaic cell or Solar cell is an electrical gadget or device that converts light energy into electricity by photovoltaic effect. Solar cells are the basic elements of photovoltaic modules or solar panels.

Solar energy is abundantly available. It can be an independent or stand-alone generating unit or a grid connected generating unit based on the accessibility and availability of a grid nearby. Therefore solar energy can be used to light up rural areas where the availability of conventional electric grids is very less. Another pros of using solar energy is that it is portable and can be operated wherever whenever required.

After being installed they produce or generate electricity from solar radiation without releasing any greenhouse gases. Basically, the efficiency of a solar power plant is mostly affected by three factors: the efficiency of the PV module or solar panel (in commercialized solar panels, it lies between 8-15%), the efficiency of the inverter used (95-98 %) and the efficiency of the *Maximum power point tracking* (MPPT) algorithm used to design (which is over 98%). Improving the efficiency of the PV panel and the inverter is not easy as it is technology dependent. Alternatively, improving the tracking of the MPP with new control algorithms is better, less-expensive, leading to an increase in power generation and a reduction in its price.

MPPT algorithms are important since PV arrays gives a non-linear Voltage-Current characteristic curve with a single point at which the power developed is maximum. This point is dependent on the temperature and the solar irradiance. These conditions may change during the day and night and are also distinct depending on the season in a year. Further, solar irradiation can vary drastically depending on atmospheric condition like clouds. It is most essential to track the MPP appropriately under all possible varying conditions.

In this project, MPPT algorithms, *Perturb and observe* (P&O), *Incremental conductance* (InCond) are implemented. The algorithm performs a wide-range search in order to detect MPP in rapidly changing weather conditions, and keeps the system continuously operating close to it. We have developed MPPT based charge controller and a Boost converter and for charging the batteries of E-Rickshaws.

1.2 Literature Survey:

The subject of solar energy generation and utilization has been worked upon by many research scholars across the globe. It is well known that solar cell works at lower efficiency and hence a better control technique is necessary to increase the efficiency of the solar cell module. In this area research scholars have developed the Maximum Power Point Tracking (MPPT) algorithms.

Moein Jazayeri and Sener Uysal have successfully illustrated the model of a solar cell module and the change or variation of the current-voltage curve and the power-voltage curve caused by the changes in solar irradiation and changes in ambient temperature in IEEE trans. on “A Simple MATLAB/SIMULINK Simulation for PV”.

David Sanz Morales has given a detailed report on Maximum Power Point Tracking Algorithms for Photovoltaic cell or PV cell Applications and has estimated and compared different algorithms for maximum power point tracking at varying radiation functions to estimate the variation of the output power in two cases using the MPPT algorithms and optimized MPPT algorithms.

Kok Soon Tey and Saad Mekhilef have also explained modified Incremental Conductance Algorithm for photovoltaic system under partial shading conditions and load variations in detail.

1.3 Motivation:

The motivation behind this project is to contribute to power for charging of E-Rickshaws (basically charge rickshaw from both electricity and solar power), this will reduce the dependency for charging on electricity.

1.4 Objective:

The major objective will be to study MPPT system and successfully and efficiently implement the MPPT algorithms in MATLAB Simulink models. Modeling the Boost converter (power electronic converter) and the solar cell array in Simulink and interfacing both with the MPPT algorithms to obtain the maximum power point operation will be of prime concern. With the help of all these models in Simulink, we tried to develop the prototype of MPPT based charge controller for E- Rickshaws.

1.5 Report Outline:

This report first introduces 'PV cell technology', and various 'battery charging and MPPT' techniques. Then the implemented hardware is explained and then, the performed simulations and test results are shown. Then cost analysis is done, future improvements are mentioned.

2. PV cell technology

2.1 PV cell:

PV cells are basic components of Photovoltaic panels. In general, they are made of crystalline silicon.

Solar cells works based on photoelectric effect principle: the ability of some semiconductors to convert EM radiation directly into electrical current. A PV cell is basically a p-n junction made from two differently doped layers of silicon. Metallic contacts are made at both sides to complete the circuit for current flow. The n-layer side faces the solar irradiance. Several PV cells are connected in series and parallel according to the requirement of current and voltage ratings. The cross section of PV cell is shown in Fig-2.1.

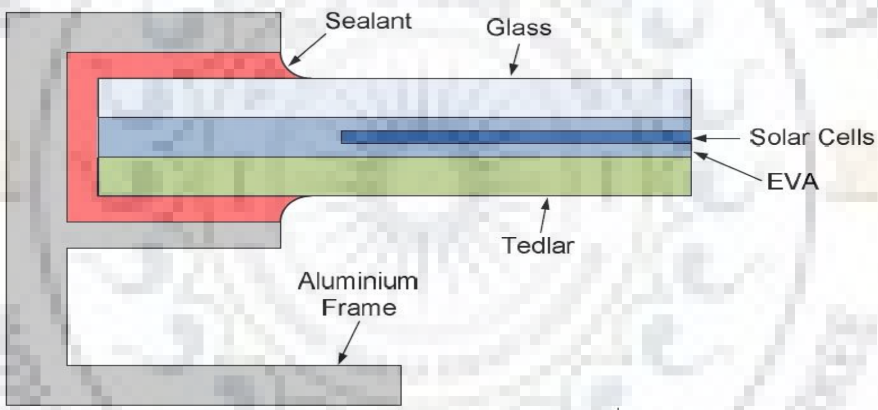


Fig – 2.1: Cross section of PV cell (Source: [6])

The PV panel used for hardware analysis have the following ratings at standard conditions (Irradiation=1000 W/m^2, Temperature=25^oC)

Electrical Specs	Mechanical Specs
P_{MAX}: 37W	Length: 660mm
V_{OC}: 21.8V	Width: 515mm
I_{SC}: 2.40A	Depth: 35.35mm
V_{MPP}: 17.6V	Weight: 4.2kg
I_{MPP}: 2.20A	No. of cells: 36

Table-2.1: PV Module (PM37) Specifications

2.2 Single-diode PV cell model:

Although many models exist in literature, to minimize the complexity, the single diode model of PV cell described in [1] is implemented in Simulink. The equivalent electrical circuit of one-diode model of a solar cell is illustrated in Fig-2.2. The model consists of a linear current source, a diode, a parallel resistance indicating the leakage current and a series resistance representing the internal resistance of a solar cell.

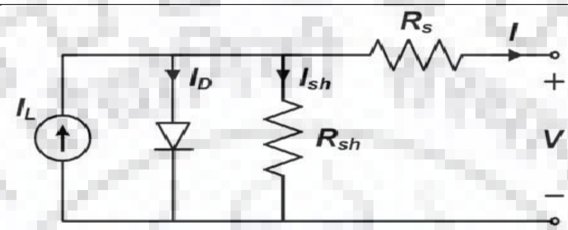


Fig – 2.2: Single-diode model of PV module (Source [1])

According to the single-diode model of PV cell, the voltage and current relationship can be given by the following equation.

$$I = I_{ph} - I_s \left(e^{\left(q(V + R_s I) / nkT \right)} - 1 \right) - \frac{(V + R_s I)}{R_{sh}} \quad (2\text{-}1)$$

Determination of I_{ph}:

$$I_{ph} = [I_{sc} + k_i (T - T_{stc})] * \left(\frac{G}{G_{stc}} \right) \quad (2\text{-}2)$$

Determination of I_S:

$$I_S = I_{S,STC} \left(\frac{T_{STC}}{T} \right)^3 exp \left[\frac{qE_g}{nk} \left(\frac{1}{T_{STC}} - \frac{1}{T} \right) \right] \quad (2\text{-}3)$$

Where,

$$I_{S,STC} = \frac{I_{SC}}{exp(V_{OC}/nV_t) - 1} \quad (1\text{-}4)$$

$$E_g = 1.16 - 7.02 * 10^{-4} \left(\frac{T^2}{T - 1108} \right) \quad (2\text{-}5)$$

Determination of Series and Shunt Resistance:

Due to lack of datasheet of the used PV panel the method mentioned in [1] is used.

Simulated PV cell model and PV panel block parameters are shown in the following figure:

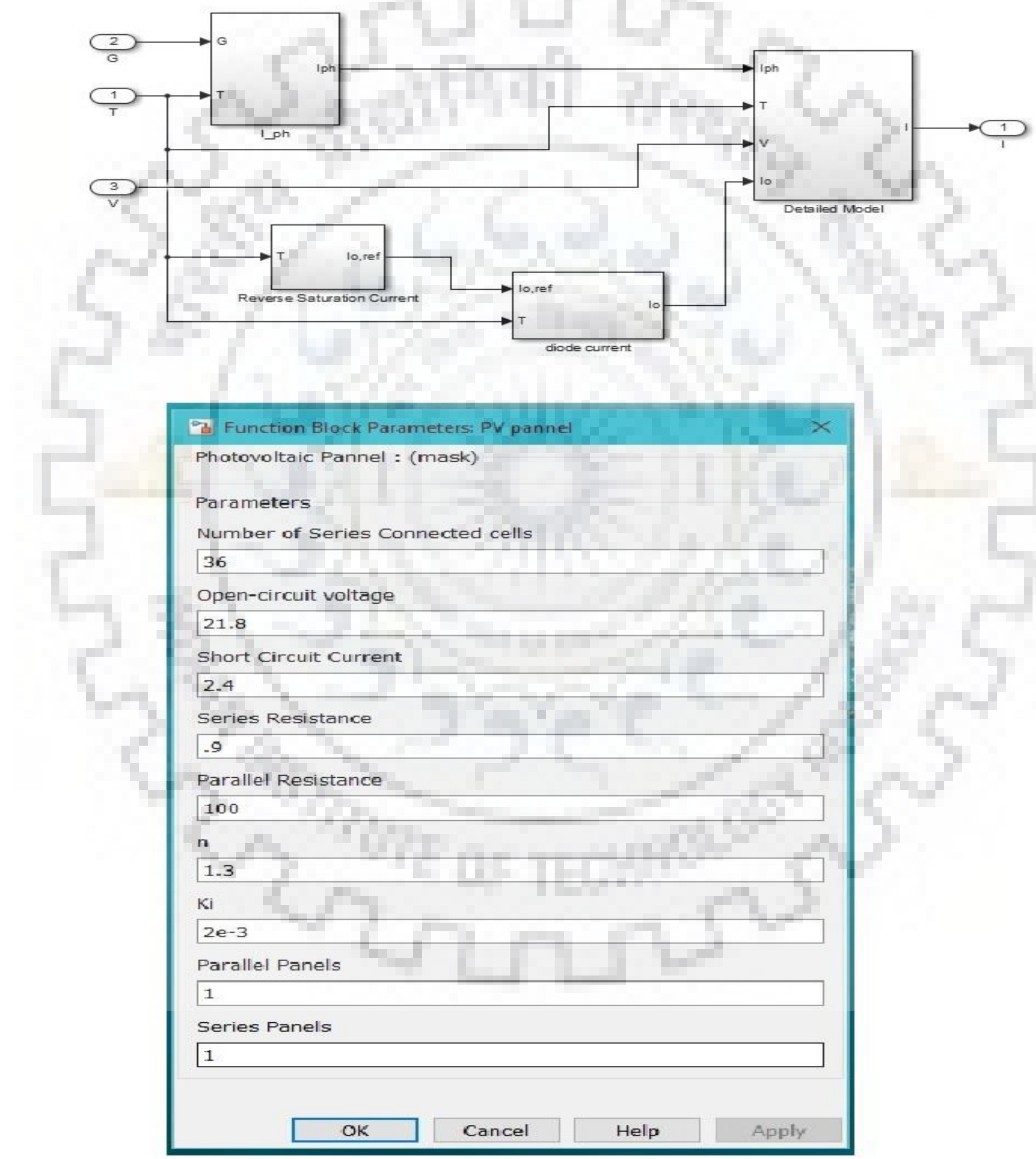


Fig - 1.3: MATLAB Simulation of PV module

2.3 PV module characteristics and its dependence on Temperature and Irradiance:

The ideal P-V and I-V characteristics of the PV panel are shown in the Fig-2.4.

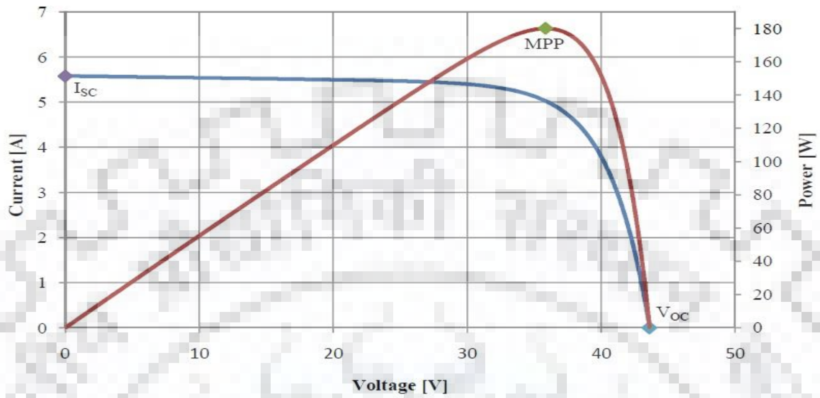


Fig - 2.4: Ideal I-V, P-V characteristics of PV panel (Source: [6])

One can observe the non-linear characteristics and can also realize that maximum power is extractable at a particular voltage.

The two important factors that have to be taken into account are temperature (T) and irradiance (G). These parameters strongly affect the P-V and I-V characteristics.

This effect can be seen in the following figure.

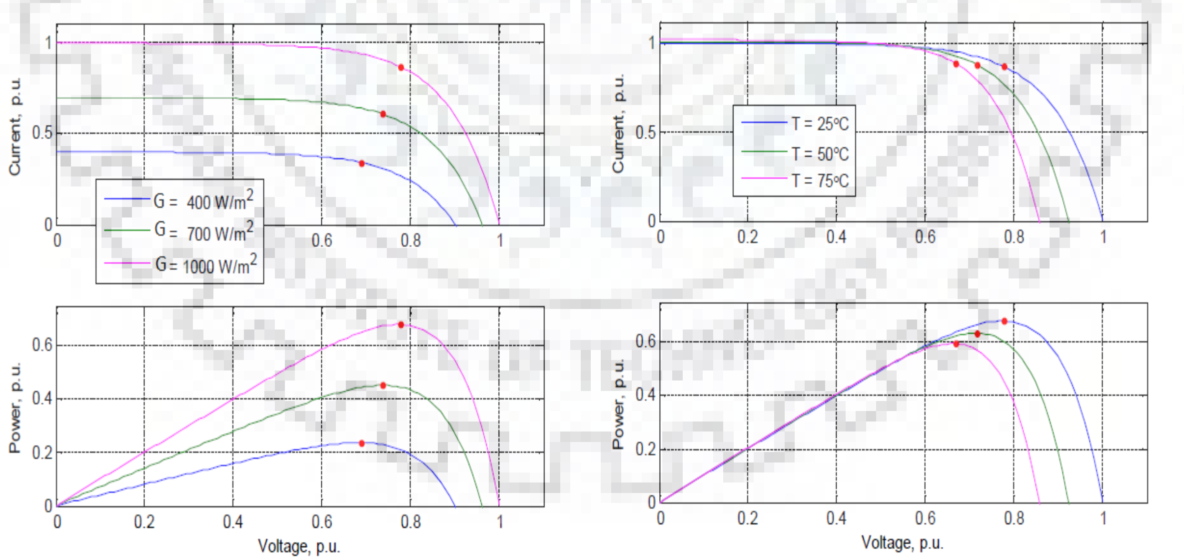


Fig - 3.5 – Effects of T, G on I-V, P-V characteristics

One may observe that temperature mostly affects V_{OC} whereas irradiance affects I_{SC}. Due to these the MPP also keeps on varying with T and G.

3. Solar powered charging of batteries

There are many ways to charge a rechargeable battery using solar panels. A simple and straight forward method is to connect it directly or use sophisticated methods such as PWM, MPPT Techniques. Each of them is explained below.

Note: Specifications of the batteries used (2 in series):

Type: Lead-Acid battery; Nominal Voltage: 13.8 Volts; Capacity: 7 Amp-hrs.

3.1 Direct Charging:

In this method, the terminals of the PV module are directly connected to those of the battery and are disconnected when the battery is charged. The advantages of this method lie in simplicity and ease of implementation. There are many disadvantages to this method which are explained below. The current through the battery is either full or zero (bang-bang type). This reduces the life of the battery. Another disadvantage is that the battery may be over-charged which increases stress over it and may lead to its damage or even explosion.

A better way to charge the battery is to pass full current when '% charge' is below certain value, say 80% and gradually make it zero as '% charge' increases to 90%. The graph of '% charge' vs. charging current in this case is shown below.

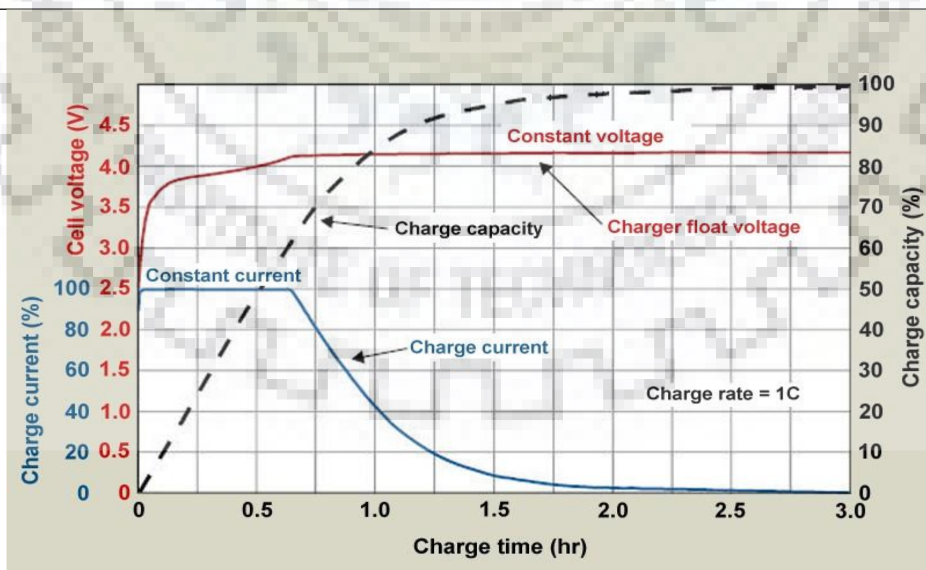


Fig – 3.1: Graph: Ideal %-Charged Vs. Current through battery

Source: www.batteryuniversity.com

3.2 PWM based charge controller:

The graph shown in Fig-3.1 may be achieved by PWM based charge controller as explained below. A PWM based charge controller regulates the charging-current depending on the battery voltage. So, it also eliminates the problem of over-charging and thus eliminates the stress on the battery.

Block diagram:

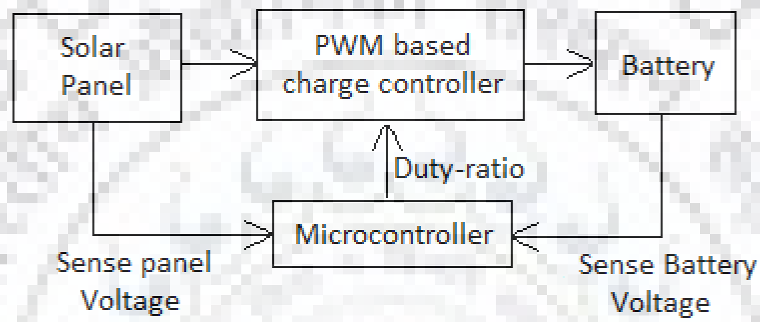


Fig – 3.2: Block diagram of PWM based charge controller

The Boost converter circuit explained later is used with an exterior current control loop that controls the current passing through battery. The concave up graph for charging-current may be implemented either with respect to time or with respect to precise battery voltage which is a function of %-charge on the battery.

However, this method is good on the part of battery by increasing its life time, but, it is inefficient on the part of the PV module by underutilizing it. To fully utilize the PV module, MPPT based charge controller is used which is explained below.

3.3 MPPT based charge controller:

It is clear from the non-linear VI characteristics of PV module shown earlier that there is unique point ($V_{P,\ MAX}$, $I_{P,\ MAX}$) for a given 'temperature' and 'solar irradiation' corresponding to maximum power output from the panel. The goal of MPPT based charge controller is to operate the solar panel at this point. It may be noted here, that the voltage of the panel at this point is different from the voltage of battery to be charged, so, a DC-DC converter is needed to match them. In our case, it is mentioned that V_{OC} of solar panel is 21.x V; this project involves charging of two lead acid batteries connected in series; so, a boost converter is implemented because $V_{P,\ MAX}$ is less than 27.6 V.

There are many MPPT techniques available. Two methods namely 'Perturb & Observe', 'Incremental Conductance' are implemented; the methods are explained in later sections. In general, in any MPPT technique, the essence is that the point of maximum power output is tracked and the solar panel is operated at it and its vicinity is kept on checked. If due to some reasons (such as 'cloud cover', 'object shadow in case of non-stationary panels' etc.) the point of MPP changed, then the operating point is changed to new MPP.

The main advantage of MPPT technique is that PV module is not under-utilized. Also, the batteries take less time to charge because

$$time = \frac{Energy}{Power} = \frac{Energy\ required}{P_{max}} \Rightarrow (minimum)$$

Many batteries may be charged at the same time and quickly. There is a tradeoff between cost and efficiency.

4. MPPT Techniques Implemented

As said earlier, two MPPT techniques were implemented. They are:

1. Perturb & Observe method
2. Incremental conductance method

The following section explains the above two methods.

4.1 Perturb & Observe method: (P&O method)

In P&O method, the point of operation is perturbed and power output of PV module is observed and next perturbation is decided based on it. In simple terms, this can be thought of as moving on the PV characteristic (which looks like a hill) in one direction and changing the direction if a downward slope is encountered. The method is discussed below in detail.

Consider the following figure which shows the PV characteristics of a PV module at some constant temperature and irradiance.

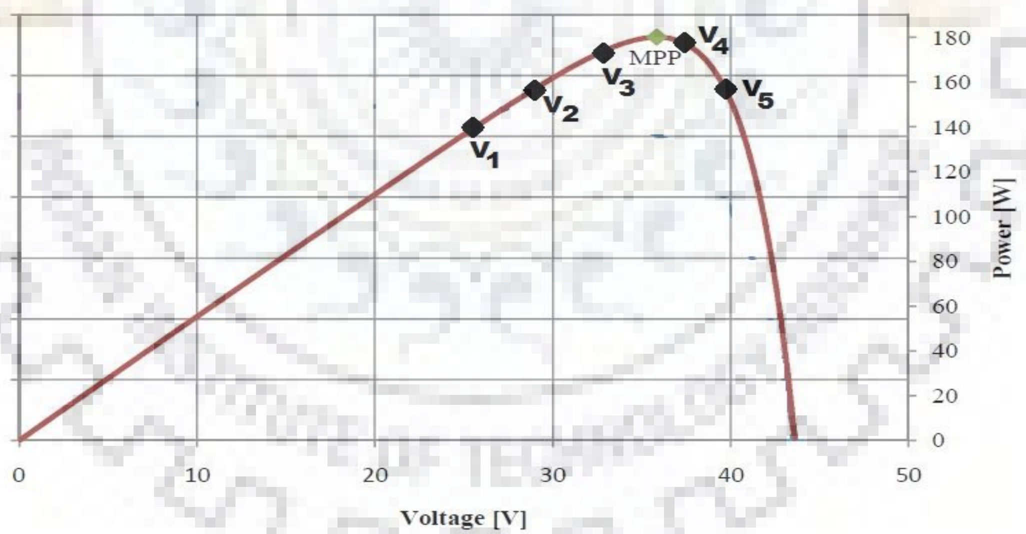


Fig – 4.1: Illustration of P&O method of MPPT

The current voltage of operation is shown as V_1 in the figure. Clearly, this point is not the point of maximum power output from the PV module. Now, the operating point is perturbed. Suppose, the operating voltage is increased, i.e. point of operation is changed from V_1 to V_2, then, an increase in power output is observed. This means that an increase in operating voltage led to an increase in power output. So, the operating voltage is further increased to V_3. Same discussion as above tells that operating voltage be changed to V_4 and then to V_5. This time, the increase in operating voltage from V_4 to V_5 led to a decrease in power output. So, the direction of change in operating voltage is reversed, i.e. from now the change is made negative. The operating point goes from V_5 to V_4, and an increase in power output is seen, so, the operating point further goes to V_3, this time power output decreased and the direction is reversed. The process repeats and the point of operation oscillates between V_3 and V_5. Thus P&O technique is able to track and operate in the vicinity of the MPP of the PV module.

It may be noted that there is a tradeoff between time required to track MPP and oscillations about the tracked MPP based on step-size ($V_2 - V_1$ in the above figure) because, if step-size is more, it will take less time to reach MPP, however, the interval of oscillation would be more (consider $V_5 - V_3$ in the above discussion).

The following is the block diagram of the above P&O method:

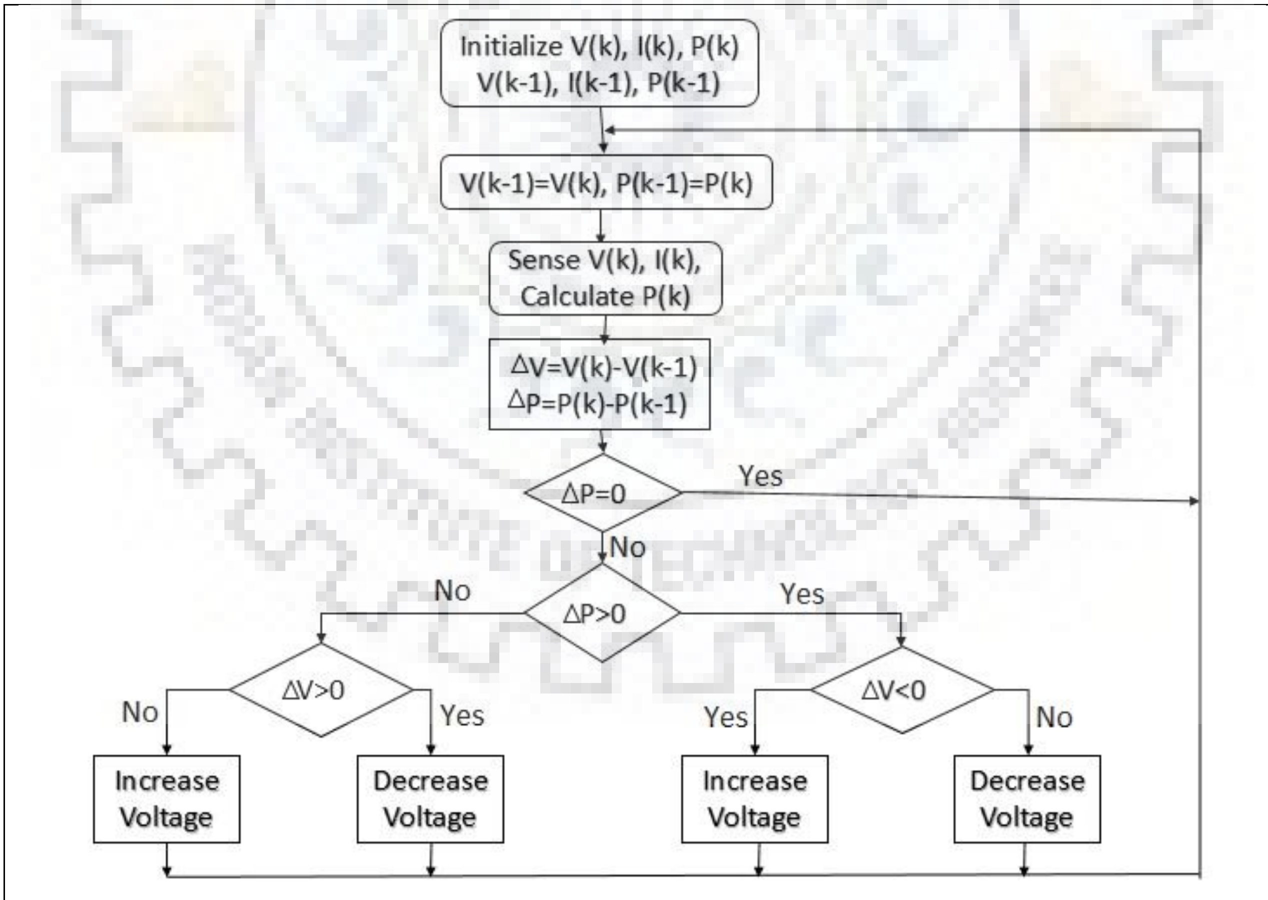


Fig – 4.4: Block diagram of P&O method for tracking MPP of PV module

4.2 Incremental Conductance Method:

For ease, the P-V characteristics of a PV module at a constant temperature and irradiance are redrawn below.

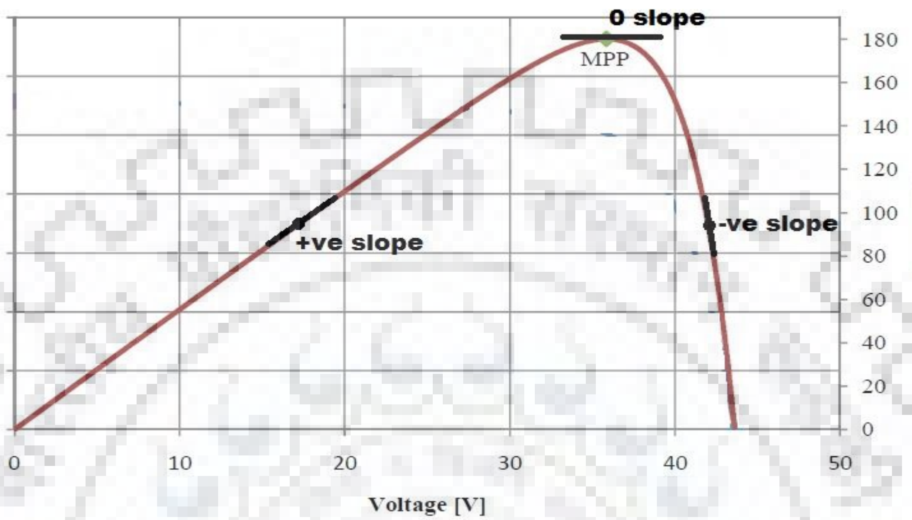


Fig – 4.5: Illustration of Incremental Conductance method

It can be seen from the above figure, that the slope, "dP/dV"

- at any point on the curve in the region towards left of the MPP is positive
- the MPP is 0
- at any point on the curve in the region towards right of the MPP is negative

The Incremental Conductance MPPT technique is based on the above fact. The change in power, and voltage are measured and if

- "dP/dV" > 0: operating voltage is to be increased
- "dP/dV" = 0: operating voltage is to be retained
- "dP/dV" < 0: operating voltage is to be decreased

However, in the above method, power has to be calculated by multiplying 'V_{SOLAR}' and 'I_{SOLAR}' after measuring them. In order to eliminate this calculation, we may express the above in conductance terms using the following equation.

$$\frac{dP}{dV} = \frac{VdI + IdV}{dV} = V\frac{dI}{dV} + I \quad (4\text{-}2)$$

The above technique in Incremental conductance terms using equation 4-1:

•	$\frac{dP}{dV} > 0 \Rightarrow V\frac{dI}{dV} + I > 0 \Rightarrow \frac{dI}{dV} > -\frac{I}{V}$	: increase operating voltage
•	$\frac{dI}{dV} = -\frac{I}{V}$	: retain operating voltage
•	$\frac{dI}{dV} < -\frac{I}{V}$	: decrease operating voltage

The following is the block diagram of the above Incremental conductance method.

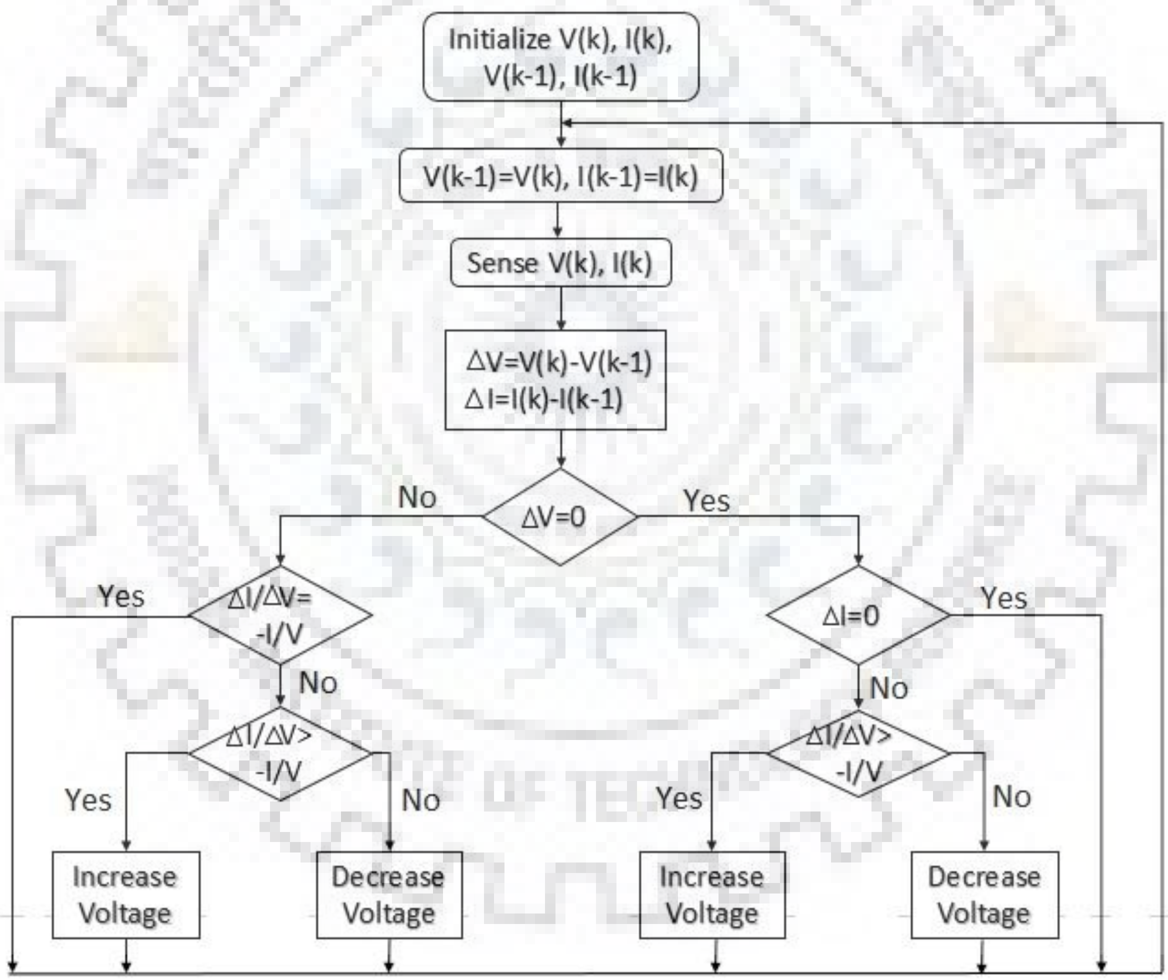


Fig – 4.4: Block diagram of Incremental conductance method

It may be noted that, while implementing the above method, the values of “dP”, “dV”, “dI” are generally small after reaching MPP. Then the noise added by sensors may play role in defining the sign of “dP/dV” or “$dI/dV + I/V$”, so, a constant tolerance value is used besides averaging readings from sensors.

In order to speed up the performance of the system, Incremental conductance was also implemented with P, PI controllers. In both of them, the value of ‘dP/dV’ is considered as error. The change in duty-ratio is given by

$D_{new} = D_{old} - K_P e$, for P-controller

$D_{new} = D_{old} - K_P e - K_I(\sum e)T$, for PI controller where T is sampling time

5. Implemented Circuit

This section explains the implemented circuit.

- Power circuit (Boost converter)
- Control circuit (MPPT charge controller)

5.1 Boost Converter:

The following is the circuit diagram of the boost converter:

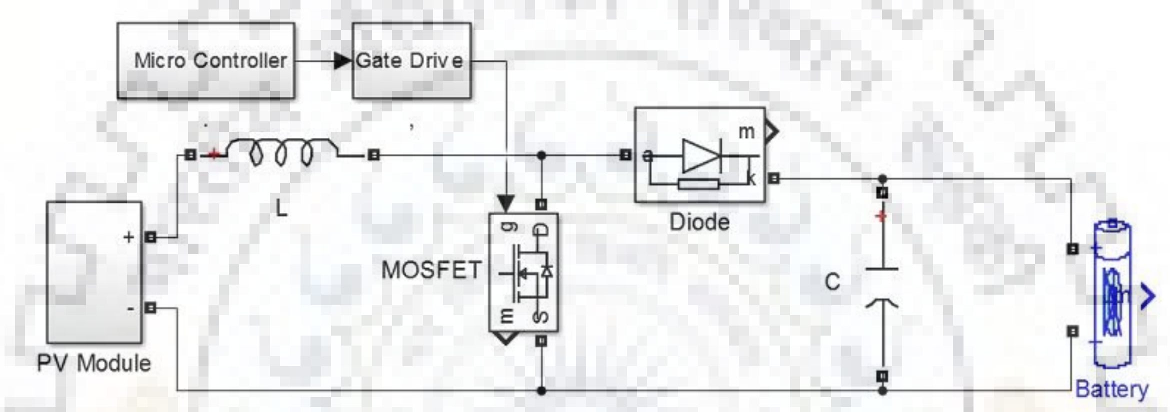


Fig – 5.6: Circuit diagram of Boost converter (created in MATLAB)

The equations for the "relationship between input and output voltages" and "values of inductance and capacitance" for boost converter are given respectively by

$$V_{out} = \frac{V_{in}}{1 - D} \quad (5\text{-}3)$$

$$L = \frac{V_{in}}{f \Delta I_L} D \quad (5\text{-}4)$$

$$C = \frac{I_{out}}{f \Delta V_{out}} D \quad (5\text{-}5)$$

(Derivations are given in the Appendix)

For this project, the values for inductor and capacitor are calculated by taking the following values:

- $V_{in} = 11V; V_{out} = 26V \Rightarrow D = 0.5769$
- $f = 25{,}000Hz$

- $\Delta I_L = 30\% \; of \; I_{out} = 30\% \; of \; 0.8A = 0.24A$
- $\Delta V_{out} = 0.07\% \; of \; V_{out} = 0.07\% \; of \; 26V = 0.0182V$

So,

$$L = \frac{11}{25000*0.24} * 0.5769 = 1057.65\mu H$$

$$C = \frac{0.8*0.5769}{25000*0.0182} = 1014.33\mu F$$

According to the online boost converter calculator [9], the values are

$L = 1015.625\mu H$, $C = 1071.428\mu F$. These are close to the calculated values.

Implemented Boost Converter:

The following is the photograph of the hardware implementation of the boost converter:

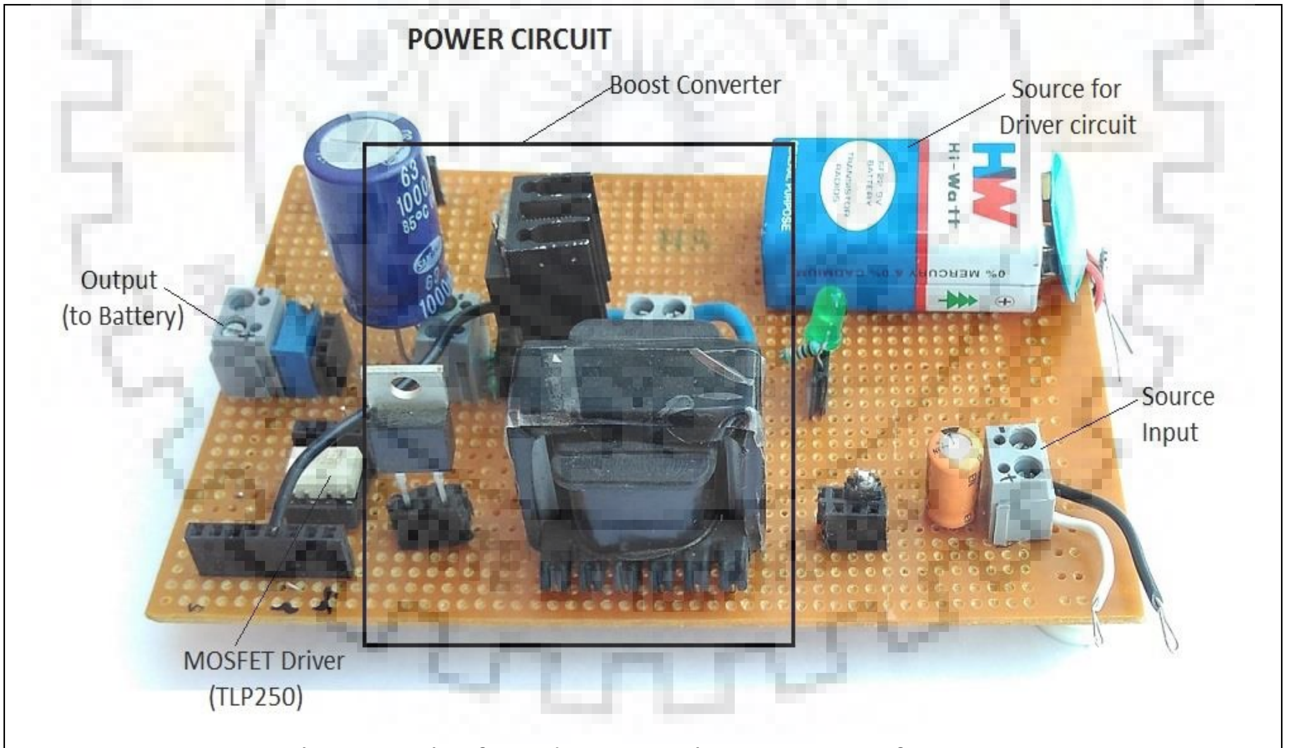


Fig – 5.7: Photograph of Hardware implementation of Boost converter

N-Channel power MOSFET (IRF740):

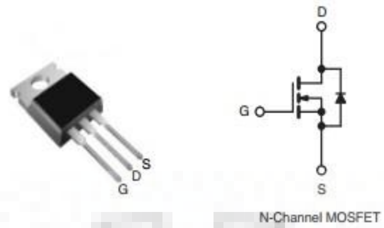


Fig – 5.8: IRF740 power n-channel MOSFET (Source: IRF740 Datasheet)

Specifications:

V_{DS} max.	400V
V_{GS} max.	±20V
R_{DS}	0.55Ω (V_{GS} = 10V)
Maximum Power Dissipation	125W
Maximum Pulsed Drain Current	40A

Table-1: Specifications of the chosen MOSFET

Reason for the choice: MOSFET with less R_{DS} and C_{ISS} has to be chosen in order to minimize losses. The two losses pertaining to the MOSFET are given by

$$\text{Resistive loss during conduction} = {I_{DS}}^2 R_{DS} \quad (5\text{-}6)$$

$$\text{Frequency dependent capacitive loss} = C_{ISS} V_{GS} \frac{f}{2} \quad (5\text{-}7)$$

The chosen MOSFET has fewer losses at the operating frequency and nominal load current.

Diode (MUR1650):

Specifications:

Peak Reverse Voltage	500V
Maximum reverse recovery time	60ns
Forward voltage drop	0.8V
Peak repetitive forward current	16A

Table-2: Specifications of the chosen Diode

Reason for the choice: The things considered while choosing diode are V_{PRV}, maximum current through it, maximum switching frequency, and forward voltage. MUR1650, a schottky diode, is chosen.

MOSFET Driver:

The resistive loss in the used power MOSFET, IRF740, is less if the amplitude of pulses given to it is 10V. As the Arduino is able to generate 5V pulses, TLP250, an IGBT/power MOSFET driver is used. It is the white colored chip at the bottom-left of Fig-5.2. The following picture shows the internal circuitry of TLP250 along with its pin configuration.

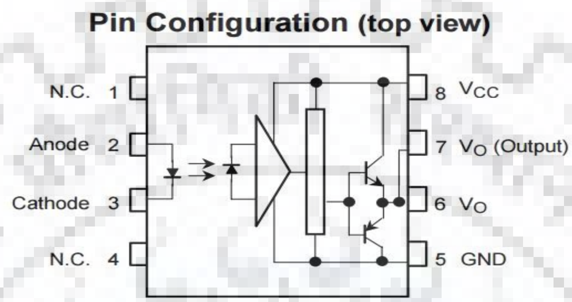


Fig – 5.4: Internal circuitry and pin configuration of MOSFET Gate Driver TLP250
Source: TLP250 Datasheet

It consists of a GaAlAs light emitting diode between pins 2 and 3 as shown in the above figure. Beside it, there is a photo-detector. When pulses are given to across pins 2, 3; current passes through the LED which then emits light; the photo-detector upon detecting that light, gets switched on; then the applied voltage across V_{CC}(pin 8) and GND(pin 5) appears across V_O(pin 6 and 7 – internally shorted) and GND. In Fig-5.2, the TLP250 is given 5V pulses across its pins 2, 3 from Arduino and a constant 9V from battery across pins 8(V_{CC}), 5(GND). Thus, 5V pulses from Arduino are effectively made into 9V pulses to be fed as V_{GS} to the MOSFET.

It may also be pointed here that the designed hardware is modular, i.e. the inductor, capacitor, diode or the MOSFET may be replaced with those of higher/lower ratings (one may see the use of gray-connectors and female header pins to achieve modularity in the photograph). This facilitates the formation of boost converters of different ratings on the same base whenever required.

5.2 Control Circuit:

The following is the schematic of the implemented control circuit.

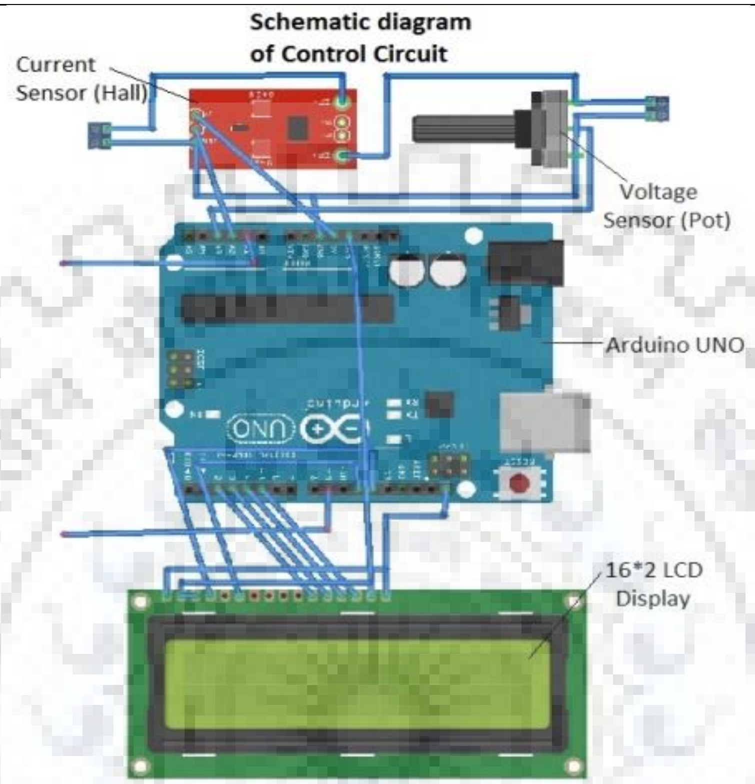


Fig – 5.5: Schematic of control circuit (made using the software 'Fritzing')

At the top of the figure, there is the circuitry to sense voltage and current of the PV module. This is explained in detail here. At the top-right, a potentiometer is there which is connected parallel to a gray connector. This gray connector is for connecting to the source terminals i.e. the PV module. The potentiometer senses the voltage of PV module. At the top-left, there is another gray connector. The negative lead of this gray-connector is connected to the negative terminal of potentiometer and the positive lead of the gray-connector is connected to the positive lead of the potentiometer through the current sensor. These voltage and current readings are used in the MPPT tracing methods.

At the center of the figure, there is the Arduino Uno microcontroller which runs the algorithm and issues PWM wave to MOSFET and also displays some values on the 16x2 LCD display.

The following is the photograph of the hardware implementation of the control circuit.

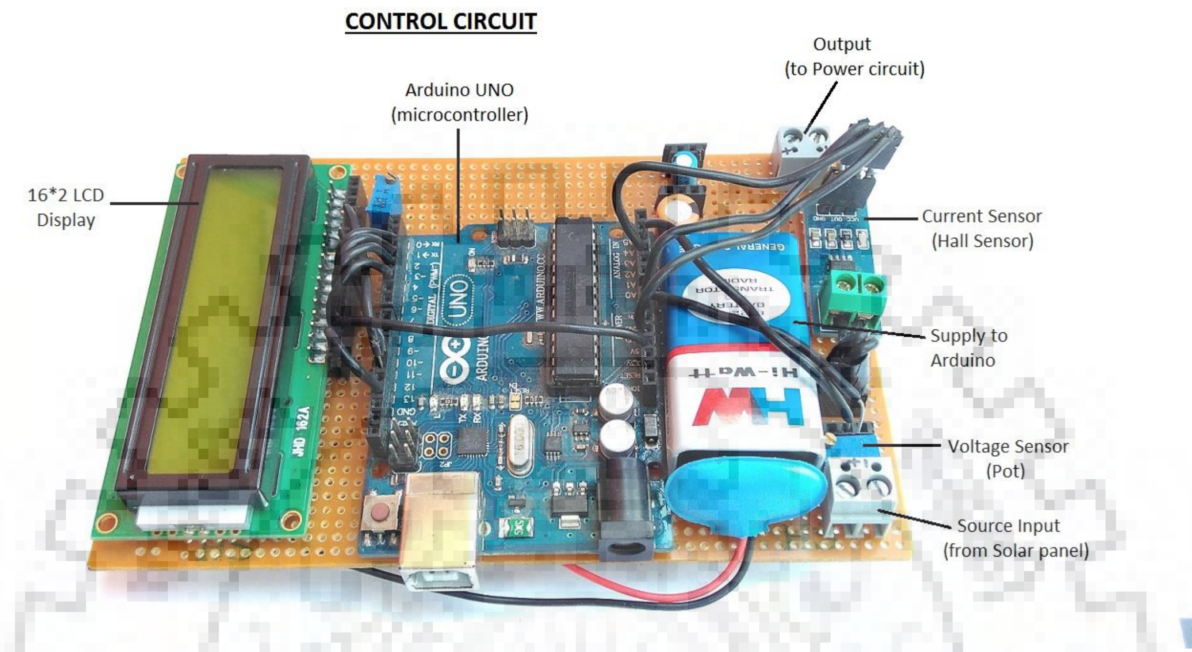


Fig – 5.6: Photograph of Hardware implementation of control circuit

Current sensor (ACS712):

ACS712 is a hall-effect based current sensor which outputs an analog voltage proportional to the current passing through its input current pins (IP_+ and IP_- in Fig-5.7.a). It maps $[-I_{INPUT,\ MAX}, I_{INPUT,\ MAX}]$ to $[0, V_{CC}]$ where '$I_{INPUT,\ MAX}$' is given by the specifications of the chip and 'V_{CC}' is set by the user. From the above, the equation of mapping can be derived as follows

$$V_{out} = \frac{I_{in} - (-I_{INPUT,MAX})}{I_{INPUT,MAX} - (-I_{INPUT,MAX})} * V_{CC} = \frac{I_{in} + I_{INPUT,MAX}}{2I_{INPUT,MAX}} * V_{CC} \quad (5\text{-}8)$$

From above equation, it is clear that 0 current corresponds to $V_{CC}/2$. Other specific details such as internal functioning, need of external capacitors such as bypass capacitor (across V_{CC} and GND in Fig-5.7.a, bandwidth-setting-capacitor (across FILTER and GND in Fig-5.7.a) may be found in the datasheet. In this project, instead of ACS712 chip, ACS712 current sensor module is used which incorporates ASC712 chip along with needed external capacitors. The following figures show the chip and the module.

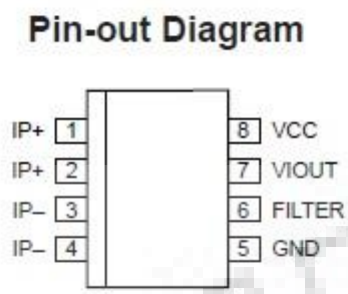


Fig – 5.7.a: ACS712 Pin Configuration
Source: ACS712 Datasheet

Fig – 5.7.b: ACS712 hall current sensor module
Source: www.embedded-lab.com

The chip may be seen at the center of the module along with needed capacitors and other components. It has a gray connector which is connected to the IP_+ and IP_- pins of the chip. Current to be measured is to be passed through this gray connector. On the right, there are 3 pins V_{CC}, OUT, GND which are connected to corresponding pins of the chip. As Arduino works at 5V, V_{CC} is given 5V. However, if the current is lower such that the mapped value of maximum input current given by equation 5-6, then V_{CC} may be increased to increase the accuracy. GND pin is connected to Arduino-GND. OUT is connected to one of the analog pins of Arduino.

Voltage regulator:

Two capacitors are present (above the battery). These are provided in case Arduino is to be powered externally using a voltage regulator. The circuitry for the voltage regulator, 7805, is shown below.

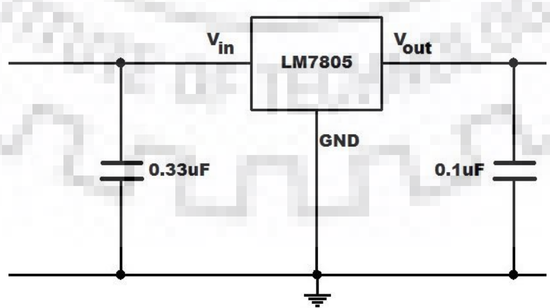


Fig – 5.8: Circuit diagram for using 7805 voltage regulator

6. Simulations and Hardware Test Results

This section presents the following simulations and hardware tests performed.

- Simulations
  1. I-V, P-V characteristics of PV module at different values of T, G.
  2. MPPT using P&O method.
  3. MPPT using Incremental Conductance method.
- Hardware test results
  1. I-V, P-V characteristics of the used PV module traced at different values of T, G.
  2. MPPT using P&O method.
  3. MPPT using Incremental Conductance method.

6.1 Simulations:

1. I-V, P-V characteristics of simulated PV module at different values of T, G:

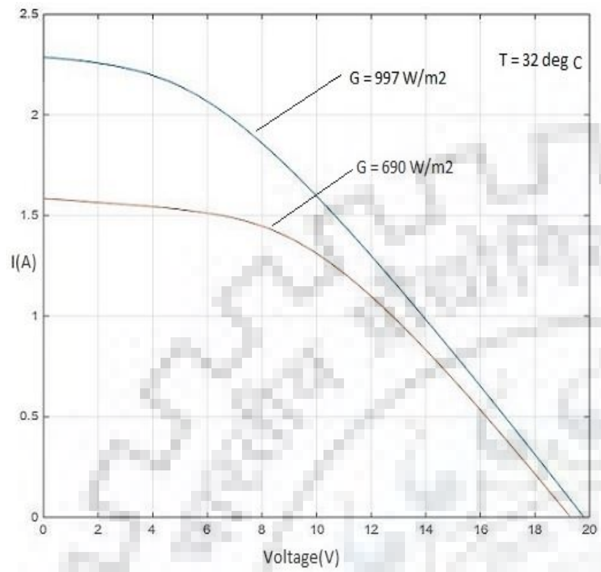


Fig-6.1a: Simulation of I-V characteristics at different G

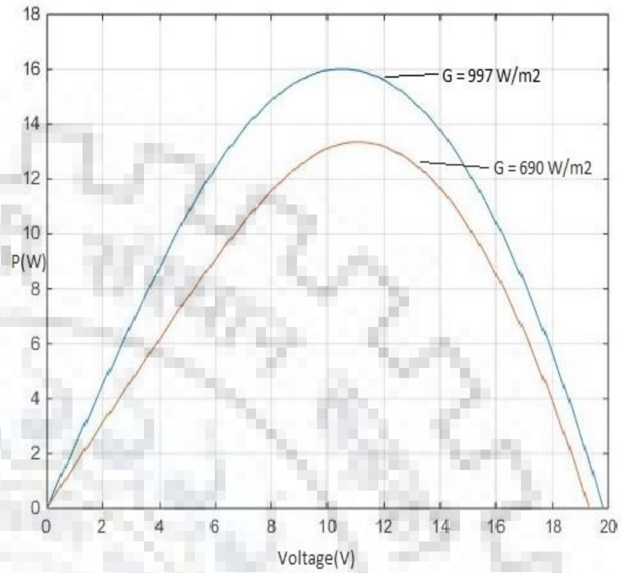


Fig-6.1b: Simulation of P-V characteristics at different G

2. MPPT using P&O method:

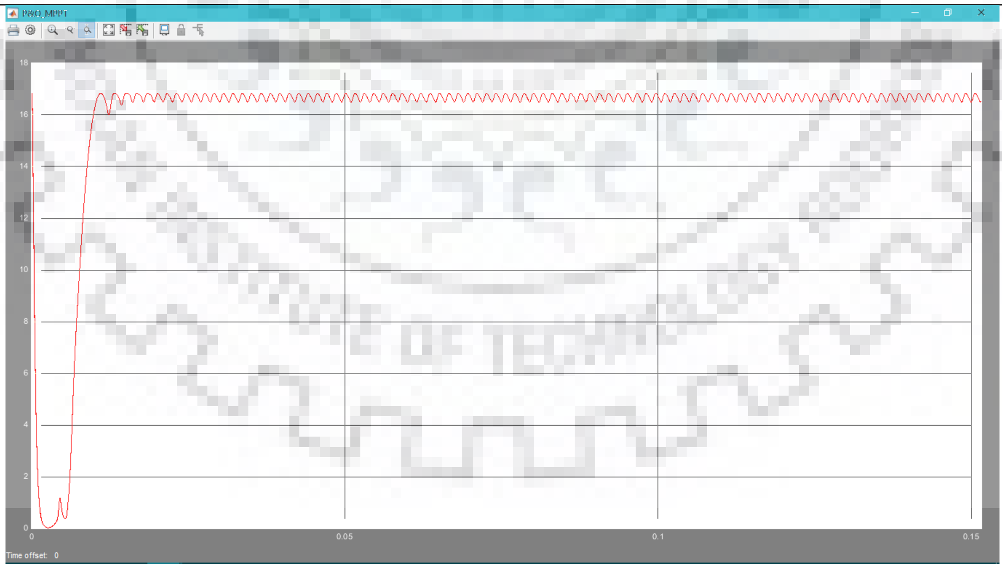


Fig – 6.2: Simulation of P&O method of tracking MPP

3. MPPT using Incremental Conductance method:

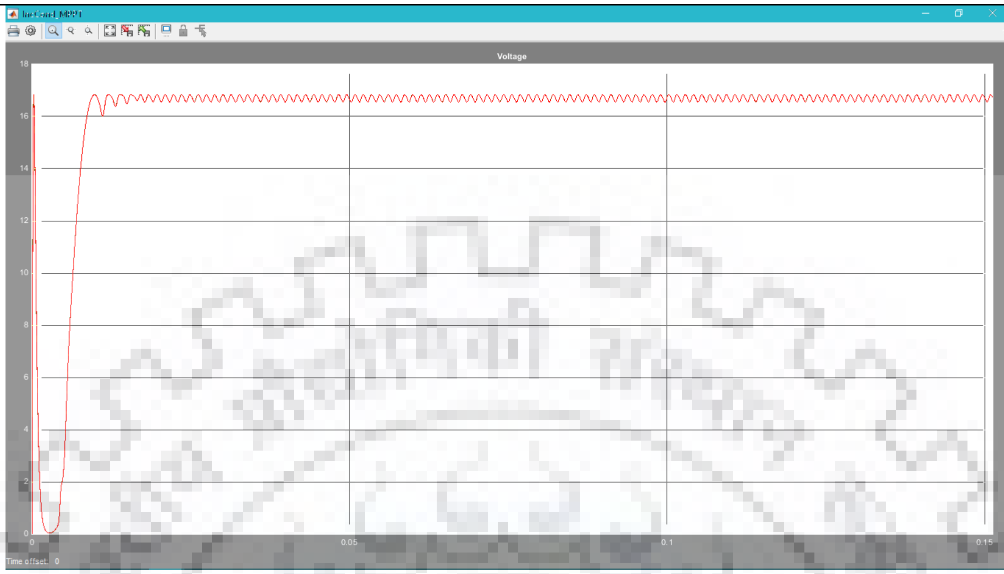


Fig – 6.3: Simulation of Incremental Conductance Method of tracking MPP

6.2 Hardware Test Results:

1. I-V, P-V characteristics of the used PV module traced at different values of T, G:

These are obtained by changing the duty of the Boost converter from '0' through '1' using Arduino. When duty is 0, $V_{IN} = V_{OUT}$ (no boosting taking place) and as $V_{BATTERY}$ is higher than V_{OC} of solar panel, no power flows to the battery and the panel is operated at V_{OC}. Now, by gradually increasing the duty, V_{OUT}/V_{IN} increases, as V_{OUT} is pinned by battery, V_{IN} decreases. Thus the operating point is changed and I-V, P-V characteristics are traced. The following curves are traced at two different irradiance conditions (997 & 690W/m^2) and at almost same temperature (32^{o}C). The data is collected from the serial port of Arduino and is plotted in Microsoft-Excel.

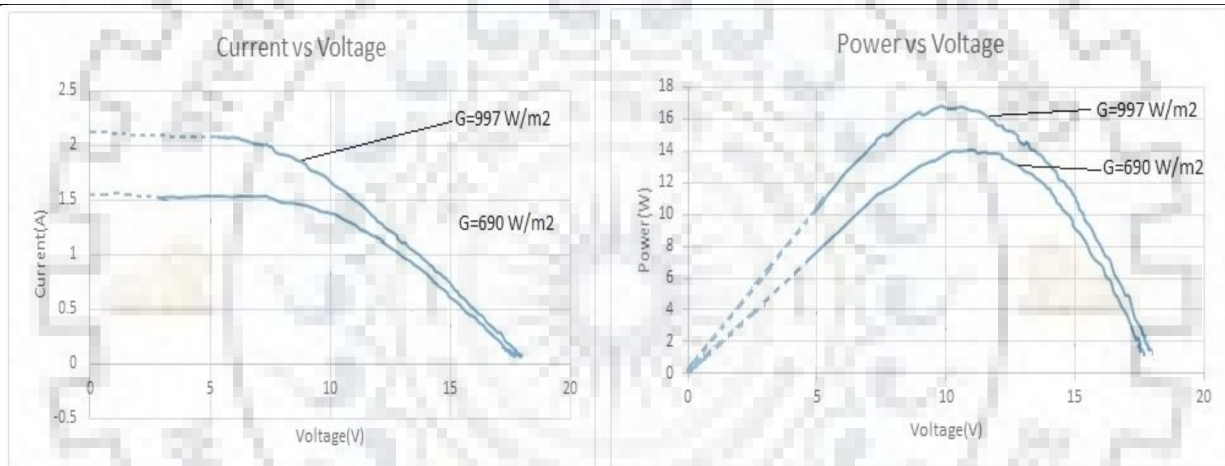


Fig – 6.4: I-V, P-V characteristics of the used solar panel traced at different 'G'

2. <u>MPPT using P&O algorithm</u>:

The following two pictures show the results of tracking and operating at MPP using Perturb & Observe algorithm at conditions mentioned in the pictures.

Fig-6.5 is the result of MPPT by P&O method with duty-ratio step size of ‘2/255’.

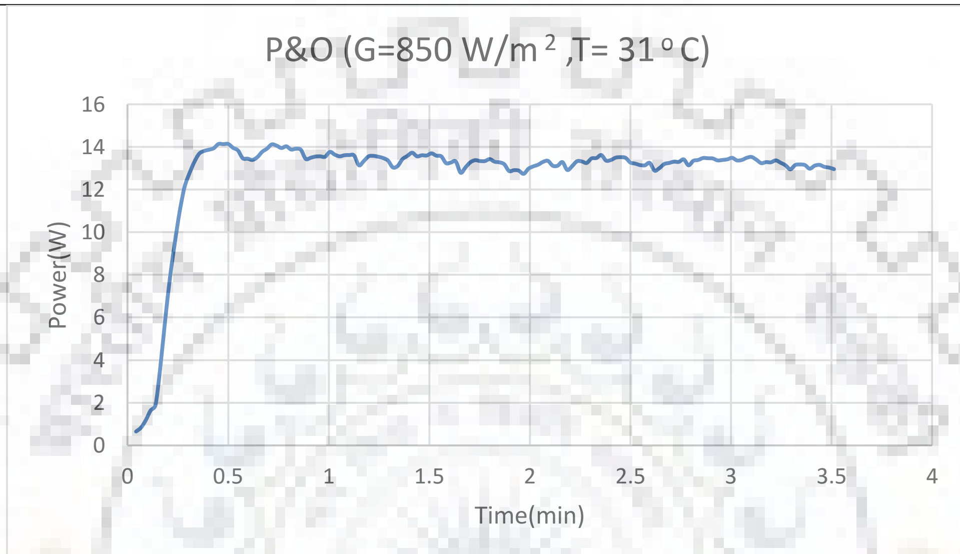


Fig – 6.5.a: Result of MPPT by P&O method with duty-ratio step size of 2/255

Fig-6.6 is the result of MPPT by P&O method with duty step size of ‘1/255’. Oscillations about the MPP are reduced by introducing a tolerance of ±0.1W.

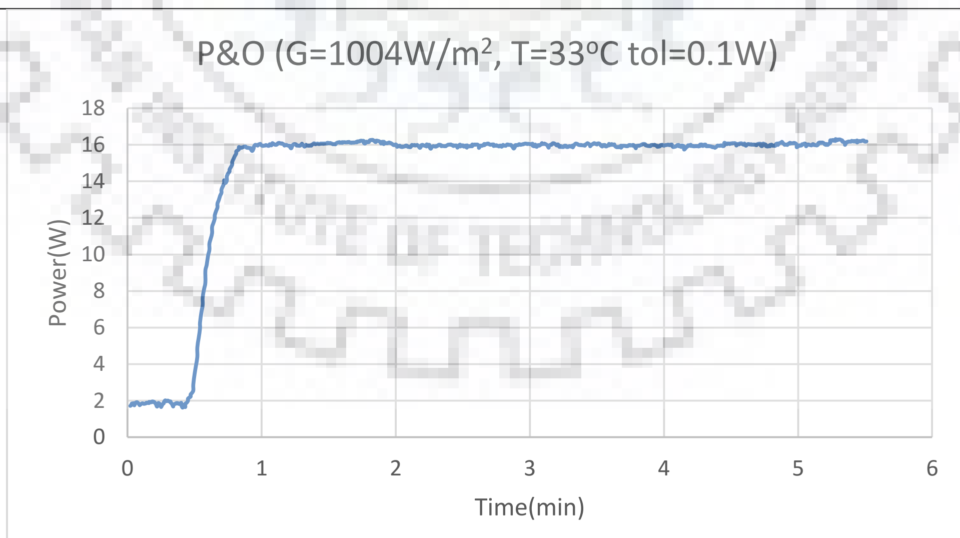


Fig – 6.5.b: Result of MPPT by P&O method with duty-ratio step size of 1/255 and tolerance in power of ±0.1W

3. <u>MPPT using Incremental Conductance method</u>:

Incremental Conductance with a duty-ratio step size of ‘2/255’ and tolerance of ±0.05W is implemented and the resulting plot is shown in Fig-6.7.

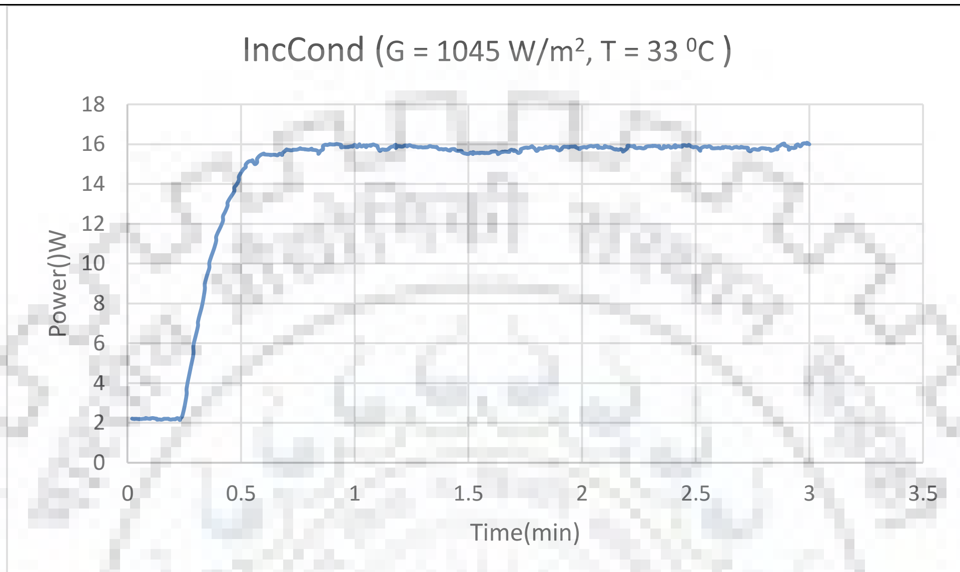
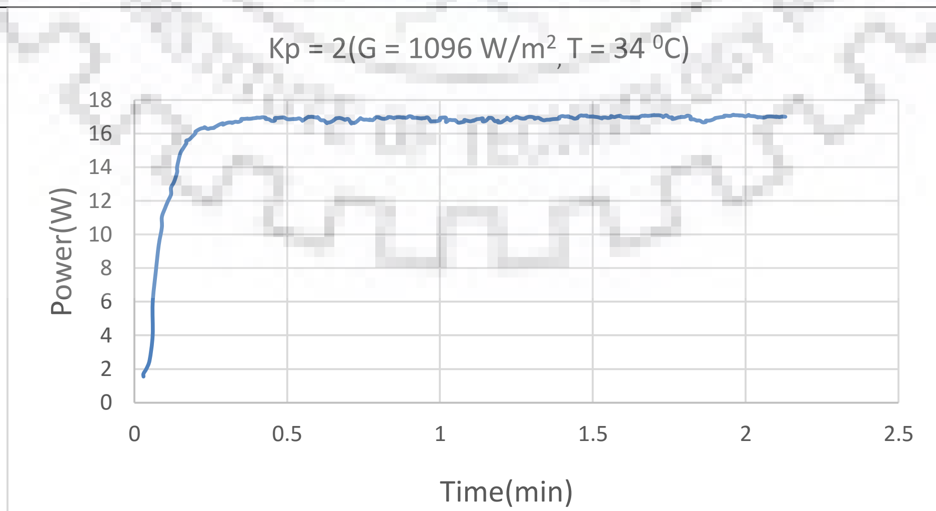


Fig – 6.6: Result of MPPT by Incremental Conductance with duty-ratio step size of ‘2/255’ and tolerance of ±0.05W

3.1 <u>Incremental Conductance with P controller</u>:

P-controller is added to track the MPP quickly as mentioned in chapter-4. The following two figures are the result of MPP tracking using two different K_P mentioned in the plots.



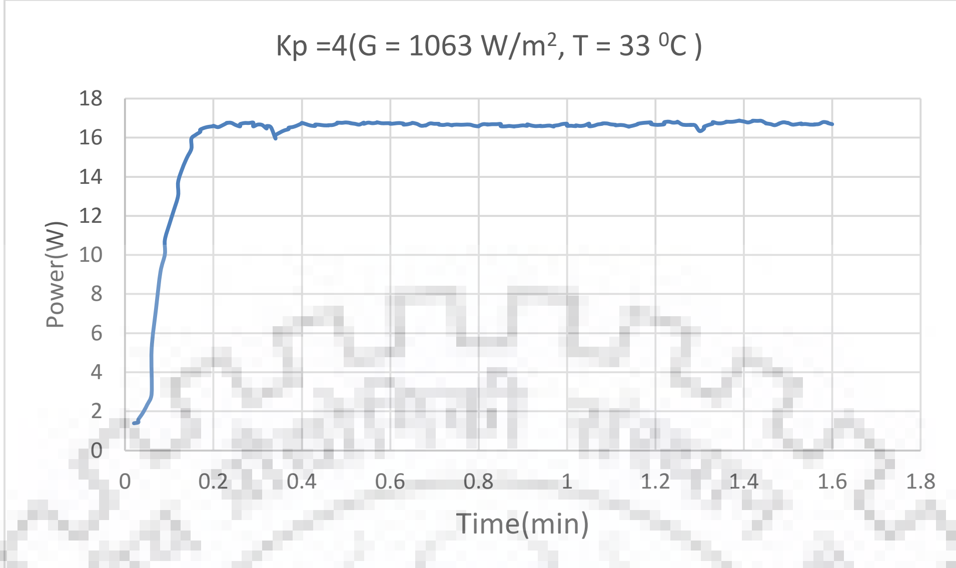
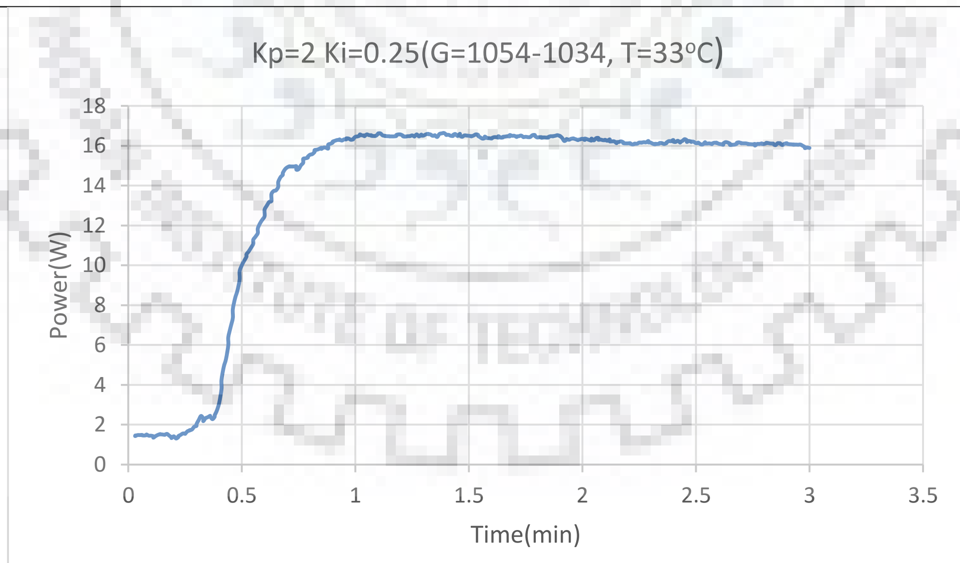


Fig – 6.7: MPPT by Incremental Conductance method with P-controller at two different values of K_P

<u>3.2 Incremental Conductance with PI controller</u>

To filter the P-controller caused oscillations Integral controller is added. The following figures shown are MPPT by Incremental conductance using PI controller at different values for K_P & K_i mentioned in plots.



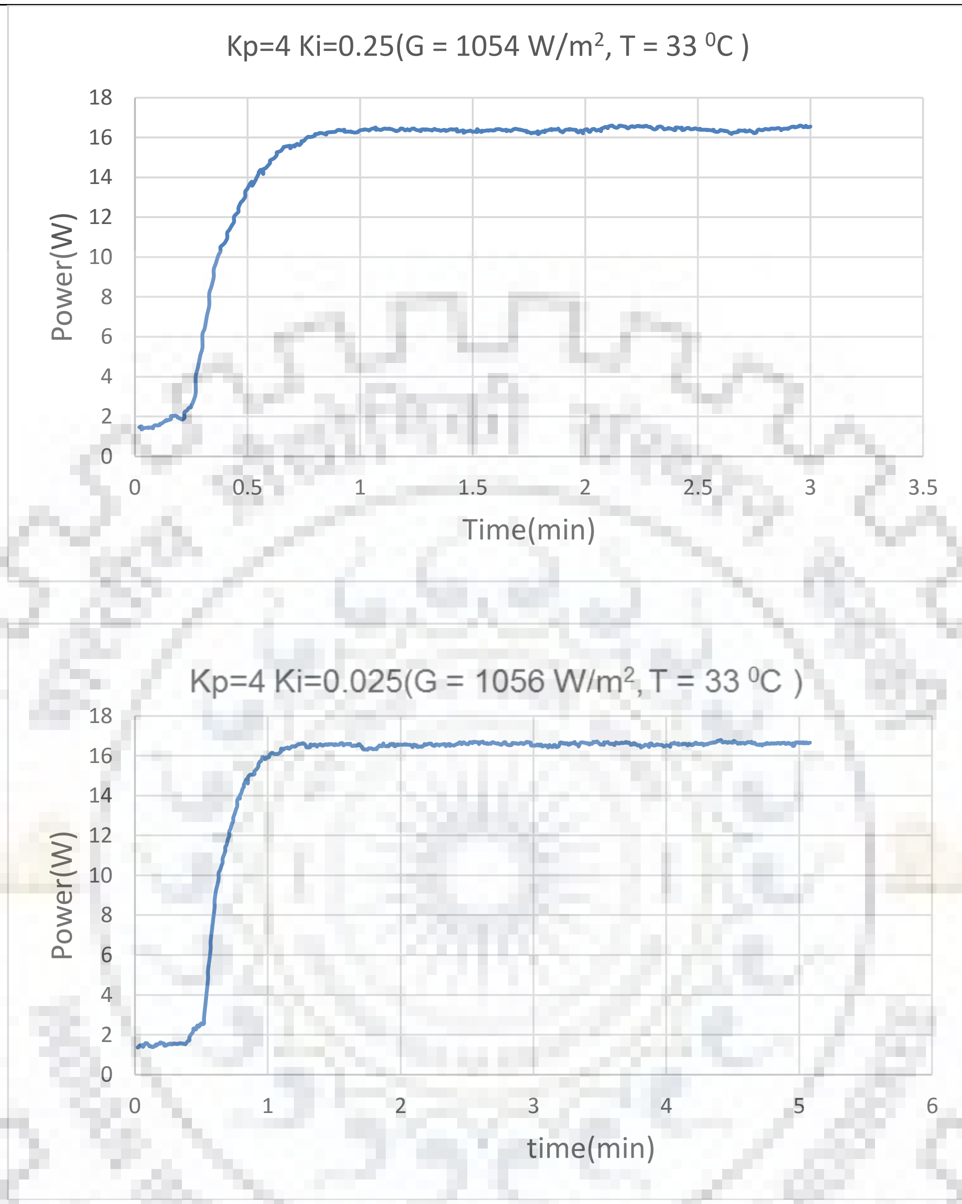


Fig – 6.8: MPPT by Incremental Conductance method with PI controller for different values of K_P and K_i.

The following figure shows MPPT by Incremental conductance using PI controller; Here I-V, P-V characteristics of the PV module at that time are also shown to cross-check if the PV module is being operated at MPP.

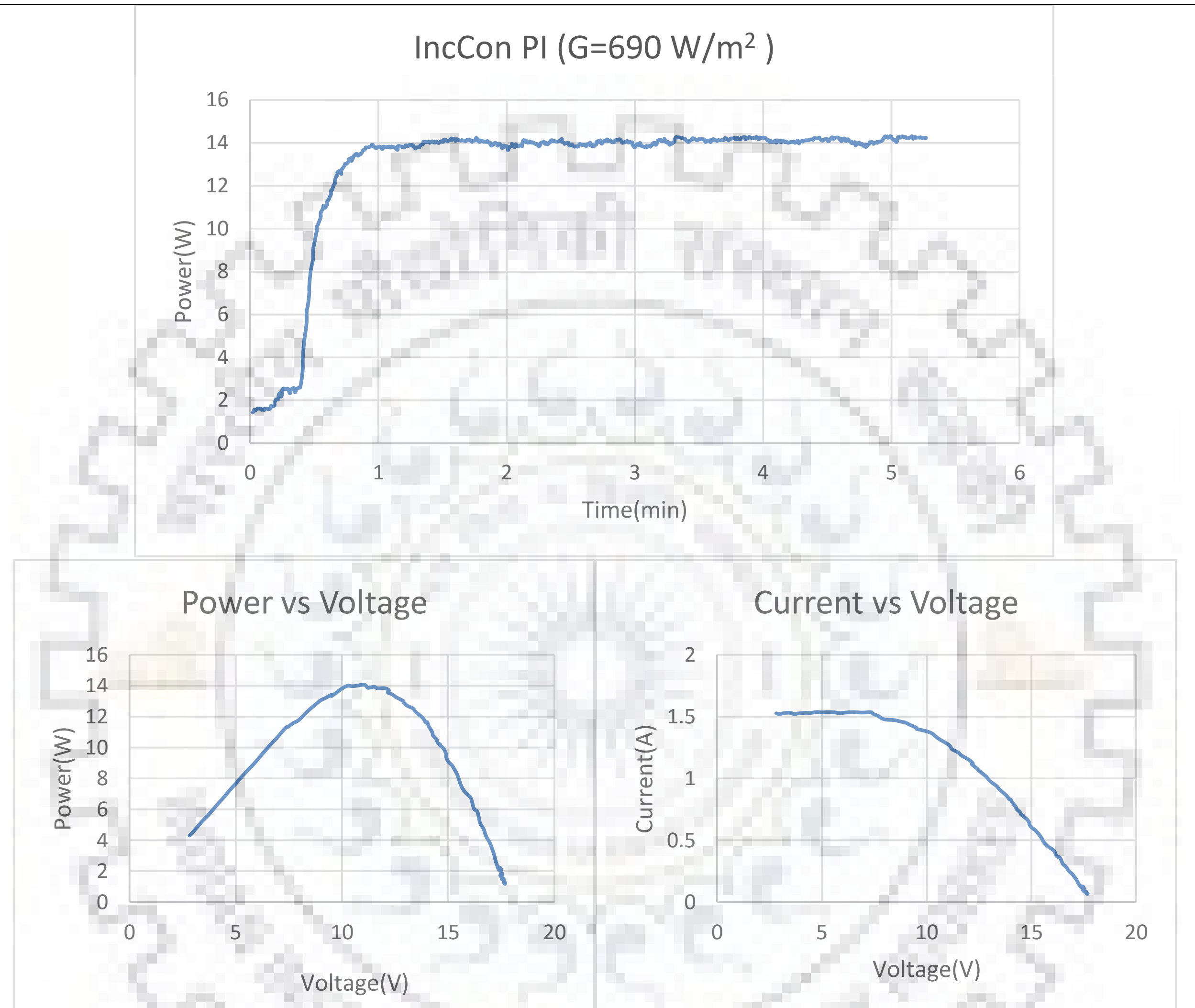


Fig – 6.9: MPPT by Incremental conductance method with PI controller along with I-V, P-V characteristics of the panel at that time

Other Tests and Results:

The following picture shows MPPT by Incremental Conductance method during varying irradiance. Large sudden changes in irradiance are achieved by altering the angle of the solar panel.

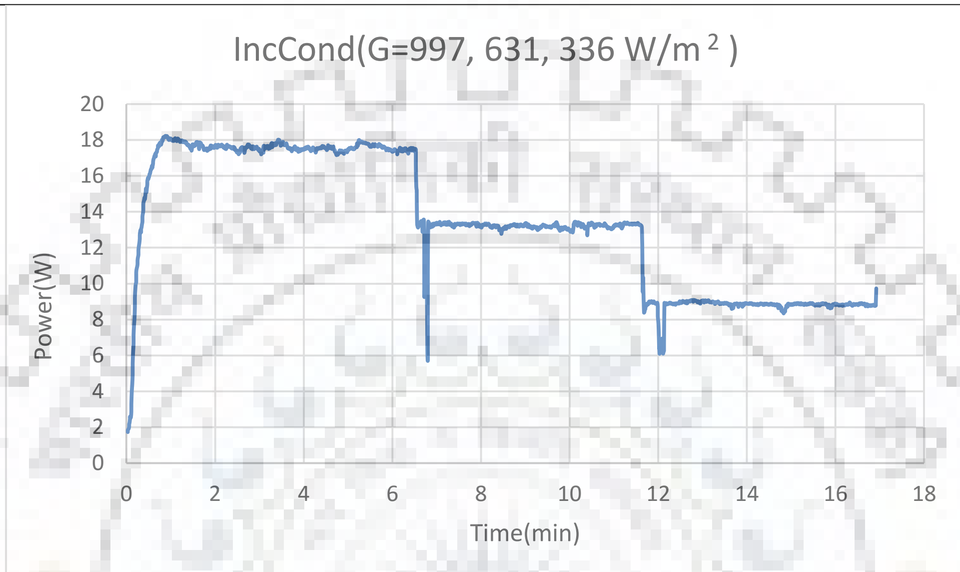


Fig – 6.10: MPPT by Incremental Conductance at varying irradiance

7. Charge controller

It is shown in Fig-3.2 showing ideal graph for '%-charge' vs. 'current' that, a good way of charging battery is to maintain constant current through it until '%-charge of the battery' reaches a pre-determined level and then to employ a smooth concave-up graph for current vs. time.

As PV modules are being used to charge the batteries, it is also desirable to operate them at MPP.

To facilitate both, i.e. good utilization of PV modules and increased battery life; the following charge controller is proposed. When battery is being charged, if the '%-charge of the battery' is less than the pre-determined level, the charge controller charges it by running MPPT method, but if the '%-charge' is greater than the pre-determined level, charging current is controlled in a closed loop.

The choice of the pre-determined level introduced above acts as tradeoff between "extent of PV module utilization" and "battery life". Fig-3.2 shows a pre-determined level of 60%. Depending on the battery, it may be chosen from the range 60-80%.

The charge controller also notifies the user if the battery over-discharges and solar power is unavailable.

The following is the block diagram of the charge controller:

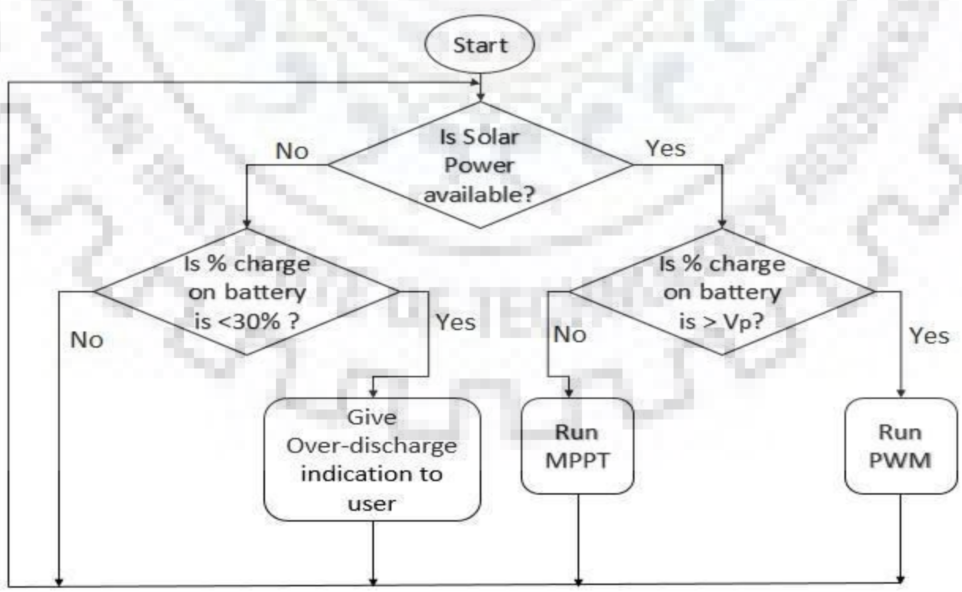


Fig – 7.9: Block diagram of charge controller

8. Cost Analysis

Cost analysis has been done for the e-rickshaw for the town Roorkee. Average solar irradiation in a year in this town, Roorkee is shown in the following figure.

Solar Irradiation in Roorkee, Uttarakhand 247667, India

Solar Radiation

Annual Average: **5.34** (kWh/m²/day)

Monthly Average	
Jan	3.35
Feb	4.45
Mar	5.80
Apr	6.82
May	7.44
Jun	6.74
Jul	5.96
Aug	5.49
Sep	5.21
Oct	5.28
Nov	4.21
Dec	3.38

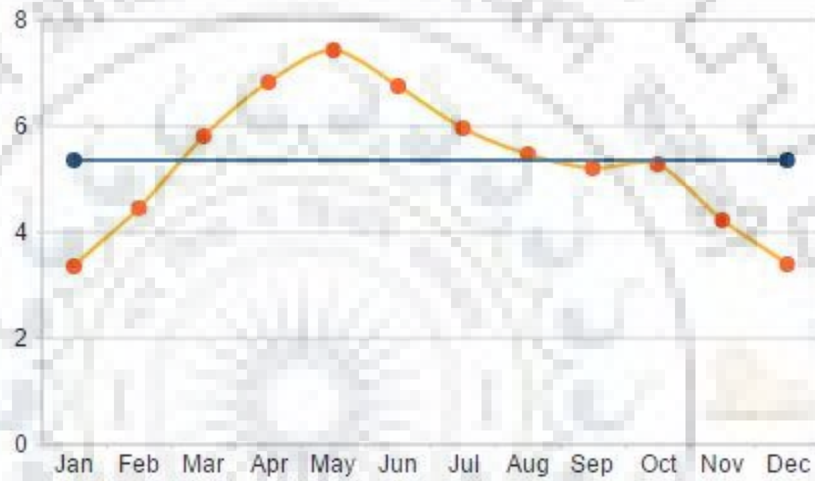


Fig – 8.1: Figure showing average monthly solar irradiation levels in Roorkee
Source: www.synergyenviron.com

<u>E-Rickshaw Specifications:</u>

<u>Electrical Specs:</u>

Battery : 12V/100 Ah Lead-acid type

Number : Four batteries

Max DoD% : 82%

Nominal DoD%: 70%

Mechanical Specs:

Dimensions : 2700 mm*997 mm*1790 mm

Load Cap : 450 kg

Cost Analysis:

Per day Energy required for Charging:

DoD % * Ah *No.bat *V = (0.7) * 100 *4 * 12 Wh = 3.36 kWh

Available area for panels: 2400 mm*950 mm + 900 mm*950 mm = 3.135 m^2

Therefore Number of panels = 3.135 / 0.34 = 9.22 = 9 (approx.)

Max. Possible power = 37 W * 9 = 333 W

Avg. Solar Insolation = 5.34 kWh/m^2/day

- ⇨ Total available insolation : 5.34 * 3.135 kWh/day = 16.74 kWh/day
- ⇨ PV Panel Efficiency: 37*(1/0.34)*(1/1000) = 0.109
- ⇨ Max. Producible Energy :16.74 * 0.109 kWh / day =1.825 kWh / day
  Considering shading factor as 0.6
- ⇨ Producible Energy per day = 1.825 * 0.6 = 1.095 kWh(units)
- ⇨ % of requirement fulfilled =1.095 /3.36 = 32.58 %
  Even though only one third of the total required energy is generated on average, the system is long-lasting and eco-friendly.

9. Effect of Partial shading on Photovoltaic Array

A PV array contains a number of PV modules that are connected in series and parallel. The power generated from the PV array is the combination of the power derived from each PV module. When one of the PV modules is shaded or does not obtain enough solar irradiation, as shown in Fig. 9.1(a), it dissipates the power generated by the other PV modules. The current-against-voltage curve of each PV module is shown in Fig. 9.1(b). If the PV array operates at current, the shaded PV module will be forced to operate at the reverse biased region and acts as a load instead of a power source. This leads to highly localized power dissipation, and the resulting local heat will cause irreversible damage to the shaded PV module. Hence, bypass diodes are added into the PV array to avoid the localized power dissipation during partial shading condition. The bypass diodes are added into the PV system configuration, as shown in Fig. 9.1(a), to protect the PV modules from self heating during partial shading. Under uniform solar irradiation level, the bypass diodes are reverse biased and have no impact. However, when the PV module operates under partial shading condition, the bypass diode is forward biased and the current passes through the diode instead of the PV module. Due to the presence of bypass diodes, multiple MPPs appear in the curve during partial shading condition. The conventional MPPT algorithms such as P&O and Incremental Conductance algorithm search the peak of the curve based on a localized initial point. Therefore, they are unable to differentiate between the GMPP and LMPP. Hence, some modifications are made in this paper to ensure successful tracking of the GMPP.

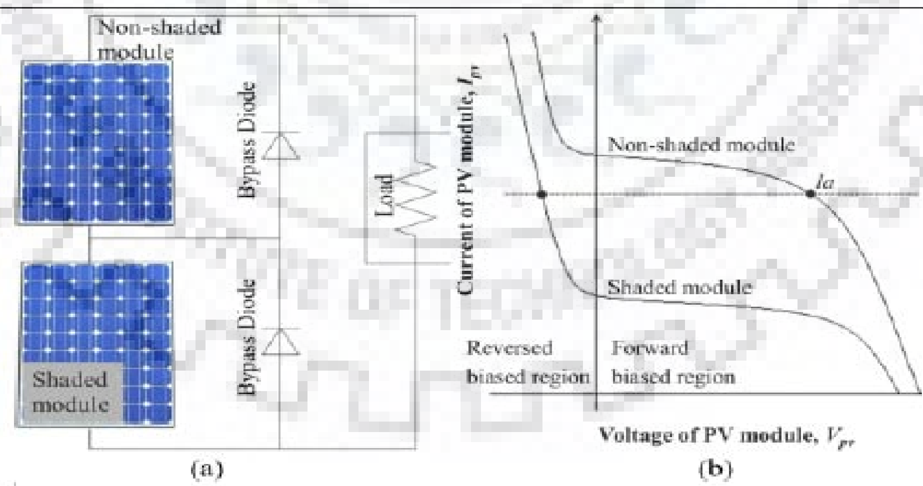


Fig – 9.1(a) PV array under partial shading condition (b) P-V curve PV modules

9.1 Algorithm to find Global MPP :

The maximum power point tracking method under partial shading condition is explained in this section. Fig. 9.2 shows the flowchart of the global maximum power point tracking algorithm. The entire logic can be divided in to two parts

a) Global search algorithm

b) Local search algorithm

Initially the global tracking process is performed and the voltage magnitude corresponding to each maximum power point is identified. There will be one global maximum power point among the local maximum power points. The value of voltage magnitude corresponding to maximum power is stored in microcontroller memory. The control algorithm adjusts the duty cycle to adjust the converter input impedance to make it operate at global maximum power point. Once the global maximum power point has been reached then the control is moved from global loop and enters to local loop. The local loop contains some ordinary MPP tracking method such as Perturb & Observe, Incremental Conductance etc.

Perturb and observe is the most common MPPT method. It is simple and easy to develop; only a few parameters are required for calculation. Once the global maximum power point has been found out then the control is locate to P & O loop and the tracking is done around global maximum power point.

According to Perturb and Observe algorithm due to a perturbation in output voltage by a small increment, if the resulting changes in power ΔP is positive, then we can move in the direction of MPP and we keep on perturbing in the same direction. If the value ΔP is negative, we are going away from the direction of MPP and the sign of perturbation supplied has to be changed. The P&O algorithm operates by periodically perturbing the operating voltage and comparing it with the previous instant. If the power difference ΔP and the voltage difference ΔV, both in the positive direction then there is an increase in the array voltage. If either the voltage difference or the power difference is in the negative direction then there is a decrease in the array voltage. If both the voltage and power difference are in the negative direction then there is a increase in the array voltage.

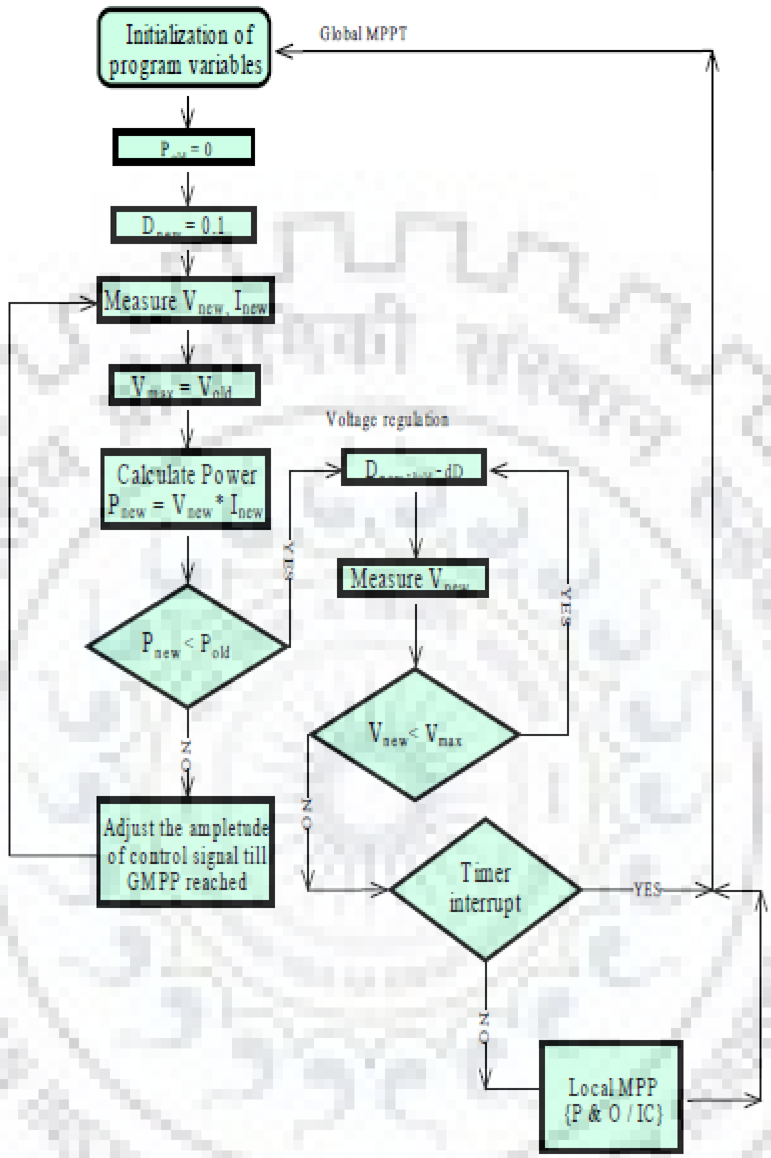


Fig – 9.2 Flowchart of the GMPPT Algorithm

9.2 MATLAB/Simulink Model for 2 PV array under partial shading condition :

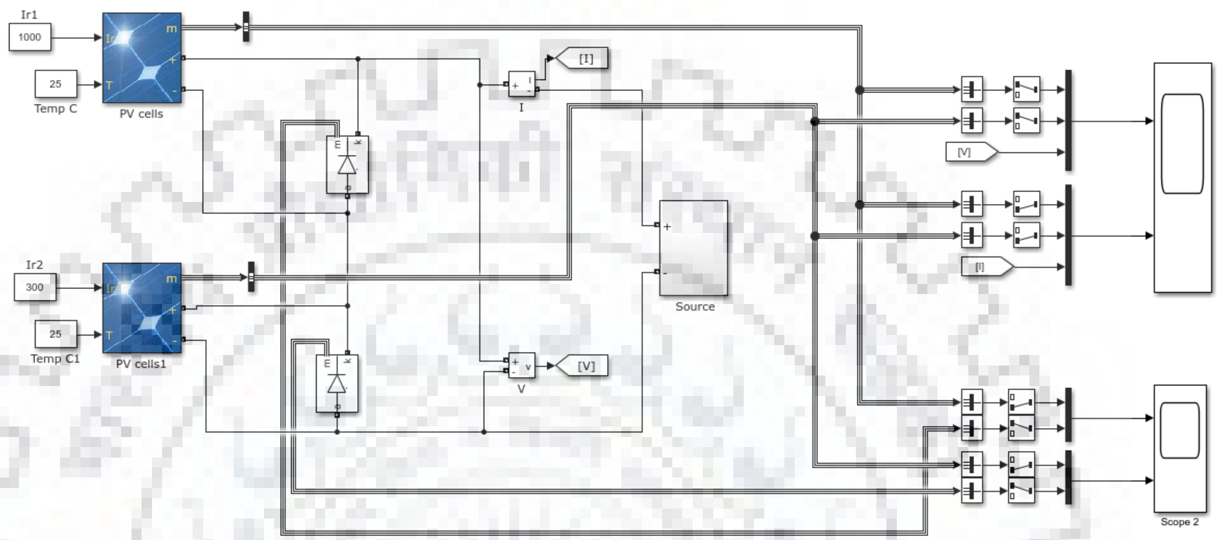


Fig – 9.3 MATLAB/Simulink model of 2 PV array under partial condition

This is a Simulation model of PV array under partial shading condition. In our simulation, we used an array consists of two PV module connected in series as in Fig – 9.3. Each module receives numeral irradiance level. The output voltage of the system is connected to controlled voltage source to simulate the output voltage of the PV array.

The output parameters for the solar array with and without bypass diodes under different shading conditions are summarized in Table- 9.1. The dependence of the current-voltage characteristic of PV module on shading is shown in results. From Table-1, we notice that we obtain almost all values of MPP with and without using bypass diodes. In the presence of bypass diode we notice that the structure of the curves become more complex with the shading effects where several local MPP appear and one of them is the global maximum.

The addition of the bypass diode becomes very important in the cases where one of the modules is under full shading. In one of the cases we used bypass diode in the full shading condition in one of the module, we still obtain an output power. However, when we remove the bypass diode we get almost zero output power. Shading causes a large reduction on total outcome power that does not commensurate with the small amount of shading. That is the relation between shading and output power is not linear. For further understanding, consider case 1. In case 1 where both models are exposed to full irradiance condition the output power equals to 166.5574 W. However, one module is under partial shading condition as in case 3, the output power decreases to 140.6206 W. If the relation is linear, we might expect to get 149.9016 W [83.2787 W from the module under full irradiance effect and 66.623 W from the module under partial shading condition]. We also noticed that in case 7, the output power is less than the expected value although we have bypass diodes. This may be interpreted that part of the power is dissipated into the deactivated parts of the circuit by the bypass diode.

We noticed that in the cases where both modules are under same irradiance condition as in case 1, we obtain little loss in the amount of output power. However, when the two modules are under different irradiance conditions as in case 3. In case 3, where module 1 is under full irradiance effect and module 2 is under partial shading effect, we expect 300 W; however, the output power is 217.5 W. We may refer this to the fact that the output power is not linearly related to the shading effect.

9.3 Simulation Results :

CASE 1 :-
Both modules exposed to full irradiance (1000W/m2) in the presence of the bypass diodes.

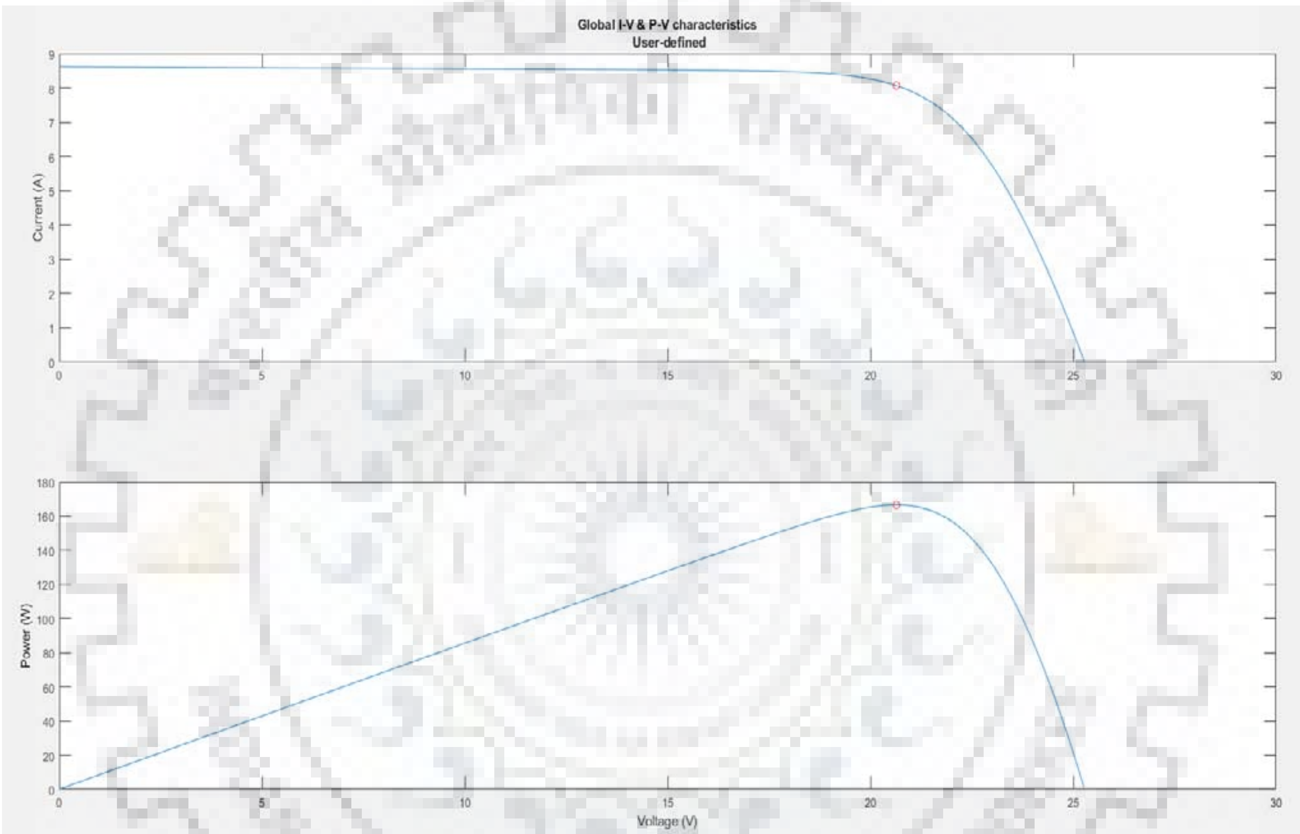


Fig- 9.4 Irradiance1 1000W/m2 and Irradiance2 1000W/m2

CASE 2 :-

One module is irradiated with 1000 W/m2 and another with 950 W/m2 in the presence of bypass diode

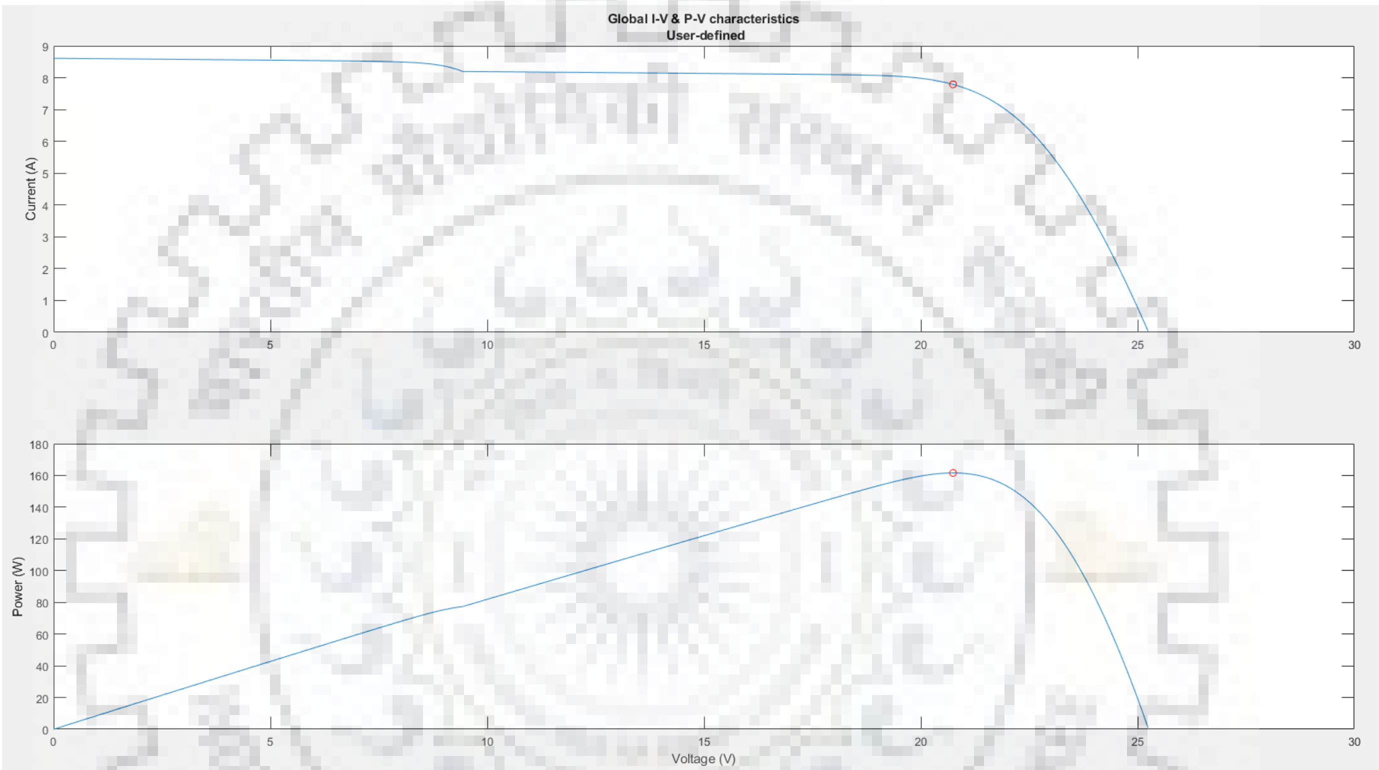


Fig- 9.5 Irradiance1 1000W/m2 and Irradiance2 950W/m2

CASE 3 :-

One module is irradiated with 1000 W/m2 and another with 800 W/m2 in the presence of bypass diode

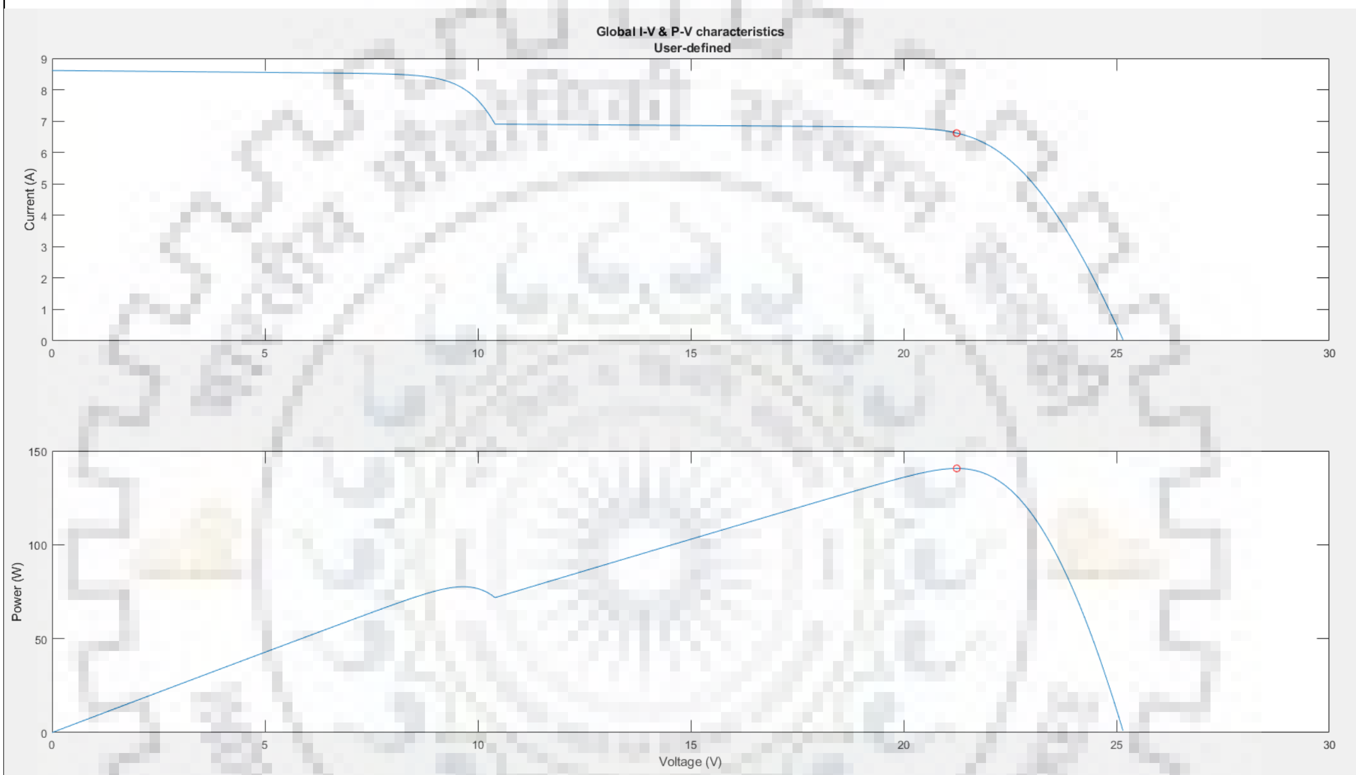


Fig- 9.6 Irradiance1 1000W/m2 and Irradiance2 800W/m2

CASE 4 :-

One module is irradiated with 1000 W/m2 and another with 500 W/m2 in the presence of bypass diode

Fig- 9.7 Irradiance1 1000W/m2 and Irradiance2 500W/m2

CASE 5 :-

One module is irradiated with 1000 W/m2 and another with 300 W/m2 in the presence of bypass diode

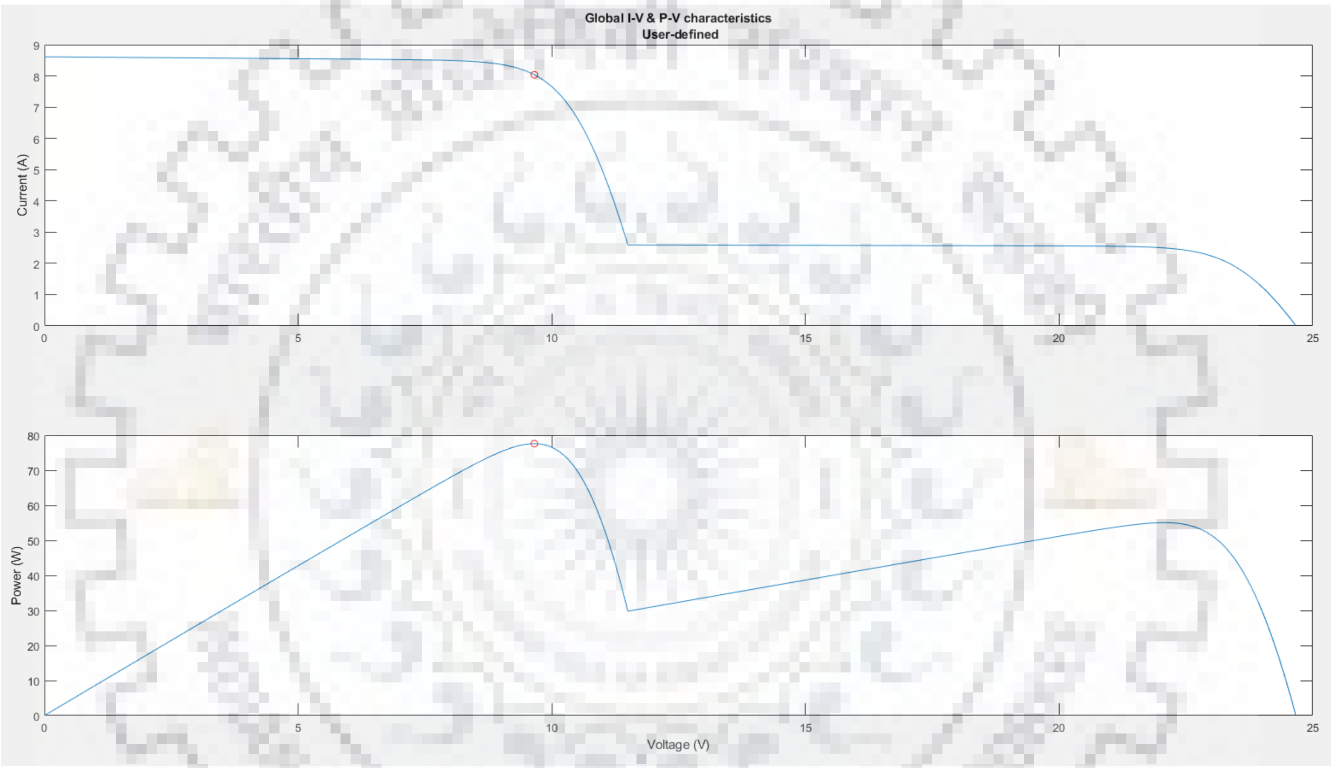


Fig-9.8 Irradiance1 1000W/m2 and Irradiance2 300W/m2

CASE 6 :-
One module is irradiated with 1000 W/m2 and another with 50 W/m2 in the presence of bypass diode

Fig- 9.9 Irradiance1 1000W/m2 and Irradiance2 50W/m2

CASE 7 :-

One module is irradiated with 1000 W/m2 and another with 0 W/m2 in the presence of bypass diode

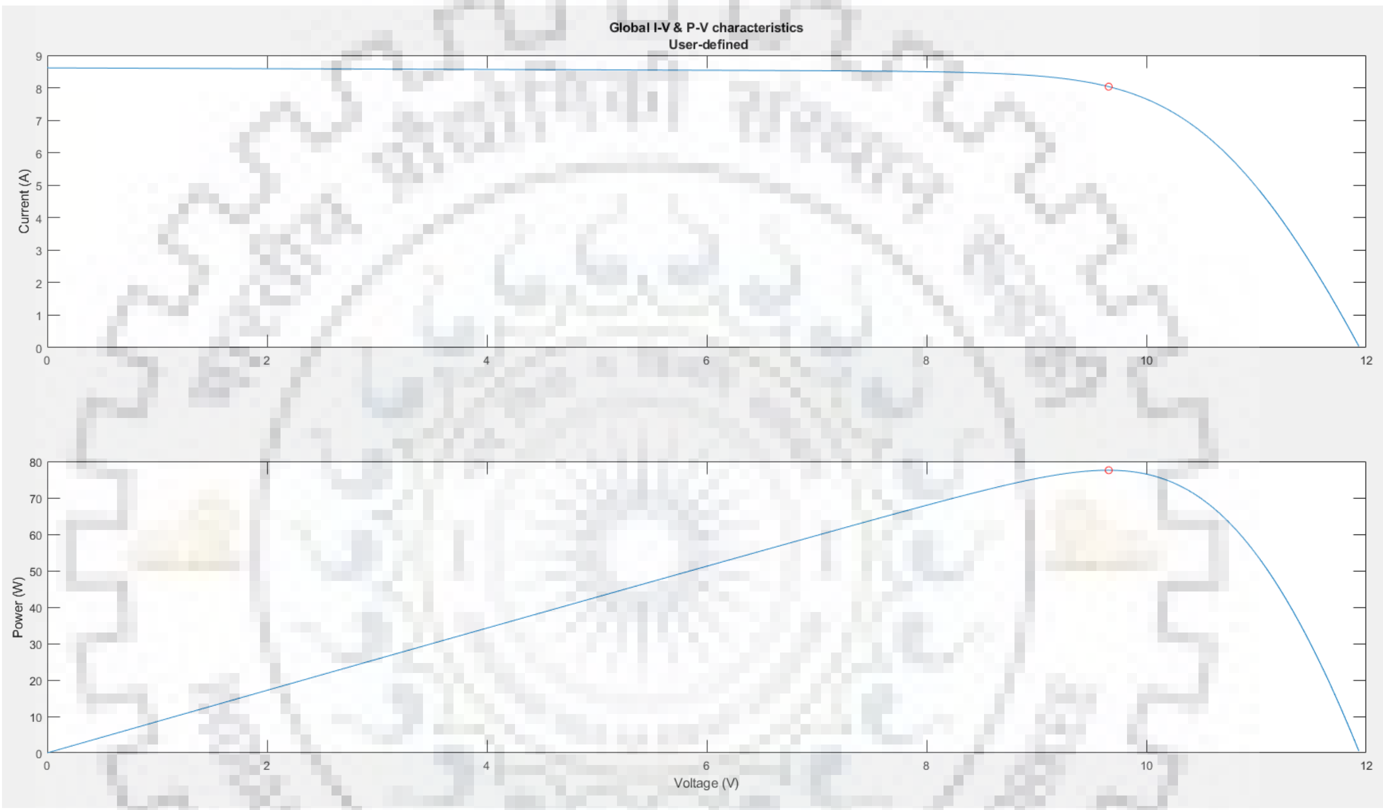


Fig- 9.10 Irradiance1 1000W/m2 and Irradiance2 0W/m2

9.4 Simulation Summary :

Case	Module 1 irradiance [W/m²] Ir1	Module 2 irradiance [W/m²] Ir2	Voltage at MPP [volts]	Current at MPP [A]	Power MPP [W]
1	1000	1000	20.6411	8.0692	166.5574
2	1000	950	20.7422	7.7899	161.5812
3	1000	800	21.2478	6.6181	140.6206
4	1000	500	21.8546	4.1525	90.7508
5	1000	300	9.657	8.0353	77.5969
6	1000	50	9.657	8.0335	77.5794
7	1000	0	9.657	8.0332	77.5759

Table 1:- Summary of diverse shading situations effects on 2 PV modules in the presence of bypass diodes

9.5 MATLAB/Simulink model for 3 PV array under partial shading condition :

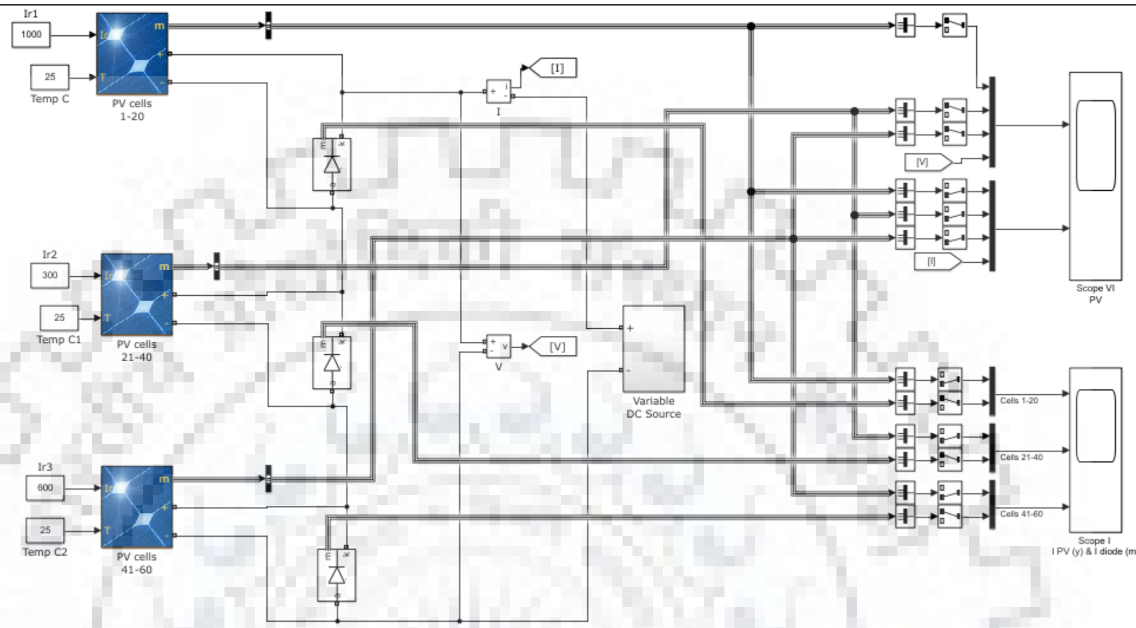


Fig - 9.11 MATLAB model for 3 PV array

This is a Simulation model of PV array under partial shading condition. In our simulation, we used an array consists of three PV module connected in series as in Fig – 9.11. Each module receives numeral irradiance level. The output voltage of the system is connected to controlled voltage source to simulate the output voltage of the PV array.

The output parameters for the solar array with and without bypass diodes under different shading conditions are summarized in Table-2. The dependence of the current-voltage characteristic of PV module on shading is shown in results. From Table-2, we notice that we obtain almost all values of MPP with and without using bypass diodes. In the presence of bypass diode we notice that the structure of the curves become more complex with the shading effects where several local MPP appear and one of them is the global maximum.

The addition of the bypass diode becomes very important in the cases where one of the modules is under full shading. In one of the cases we used bypass diode in the full shading condition in one of the module, we still obtain an output power. However, when we remove the bypass diode we get almost zero output power. Shading causes a large reduction on total outcome power that does not commensurate with the small amount of shading. That is the relation between shading and output power is not linear

9.6 Simulation Results :

CASE 1:- PV1 irradiated with 1000 W/m2. PV2irradiated with 300 W/m2 and PV3 irradiated with 600 W/m2

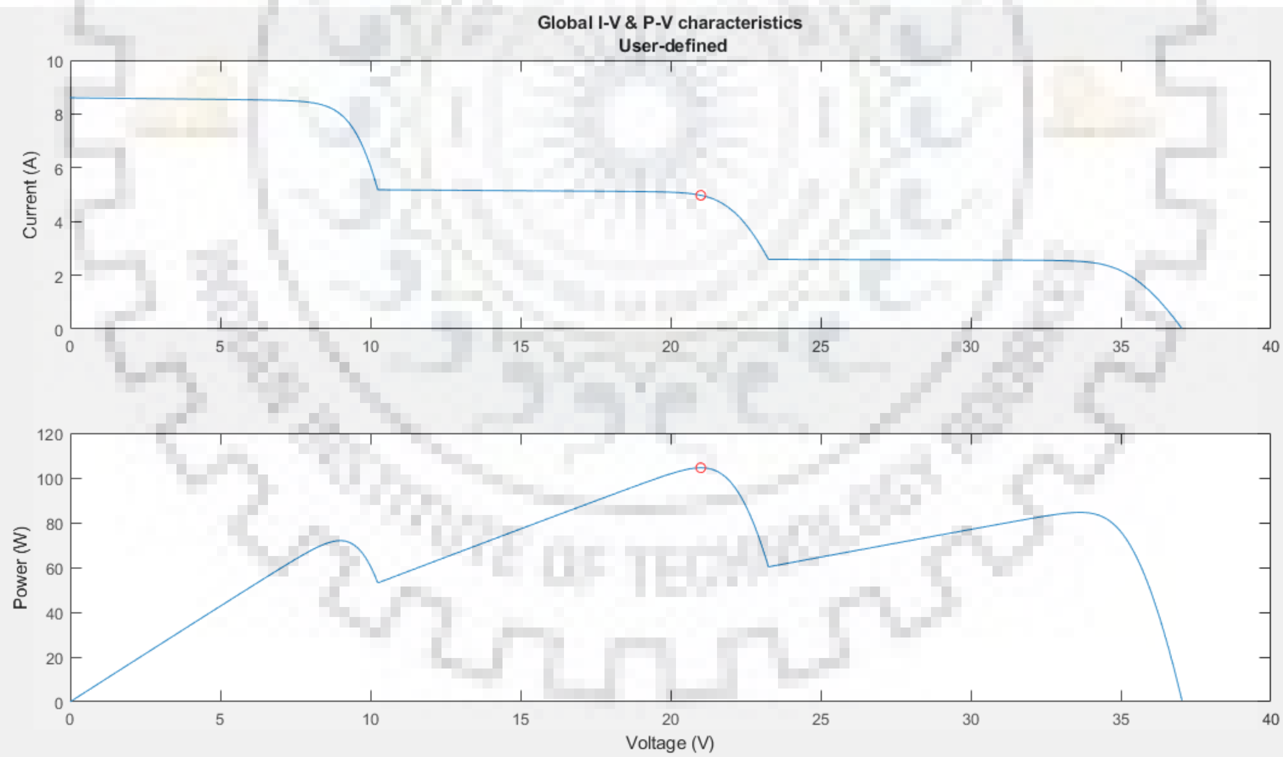


Fig- 9.12 Irradiance11000W/m2, Irradiance2 300W/m2 and Irradiance3 600W/m2

CASE 2:- PV1 irradiated with 1000 W/m2. PV2 irradiated with 800 W/m2 and PV3 irradiated with 200 W/m2

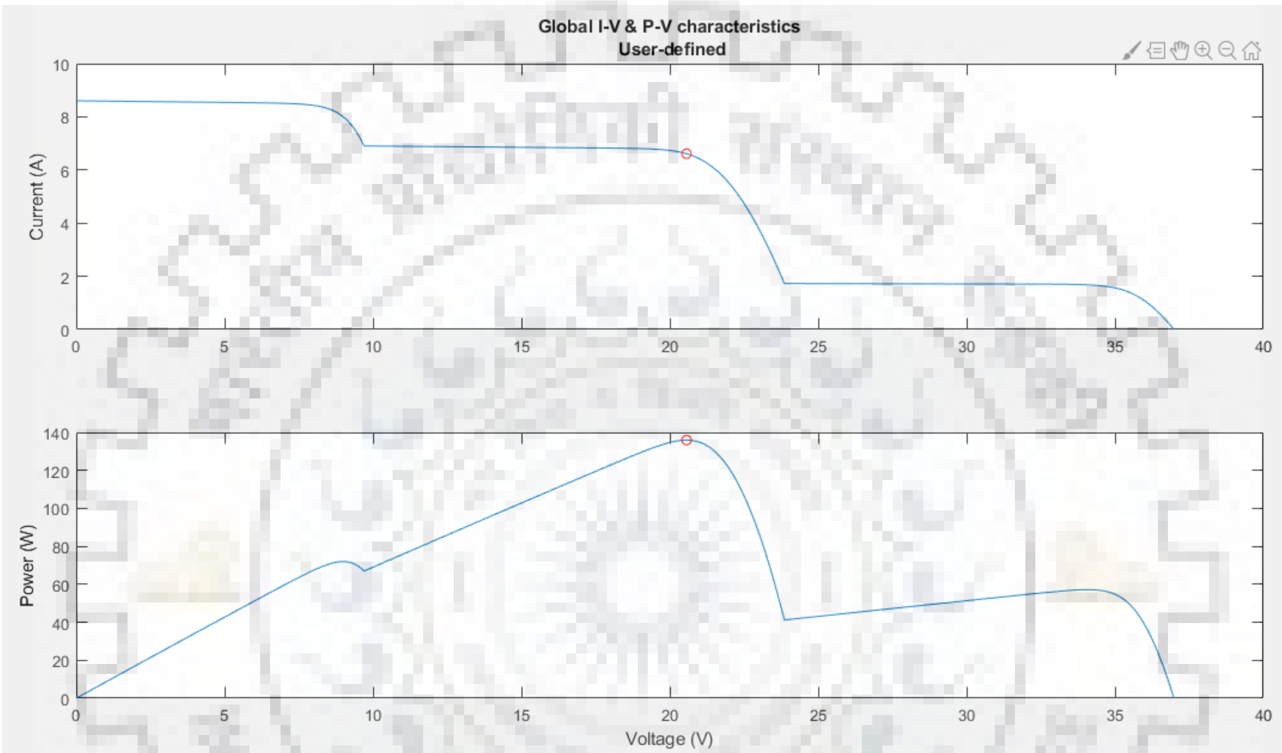


Fig- 9.13 Irradiance11000W/m2, Irradiance2 800W/m2 and Irradiance3 200W/m2

CASE 3:- PV1 irradiated with 1000 W/m2. PV2 irradiated with 500 W/m2 and PV3 irradiated with 400 W/m2

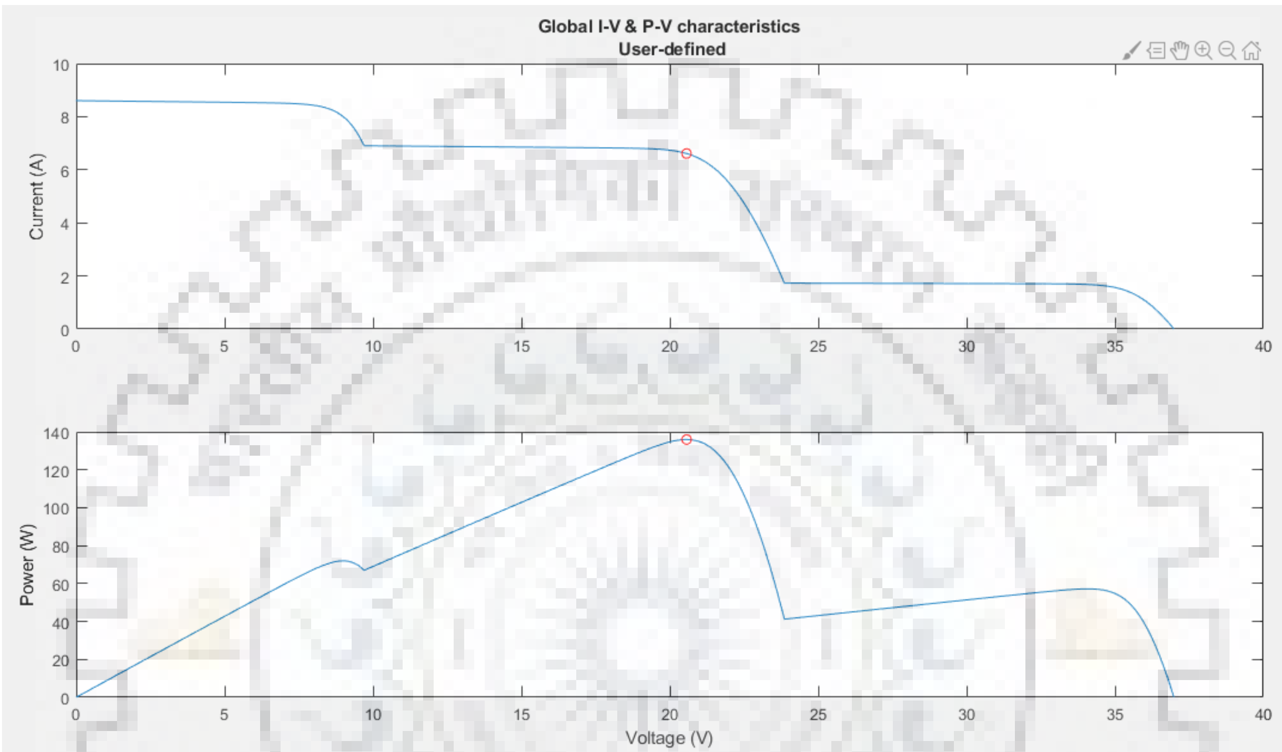


Fig- 9.14 Irradiance11000W/m2, Irradiance2 500W/m2 and Irradiance3 400W/m2

CASE 4:- PV1 irradiated with 1000 W/m2. PV2 irradiated with 500 W/m2 and PV3 irradiated with 500 W/m2

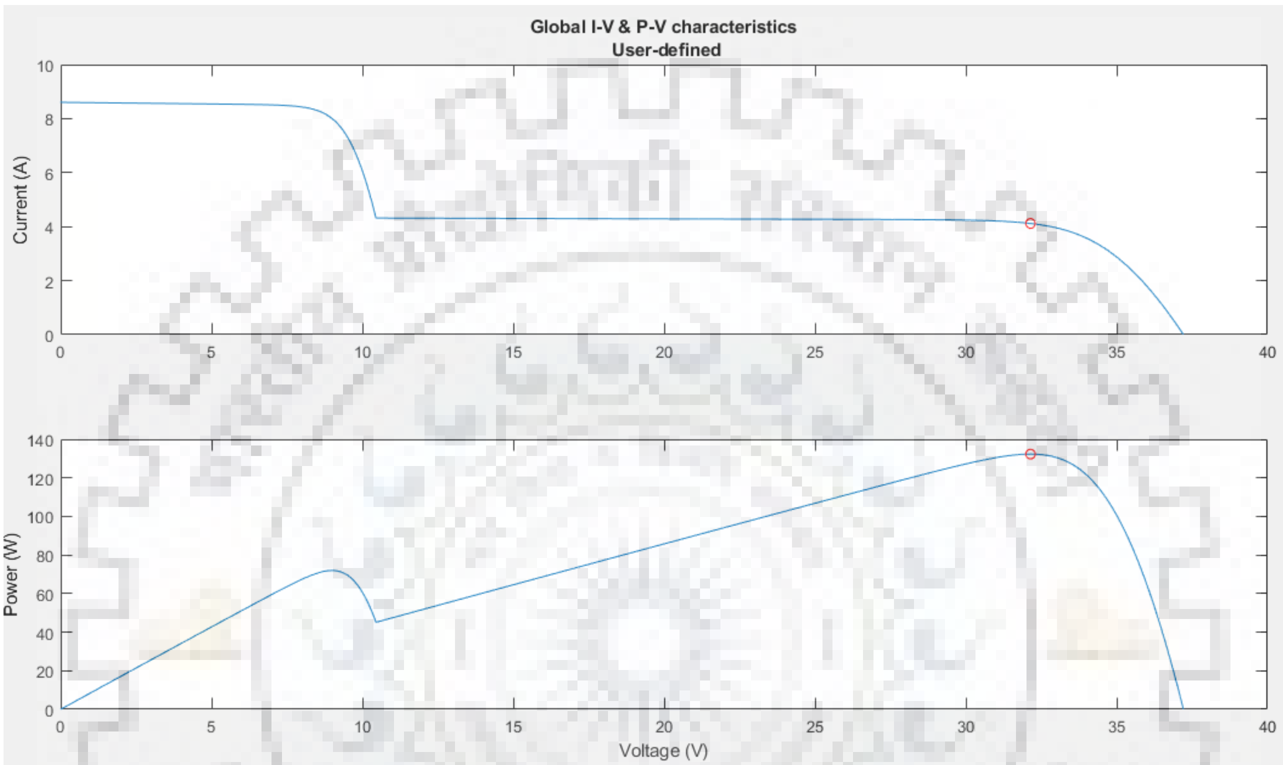


Fig- 9.15 Irradiance11000W/m2, Irradiance2 500W/m2 and Irradiance3 500W/m2

CASE 5:- PV1 irradiated with 1000 W/m2. PV2 irradiated with 500 W/m2 and PV3 irradiated with 0 W/m2

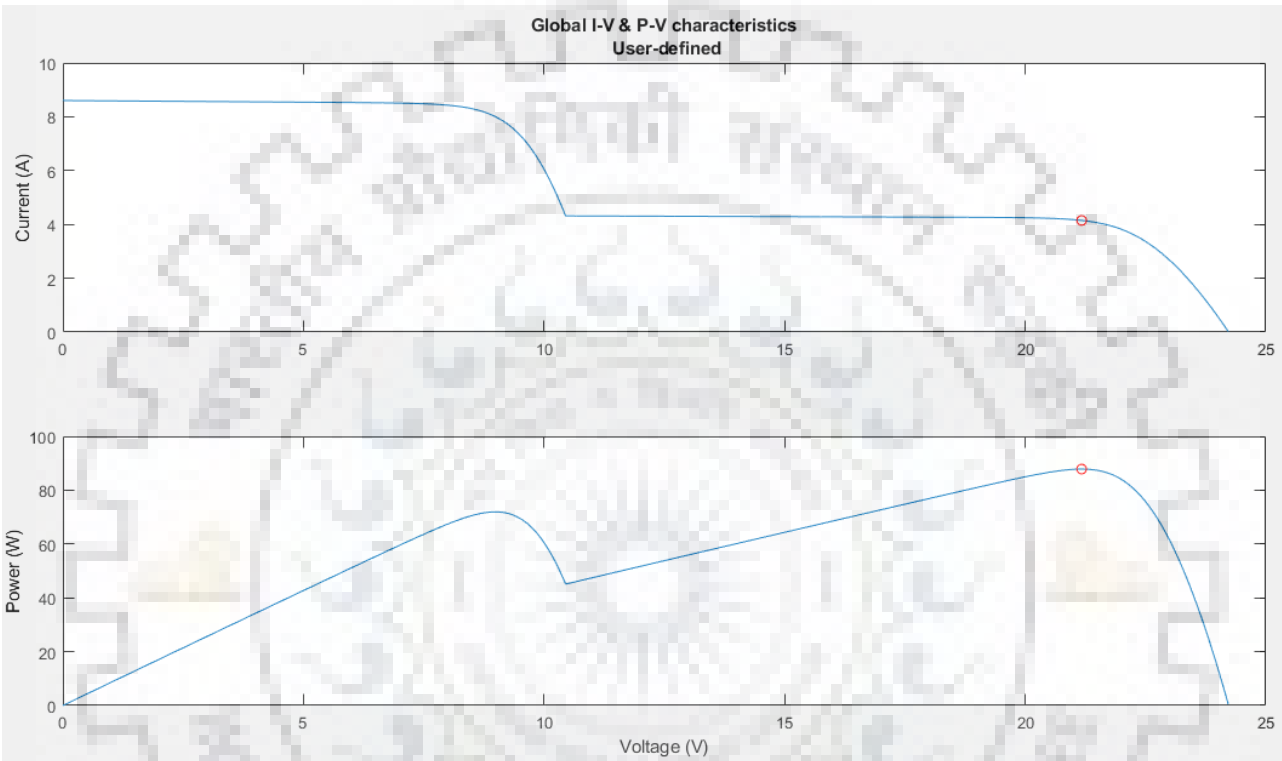


Fig- 9.16 Irradiance11000W/m2 ,Irradiance2 500W/m2and Irradiance3 0W/m2

9.7 Simulation Summary :

Case	Module 1 irradiance [W/m²] Ir1	Module 2 irradiance [W/m²] Ir2	Module 3 irradiance [W/m²] Ir3	Voltage at MPP [V]	Current at MPP [A]	Power at MPP [W]
1	1000	800	200	20.56528	6.61099	135.957023
2	1000	300	600	21.00768	4.97436	104.499791
3	1000	500	400	32.96512	3.34793	110.364992
4	1000	500	500	32.14352	4.11645	132.317454
5	1000	500	0	21.1720	4.14831	87.82811

Table 2:- Summary of diverse shading situations effects on 3 PV modules in the presence of bypass diodes

10. Future Scope

We have implemented partially shaded condition on two PV array system and three PV array system and seen different results for different irradiation levels.

We can extend our work to four PV array system and five PV array system. In case of four PV array system we should get four Maximum Power Points (MPP) and out of these four MPPs there will be one Global Maximum Power Point (GMPP). This GMPP can be traced by Perturb and Observe Method by doing some modifications.

Similarly, for five PV systems there will be five maximum power points and the P-V curve will become more complicated. But the algorithm to find global maximum power point the algorithm will be same as before.

11. Conclusion

We examined in details the effect of different shading condition on PV modules output power. We used Matlab/Simulink to perform our simulations. We realized that partial shading conditions on PV array makes the power curve more complex with the existence of multiple MPPs instead of unique MPP in the case of full insolation. In addition, we studied the effect of adding bypass diode to the modules. We conclude that the existence of the bypass diodes improve the output power value in particular in the cases where one of the modules is under full shading conditions. Shading causes a large reduction on total outcome power that does not commensurate with the small amount of shading. That is the relation between shading and output power is not linear.

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