YASAR UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MASTER THESIS

Maximum Power Point Tracking in Photovoltaic Systems

Immad ud din

Thesis Advisor: Prof. Dr. Erol Sezer

Department of Electrical and Electronics Engineering

Presentation Date: 26-10-2015

Izmir-Turkey 2015

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APPROVAL

This study, titled "MAXIMUM POWER POINT TRACKING IN PHOTOVLTAIC SYSTEMS" and presented as Master (Post Graduate) Thesis by IMMAD UD DIN, has been evaluated in compliance with the relevant provisions of Y.U. Graduate Education and Training Regulations and Y.U. Institute of Science Education and Training Direction. The jury members below have decided for the defense of this thesis, and it has been declared by consensus / ~~majority~~ of votes that the candidate has succeeded in his thesis defense examination dated ………………...

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Director of the Instute of Natural
and Applied Sciences,
Prof. Dr. Cüneyt Güzelis

Abstract

MAXIMUM POWER POINT TRACKING IN PHOTOVOLTAIC SYSTEMS

IMMAD UD DIN

MSc in Electrical and Electronics Engineering
Thesis Advisor: Prof. Dr. EROL SEZER
October 2015, 64 pages

Three different control algorithms for maximum power point tracking in a photovoltaic system are compared. Performance of each algorithm is evaluated by simulating the dynamic behavior of a typical photovoltaic system under different operating conditions.

The system used in simulations consists of a PV array, a dc-dc Buck converter and a simple resistive load. The output voltage of a PV array is controlled by adjusting the duty cycle of the Buck converter, which in turns, determines how much of the maximum power available in the PV array is extracted.

The three algorithm used for tracking the maximum power point are: The perturb-and-observe (P&O) method and the incremental conductance (IC) method. The performances of the algorithms are compared for different irradiances.

ÖZET

Foto-Electric Sistemlerde Guçtepe Noktasının izlenmisi

IMMAD UD DIN
Yüksek Lisans Tezi, Elektrik ve Elektronik Mühendisliği Bölümü
Tez Danışmanı: Prof. Dr. EROL SEZER
Ekim 2015, 64 sayfa

Elektrik üreten günes-paneli sistemlerinde güç tepe noktasının izlenmesi için geliştirilen üç farklı kontrol algoritması karşılaştırılmıştır. Algoritmaların performansları, tipik bir guneş paneli sisteminin farklı çalışma koşullarındaki dinamik davranışının bilgisayarlı benzetimi ile değerlendirilmiştir.

Benzetimde kullanılan sistem modeli bir foto-elektrik hücre dizisi, bir DA-DA çeviricisi ve basit bir rezistif yükten oluşmaktadır. Sistemin üretebildiği en yüksek gücün ne kadarının çekilebileceğinin belirleyen foto-elektrik hücresinin çıkış gerilimi, çevirgecin servis-süresi-oranı (hizmet çevrimi) ayarlanarak değiştirilmektedir.

Çalışmada incelen, guç tepe noktasının izlenmesi amaçlı ‘‘Dürt ve gözle’’ yöntemi,‘‘ Adımsal iletkenlik Ayarı’’yöntemi ve‘‘oransal Açık-Devre Gerilimi’’yöntemidir. Algoritmaların verimlilikleri farklı ışıma koşullarında hesaplanmış ve karşılaştırılmıştır.

ACKNOWLEDGMENTS

I would like to thank my advisor Dr. Erol Sezer for his support advice and his great knowledge. This thesis would not have been accomplished without his guidance he had provided in the entire process.

I would like to thank my parents my mother my father who are always been a constant source of inspiration for me.

Finally to someone I love who is always there to support me in pursuing my masters.

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INDEX OF SYMBOLS AND ABBREVIATIONS

Symbols	**Explanations**
V_{MPP}	Voltage at maximum power point
I_{MPP}	Current at maximum power point
P_{MPP}	Power at maximum power point
I_D	Diode current
$\mathrm{V_{PV}}$	Photovoltaic voltage
I_{PV}	Photovoltaic current
I_{PH}	Photocurrent induced from cell by irradiance
V_G	Input voltage of the buck converter
D	Duty cycle
D_P	Change of power
D_V	Change in voltage
D_I	Change in current
V_{PREV}	Previous voltage in P&O algorithm
I_{PREV}	Previous current in P&O algorithm
P_{PREV}	Previous power in P&O algorithm
$i_{l(t)}$	Inductor current of the buck converter

$V_{L(t)}$	Inductor voltage of the buck converter
ΔD	Change in duty cycle
I_{total}	Current in IC Cond algorithm
V_{total}	Voltage in IC Cond algorithm
V_{ref}	Voltage of the reference cell in the fractional algorithm
V_T	Output voltage of the Buck converter
V_{oc}	Open circuit voltage
I_{sc}	Short circuit current

Abbreviations	**Explanations**
MPP	Maximum power point
MPPT	Maximum power point tracking
P&O	Perturb and Observe
IC	Incremental conductance algorithm

CHAPTER 1

INTRODUCTION

1.1 Overview

“The use of the solar energy has not being opened up because the oil industry does not own the sun” (Ralph Nader) [Cutler J. Cleveland and Christopher G. Morris, Dictionary of Energy (2009)].

The sun is a unique, clean and infinite source of free power delivering more than 1000 kwh/square meter. 1000 kWh of energy is the amount found in 100 liters of heating oil. The present era of global warming needs to harvest the solar energy not to rely on the other sources of energy. The boost in solar energy research arises after the oil crisis in 1973, when western leaders became desperate to find alternative energy sources that will lower their dependence on foreign nations. The fossils fuel dependence has decreased all over the world with the advancement in the renewable sources of energy.

Photovoltaic energy is more static and also has the advantages of being noise, and maintenance-free. However solar energy has its own challenges in harvesting. They are highly dependent on the conditions they are placed in. Its efficiency is influenced by temperature irradiance, humidity and partial shading.

Photovoltaic power systems are categorized of according to their function operation, and their component configurations, also how the system is connected to other power sources and electrical loads. Photovoltaic systems can be designed to provide DC and/or AC power. It can operate interconnected with or independent of the utility grid, and can be connected with other energy sources and energy storage systems. The two main classifications are 1) Grid-connected, 2) Stand-alone systems.

Grid connected PV systems are designed to operate with the electric grid. The grid connected system includes the inverter as the primary component which converts the DC power of the PV system to the AC power consistent with the requirement of the utility grid. When the output power of the PV array is greater than the on-site demand, then the excess power is fed into the main grid. Otherwise, the grid supplies the difference between the demand and the PV power. The typical figure of the grid connected system is shown in fig. 1.1.

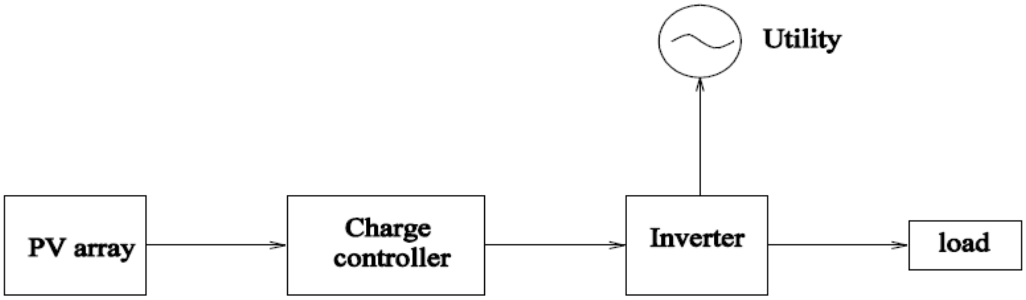


Figure 1.1 Grid connected PV System

Stand-alone PV systems are designed to operate independent of the utility grid and are designed to supply certain DC and/or AC electrical loads. The simplest stand-alone system is the direct coupled system where the DC output of the PV is directly connected to the DC load. Since there is no electrical energy storage (batteries) in direct-coupled system, the load only operates during sunlight hours for common applications like ventilation fans ,water pumps, and small circulation pumps for solar thermal water heating systems. Matching the impedance of the electrical load to the maximum power output of the PV array is a critical part of designing well-performing direct-coupled system. A MPPT (maximum power point tracker) is used between the PV array and the load to track the maximum available power extracted through the DC converter to utilize the maximum power of the array.

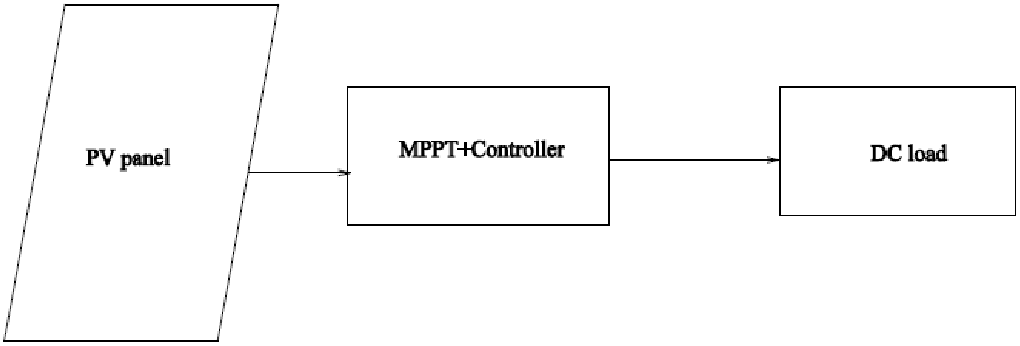


Figure 1.2 Regulated Stand-Alone System

Other types of stand-alone system include hybrid system and battery connected stand-alone system powering the DC and AC loads. Street lightning communication system and residential use are typical application of battery connected and hybrid power systems. The diagram of regulated stand-alone system with battery is shown below.

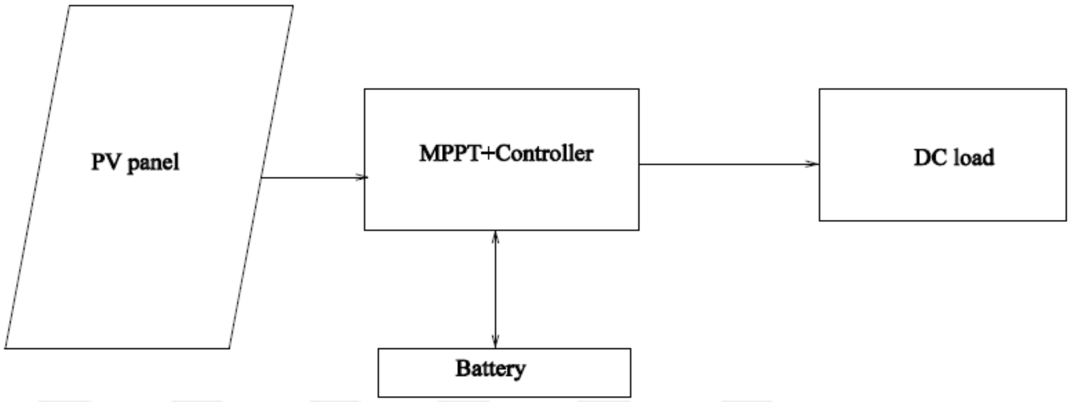


Figure 1.3 Regulated Stand-Alone System with battery storage

1.2 Literature review

A vast amount of literature is available on the topic of modeling a PV cell. Ding and colleagues [1] performed their analysis on the SIMULINK based PV model and its application under conditions of non-uniform irradiance, their research proposed that the performance of a photovoltaic (PV) module is mostly affected by array configuration, irradiance, and module temperature. It is important to understand the relationship between these effects and the output power of the PV array. Their experiments show that the proposed model has good predictability in the general behaviors of MPPT under the conditions of both non uniform and uniform irradiance

Altas and Sharaf [2] developed a simulation model to be used in matlab GUI environment. The model is developed using basic circuit equations of the photovoltaic (PV) solar cells including the effects of solar irradiation and temperature changes. The new model was tested using a directly coupled dc load as well as AC load via an inverter.

Park and Kim [3] proposed a PV cell modeling based on a single model equivalent circuit to get the characteristic nonlinear I-V curve of a PV cell. The main objective of this paper was to find the parameters of the nonlinear I-V equations. PV model algorithms were proposed which is fast accurate and applicable for all kind of PV cells..

Desai and Patel [4] showed that it is necessary to control the operating point to extract the maximum power from the PV arrays. Number of methods for Maximum Power Point Tracking (MPPT) has been reported in the literature. This paper aims to give a comprehensive comparison of different MPPT algorithms in terms of their tracking efficiencies, cost effectiveness, complexity of realization.

Faranda and Leva [5] research paper presented the comparative study of 10 widely used algorithms their performance is evaluated on the energy point of view.

Banul and Istrate [6] developed a maximum power point tracking algorithm for the PV system. The method is used to study the influence of rapidly changing irradiance level concerning performance of photovoltaic systems. A simple circuit model of the Dc/Dc buck converter connected to the photovoltaic systems is used to easily simulate the incremental conductance MPPT method.

Choudhary and Saxena [7] performed the detail analysis of Buck converter for MPPT of PV systems.

Kaur and Navdeep [8] performed the mathematical modeling of a buck converter This paper derives the mathematical modeling of a pulse width modulated (PWM) open loop buck converter operating in continuous conduction mode (CCM) and presents its verification by simulation in SIMULINK.

Murtaza and colleagues [9] performed the comparative analysis of fractional open circuit algorithm, fractional short circuit algorithm. Perturb and observe algorithm and incremental conductance algorithm. The comparative analysis provides the pros and cons of each MPPT with a resistive load. The analysis is about the time required for each algorithm to track the maximum power and the system efficiencies.

Wu and Cheung [10] performed their analysis on the MPPT of the PV system. This paper proposes a new method for the MPPT control of PV systems, which uses one estimate process for every two perturb processes in search for the maximum PV output. In this estimate-perturb-perturb (EPP) method, the perturb process conducts the search over the highly nonlinear PV characteristic, and the estimate process compensates the perturb process for irradiance-changing conditions.

Chermitti and Neçaibia [11] proposed a Comprehensive and field study to design a buck converter for photovoltaic systems. This paper tries to study an electronic converter in PV systems, namely the Buck converter, and propose an easy way to electronic converter designers to calculate component values needed to realize it.

1.3 Outline of the Thesis

The main objective of thesis is to track the maximum power point of a PV array, making the output power stable i.e. reduction of the ripples in the output power. The analysis has been performed in a practical way by creating the whole system in MATLAB (Simulink) environment.

The specific tasks include:

- Creating a photovoltaic model in matlab (Simulink).
- Finding the I-V and P-V curves for different irradiances.
- Maximum power point in these curves responds to different irradiances.
- Algorithms theory of maximum power point tracking in PV system.
- Compare and study all the algorithms its complexities and problems in tracking MPP.
- Designing of Buck converter for the PV system.
- Ripple factor calculation in the dc converter.
- Simulation of the whole PV system with the MPPT algorithm.
- Finding out the maximum available power in the cells.
- Tracking the power form the maximum available power.
- Tracking the extracted power from the cells through DC converter.
- Applying step variable and constant irradiance to the stand alone PV system.
- Efficiency of the system in each case.

Chapter 1 explains the types of PV system, application of the PV systems literature review and the research performed in the several areas of the PV system.

Chapter 2 includes the structure of the overall system the working of the PV cells, modeling of the PV cell, plotting of the P-V and V-I curves through different irradiances its linear plot in the matlab environment. It also includes the designing of the DC to DC converter, its mathematical modeling, analysis and calculation of output ripple, also the output load of the stand-alone systems is discussed. Theory of different control algorithm for the maximum power point tracking and why we need it.

Chapter 3 explains the simulation model of the whole system, modeling of cells for P-V and V-I curve, Simulink model of DC converter, Simulink model of a single cell, Simulink model for MPPT algorithm and overall final model for the stand alone PV system.

Chapter 4 finally shows the results of all the simulation performed with step, constant and variable irradiances for each of the algorithm, the comparison of each of the algorithm is explained with respect to the efficiency. At last but not the least conclusion of the analysis and recommendations for the future work.

CHAPTER 2

BACKGROUND

2.1 Structure of the System

The block diagram of a typical PV system is shown in Fig. 2.1

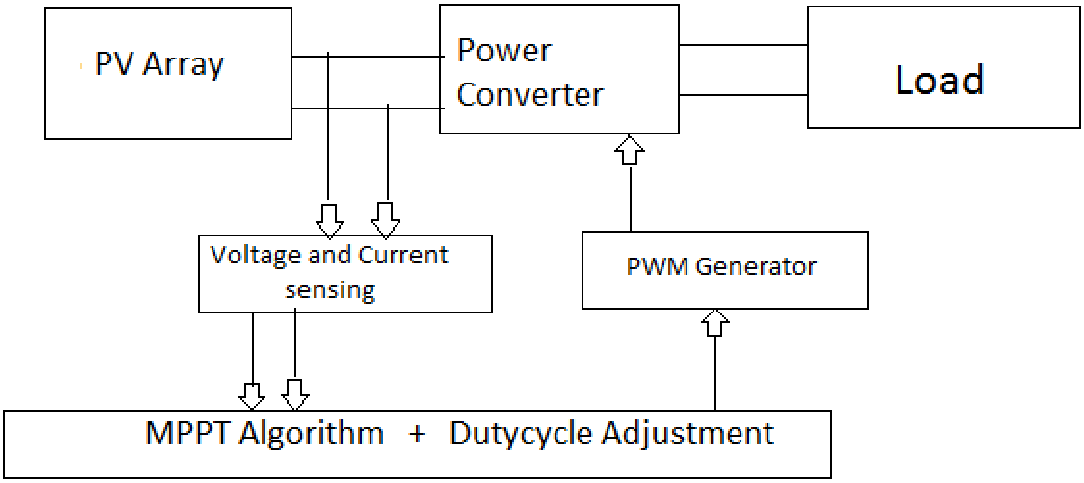


Figure 2.1 Block diagram of Stand-Alone System

The power produced by the PV array depends not only on the temperature, humidity and irradiance; but also on the output voltage of the PV array. The main task of the controller is to extract the maximum available power at any operating point by adjusting the output voltage. This is achieved by regulation of the duty cycle of the power converter.

Lowering the cost of photovoltaic electricity from solar cells is necessary for the technology to further extend its use, especially the cost of maximum power trackers. In the present decade it's very important to have a cheap tracker with maximum efficiency. Several algorithms are developed for that purpose every algorithm has its own advantages and complexities however its implementation shows the difference in tracking the maximum available power. The speed of tracking the MPP is an important factor in the control algorithms.

The instability and ripples in the extracted power is also an important part in PV system, also the ripples reduction in the DC to DC converter is necessary for the smooth power. Several steps are required to be taken while designing the DC converter.

The inefficiency in the solar cell is always important in the study of solar system. Every year research is made in the efficiency of solar cells, but overall the cells' greatest source of correctable inefficiency is in the implementation of the MPPT.

2.2 PV Array

A solar cell is an electrical device that converts energy of light directly into an electrical energy by the photovoltaic effect which is its electrical and chemical phenomenon and its electrical characteristics such as current voltage and resistance vary as the cells are exposed to light. Solar cells are building block of PV modules called solar panels.

In 1950 after the invention of transistor and semiconductor technologies by Bell's lab there was a revolution in the solar technology and scientist started to make reasonably efficient solar cells and the field started to be taken seriously as a means of generating electricity, so the first work was done in 1950 by a team in Bells lab and this basic solar cell was 6 % efficient. [The Transistor Characteristics and Applications: by Bell Telephone Laboratories, Inc. for Western Electric Co., Inc. (New York 1951)].

A solar cell is actually a PN junction with a light shining on it. By knowing the total amount of power in the light that is incident on the surface of the cells, the efficiency can be found from

$$\eta = \frac{P_{OUT}}{P_{IN}} \times 100 \tag{2.1}$$

Where Pout is the output power and Pin is the input power.

2.2.1 PV characteristics

An ideal solar cell includes a current source $\mathrm{I_{ph}}$ with ideal diode PN in parallel. Practically no solar cell is ideal, so a parallel resistance $\mathrm{R_P}$ and a series resistance $\mathrm{R_S}$ are added to the equavalent model. A solar cell is a nonlinear device and can be represented as a current source model as shown in Fig. 2.2. The output of the current source is directly proportional to the sunlight irradiance level and R_P is the parallel resistance of the solar cell whose value is usually large. The output current of the circuit is given by

$$I{=}I_{Ph} - I_D - I_P \tag{2.2}$$

where I_{ph} is the photo current arise due to the irradiance , I_D is the diode current, and I_P is the current through R_P.

The diode current is given by the Shockley diode equation.

$$I_D = I_0 * \left[e^{\frac{q*V_D}{k*T}}\right] \tag{2.3}$$

where

I_0 is the reverse saturation current of the diode.

q is the electron charge value at 1.602x10−23 C.

V_D is the diode voltage.

K is the Boltzmann constant valued at 1.381x10−23 J/K.

T is the junction temperature in kelvin.

Noting that $V_D = V + IR_S$ (2.2) and (2.3) yields

$$I = I_{ph} - I_0 * \left[e^{\frac{q*(V_D+IR_s}{k*T}} - 1\right] - \frac{(V + I * R_s)}{R_p} \tag{2.4}$$

This expression (2.4) describes the electrical behavior and gives the relationship between the voltage and current supplied by photovoltaic module.

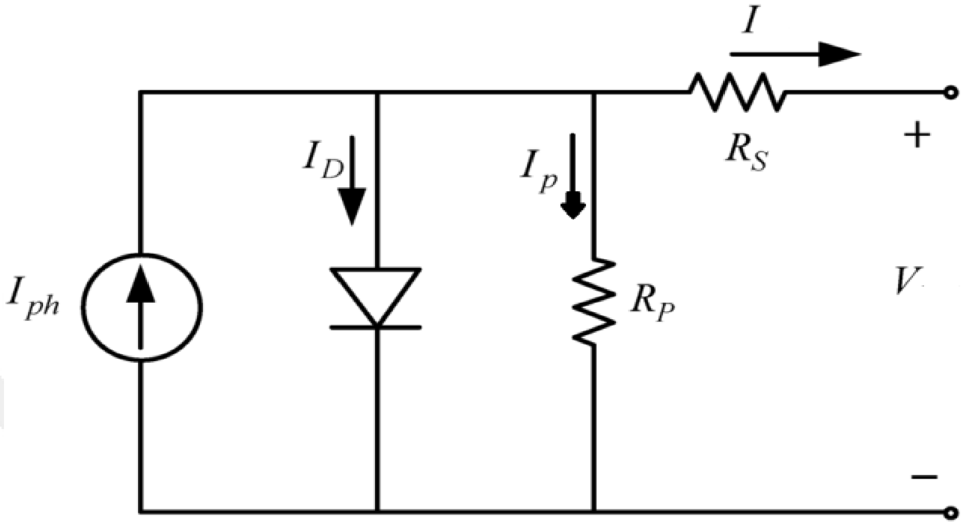


Figure 2.2 Basic Circuit of PV Cell

2.2.2 Maximum power point tracking

At any given point in time the solar module operates at a particular voltage and current. The point on the I-V and P-V curve where solar modules operate is the operating point for a given irradiance. The operating point on the curves corresponds to the unique I-V or P-V value. From Fig. 2.3 it is obvious that the solar module must operate at maximum power P_{max} , the current at that point is called the maximum current I_{max} and the voltage at that point is called the maximum voltage V_{max} .

Now without any external electrical manipulation the PV module operating point is largely dictated by the electrical load seen by the PV module at its output. To get maximum power delivered by the PV module it is imperative to force the module to operate at the operating point corresponding to the maximum power, called the maximum power point MPP. This point corresponds to the peak of the P-V curve and the knee of the I-V curve. The simplest way to do this is to force the voltage of the PV module to be at the maximum power point (MPP) or regulate the current to the right amount as that of the maximum power point (MPP) using converter, but what if after forcing the PV module to operate at the MPP. The ambient condition like irradiance or temperature change and in turn costs the P-V and I-V curve to change as well this means that the old MPP is no longer valid under these condition, thus to be continuously at the MPP at all the times there needs to track any change in the curves and find out the new MPP this process is called maximum power point tracking MPPT and the devices that perform this process are called MPP trackers. An MPP device is nothing but a hardware implementation of an MPP algorithms there are several algorithms to track the MPP effectively. They are also called MPP tracking techniques, the modern literature talk about the two broad categories of MPP techniques.1) Indirect MPPT, 2) Direct MPPT.

Indirect techniques are fix voltage method and fractional-open-circuit method, while direct techniques include perturb-and-observe and incremental conductance techniques etc. Each of these techniques has its own advantages and disadvantages.

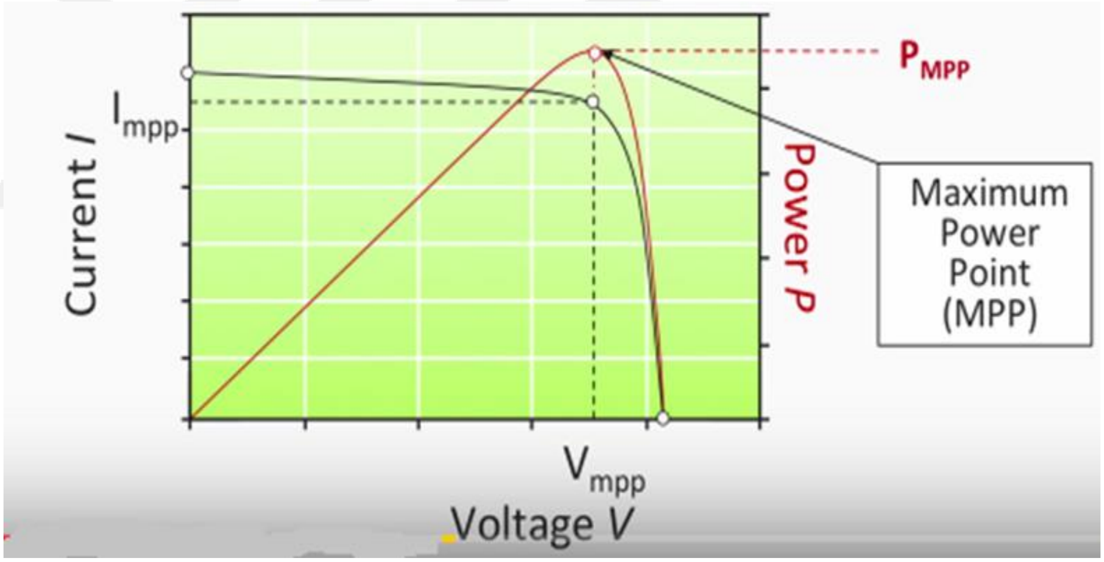


Figure 2.3 Concept of MPP

2.3 Buck Converter

The buck converter is one of the most widely used DC to DC converter in the PV system. The output generated by a PV system is given at the input of the buck converter. To find the new operating point of the PV system through the MPPT the updated point is given at the gate of the power electronics circuit. The circuit of the buck converter is given in Fig. 2.4

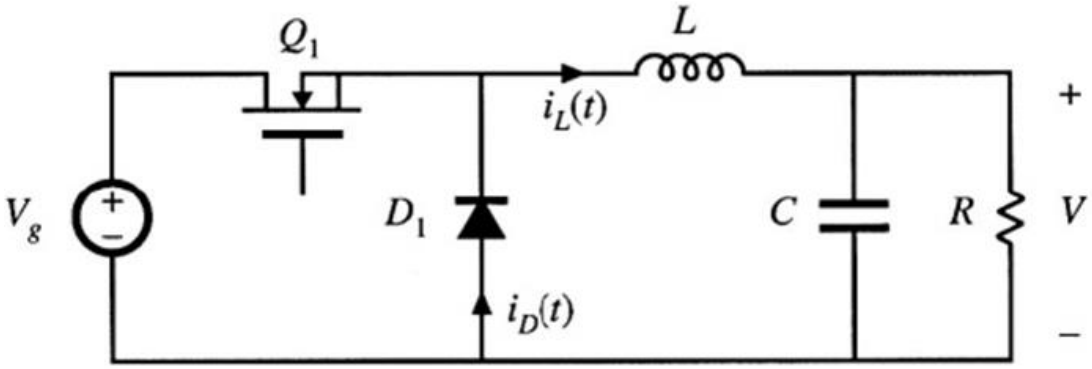


Figure 2.4 Circuit of Buck converter

There are two modes of operation in the circuit: Switch OFF and Switch ON. When the switch is off there is no current flow it is called the OFF time of the circuit and when the switch is turned on its called the ON time of the circuit.

2.3.1 Mathematical modeling

To analyze the circuit lets define the duty cycle first. Fraction of time during the duty cycle is the time at which the switch is on over the period i.e.

$$D = \frac{T_{on}}{T_{ON} + T_{off}} \tag{2.5}$$

For the mathematical modeling of this circuit some assumptions are made:

1 The circuit is in the steady state.
2 Inductor current $\mathbf{i_L}$ is continuous.
3 Capacitance of the capacitor is high enough to hold the output voltage across the load $\mathbf{V_o}$.
4 The switch close at t =DT.
5 The switch opens at t = (1-D)T.
6 The components are ideal there are no losses.

When the switch is ON the circuit will become:

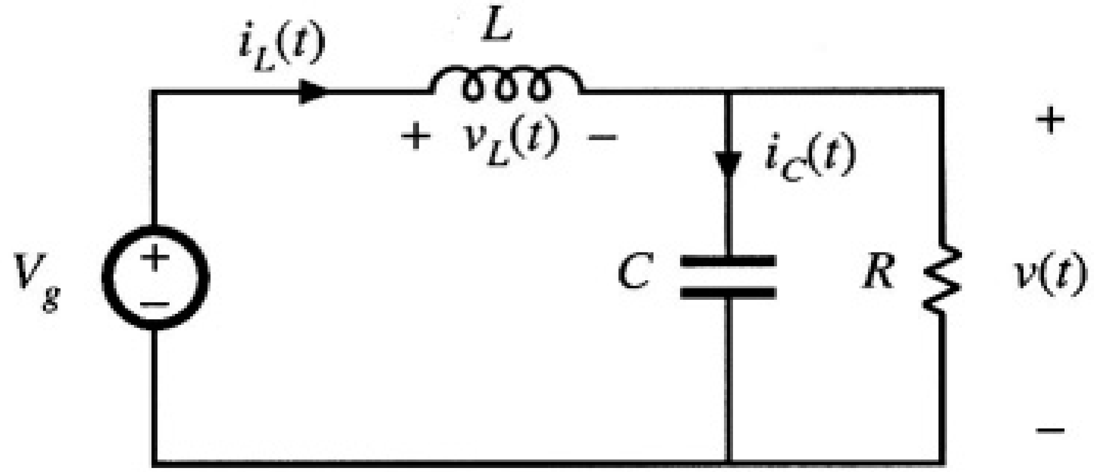


Figure 2.5 Buck converter with switch ON

The diode will act as an open switch meaning that there would be a current flowing from the Dc source to the output resistor, so the current flowing will charge the inductor and capacitor and supply the current to the load. When the switch is OFF the circuit will be in mode 2:

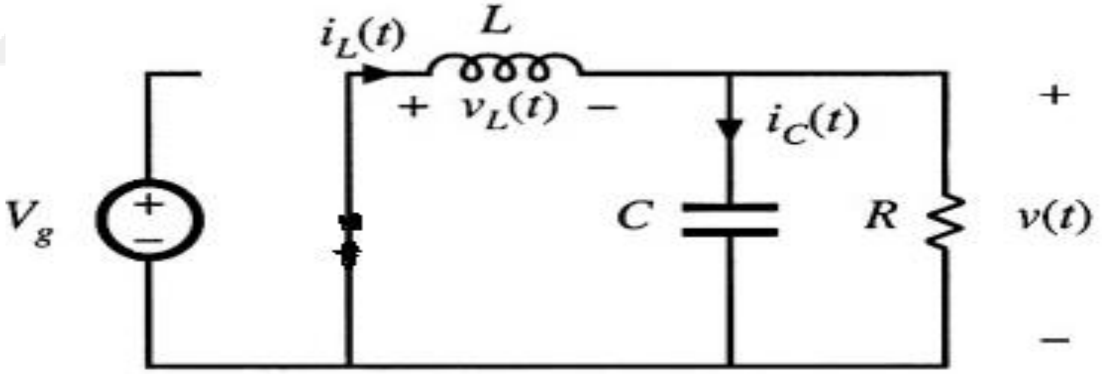


Figure 2.6 Buck converter with switch OFF

Mode shows the circuit in discontinuous mode and the diode is conducting due to the charge stored in the inductor will make the diode turn on. The inductor current waveform in fig. 2.7 shows the behavior of the system during these 2 modes, the inductor current starts after the steady state with a minimum value $i_L(0)$ upto a maximums value $i_L(DT)$ during the first switching time up to DT, until the switch is open then the inductor will discharge through the load resistance and its value will start to decline up to T.

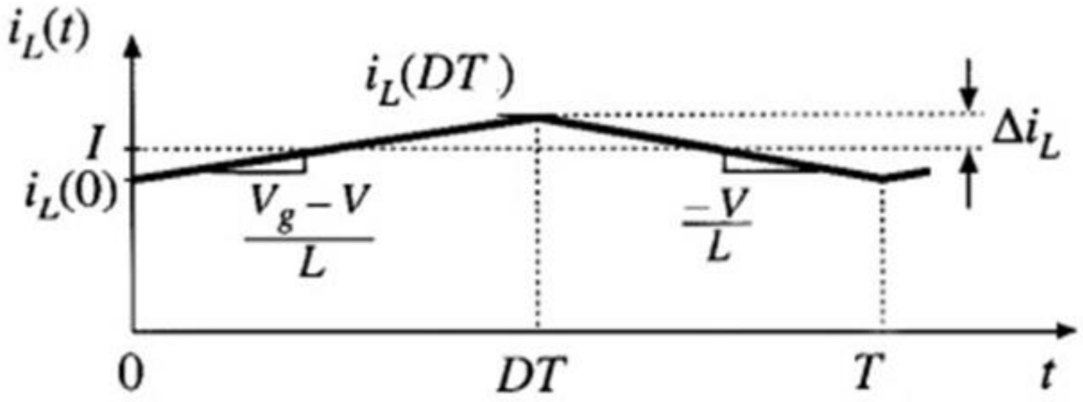


Figure 2.7 Inductor current waveform

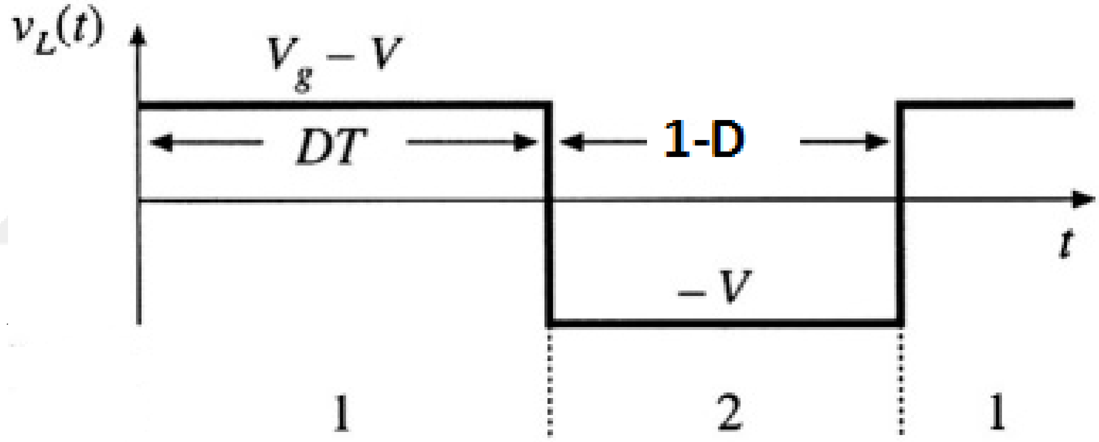


Figure 2.8 Inductor voltage waveform

Now

$$V_L = L\frac{d_i}{d_t} \tag{2.6}$$

From graph

$$i_l(t) = i_L(0) + \frac{V_G - V_T}{L}T \tag{2.7}$$

It can be written as

$$i_L(DT) = i_L(0) + \frac{V_{G-V_T}}{L}T \tag{2.8}$$

Equation (2.9) shows the maximum current when the switch is closed. During the second mode when the switch is open and the current start to decline until it reach time T.

$$V_L = \text{-V} \tag{2.9}$$

Substituting from (2.8) we get

$$i_L(0) = i_L(DT) - \frac{V_T}{L}(1-D)T \tag{2.10}$$

To find the peak-to-peak ripple of the current

$$\Delta i_L = i_L(0) - i_L(DT) \tag{2.11}$$

$$\Delta i_L = \frac{V_G - V_T}{L}\text{DT} \tag{2.12}$$

$$\Delta i_L = \frac{V_T}{L}(1-D)T \tag{2.13}$$

So the final equation becomes

$$V_T = V_G * \text{D} \tag{2.14}$$

Equation (2.15) shows that the output voltage is equal to the input voltage time's duty cycle. The waveform of one complete duty cycle is shown in Fig.2.8.

2.3.2 Output ripple value selection

It is of interest calculate the inductor current ripple Δi_L as shown in Fig. 2.7 ,the peak inductor current is equal to the average current plus peak to average current ripple Δi_L. This peak current is also for the semiconductor device in the circuit; therefore knowledge of peak current is necessary. Since we know the slope and length of the inductor current during the first time interval the ripple magnitude can be calculated and also during the first time interval the symmetrical current will become $2\Delta i_L$ so the change in current $2\Delta i_L$ will be

$$2\Delta i_L = \frac{V_G - V_T}{2L}DT \tag{2.15}$$

The typical value of Δi_L lies between 10 % to 20% of the full load value of I. Higher value will lead to the increase of current in the circuit and ultimately size and cost will be increased. The inductor value can be chosen such that acceptable inductor ripple is attained.

$$L = \frac{V_G - V_T}{2\Delta i_L} DT \tag{2.16}$$

Equation (2.17) is used to select the value of inductance in the buck converter.

2.4 Simple Resistive Load

All the analysis in this thesis are performed for the stand alone system, in the final simulation model the output load is selected to be a simple resistance and the results are obtained from a simple resistive load i.e. the final power generated form the buck converter is calculated from the resistive load which can be employed for different application. The change in the value of the resistance can affect the performance of the whole system. The value of resistance is selected to be the most effective which in turns gives stable results.

2.5 Control Algorithms

In this thesis two algorithms are implemented, both are direct method, each of these algorithms are discussed below in detail.

2.5.1 Perturb-and-Observe algorithm

In this algorithm perturbation is provided to the PV module this would translate to the increase or decrease in power , if an increase in voltage leads to an increase in power, it means that the operating point is to the left of the MPP, and hence further voltage perturbation is required towards the right to reach the MPP, conversely if the increase in voltage leads to a decrease in power, this means that a current operating point is to the right of the MPP , hence further voltage perturbation is required towards the left to reach the maximum power point. In this way the algorithms converges towards the MPP over the several perturbation. This algorithm takes advantage to the fact that the P-V curve has an increasing nature to the left of the MPP and a decreasing nature to the right of the MPP.

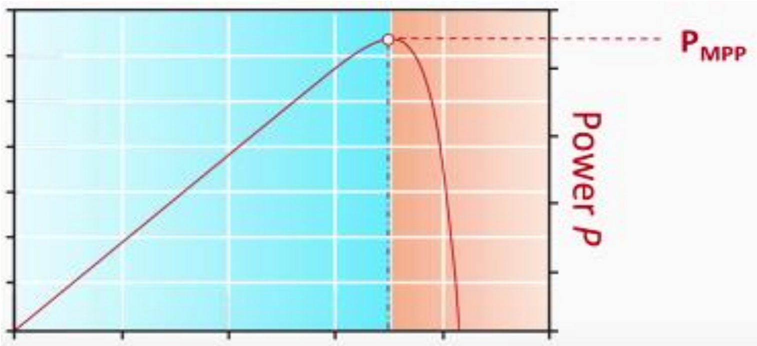


Figure 2.9 P&O algorithm MPPT

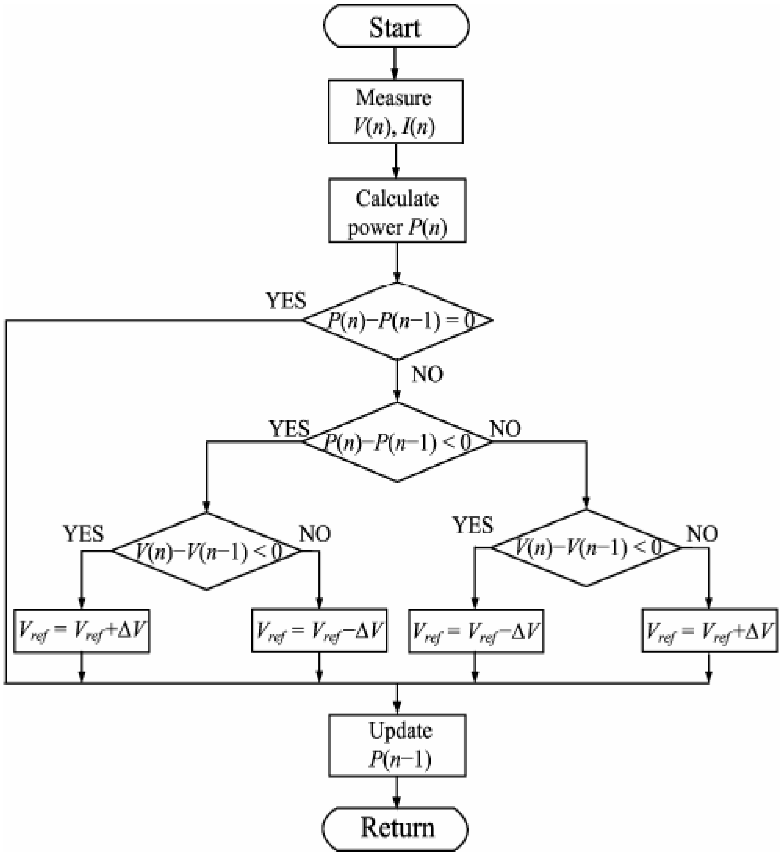


Figure 2.10 Flow chart of P&O Algorithm

The flow chart of this algorithm shows the increase or decrease of the power and perturbations are made to reach the MPP.

2.5.2 Incremental Conductance Algorithms

Another kind of direct maximum power point tracking algorithm called the incremental conductance algorithm, to better understand the algorithm first the relation between the conductance and incremental conductance should be defined:

Conductance of an electrical component is the ratio of current to the voltage i.e. the reciprocal of resistance. Now at the maximum power point the slope of the P-V curve is 0.

$$\frac{d_p}{d_v} = 0 \tag{2.17}$$

Now equation (2.17) can be written as

$$\frac{d_p}{d_v} = \frac{d(I * V)}{d_v} \tag{2.18}$$

Basic differentiation gives us

$$\frac{d_P}{d_v} = I + \frac{V * d_I}{d_v} \tag{2.19}$$

If the sampling steps are small enough we can write the equation (2.19) as

So at MPP

$$\frac{\Delta I}{\Delta V} = -\frac{I}{V} \tag{2.20}$$

To the left

$$\frac{\Delta \mathrm{I}}{\Delta \mathrm{V}} > -\frac{\mathrm{I}}{\mathrm{V}} \tag{2.21}$$

To the right

$$\frac{\Delta I}{\Delta V} < -\frac{I}{V} \tag{2.22}$$

The algorithm exploits these basic facts about the I-V and P-V curve of a solar module, in general the algorithms imposes a voltage on the PV module at every iteration measures the incremental change in the conductance compares it with the instantaneous conductance and decides if the operating point is to the left or to the right of the MPP.

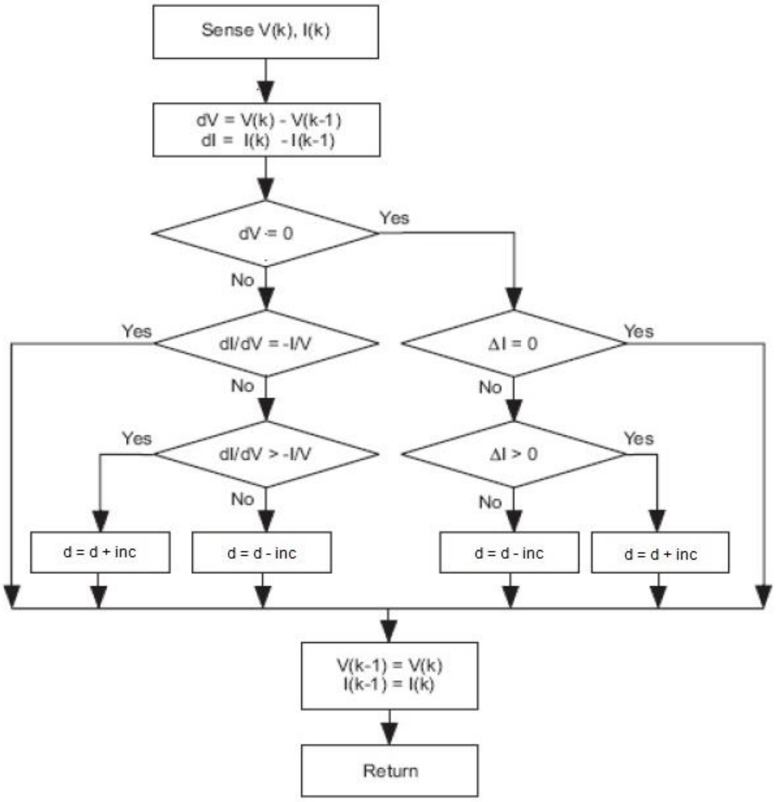


Figure 2.11 Flow chart of Incremental Conductance

In Fig. 2.11 the instantaneous voltage and current are the observable parameters while the instantaneous voltage is also the controllable parameter, V_{ref} is the voltage value forced on the PV module by the MPPT device it is the latest approximation of the MPP voltage, for any change in the operating point the algorithm compares the instantaneous and incremental conductance values.

If incremental conductance is more than the negative of the instantaneous conductance it means the current operating point is to the left of the MPP, and as a result the V_{ref} is incremented, conversely if the incremental conductance is lower than the negative of the instantaneous conduction the current operating point is to the right of the MPP and V_{ref} is decremented.

This process iterates until the incremental conductance is the same as the negative of the instantaneous conductance, in which the reference voltage is equal to the MPP voltage. Fig. 2.12 explains the working of the incremental conductance algorithm.

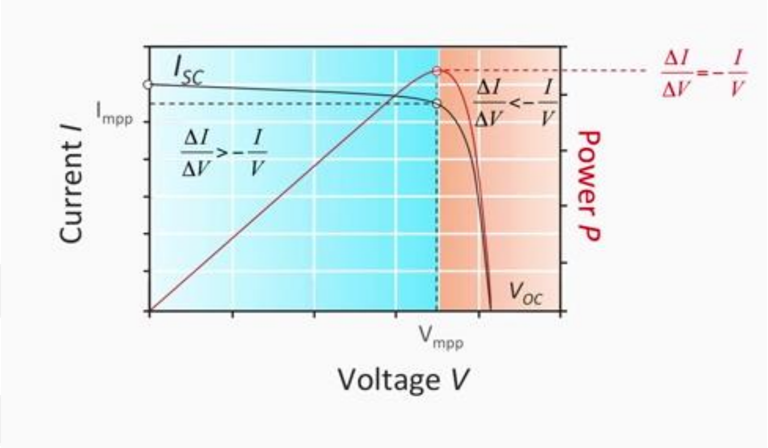


Figure 2.12 Working of Incremental conductance algorithm

CHAPTER 3

SIMULATION MODELS

3.1 Simulink Model to Obtain P-V and I-V Curves

In this chapter the simulation of the whole system is performed and the results are obtained, Constant step and variable irradiance is applied to the system respectively. The maximum power available is calculated from a single cell through slope intercept form, the voltage and current of the cell is sensed, shown in the simulation also the power extracted from the maximum power available. Through the sensed current and voltage of the cell the MPPT control algorithms are implemented and final duty cycle is given at the gate of the Mosfet i.e. the calculated duty cycle through the MPP control algorithm, the output of PV cell is the input of the buck converter. The PWM is applied to the buck converter.

In Simulink there are many ways of modeling devices, components or modeling complex systems. the solar cell can be modeled in several ways using Simulink libraries ,one of its most advanced library is Simscape and going one step further in advance component there is a built in implemented solar cell.

To find the P-V and I-V curve of solar cell a model is built as shown in Fig. 3.1, a photovoltaic array can be built by combining the cells in series or in parallel. The series or parallel combination of the cell increases the voltage and current of the cells respectively but the overall nature of the I-V and P-V curve remains the same in this model, but in this thesis the analysis are performed on a single cell for the P-V and V-I curves the is connected to a variable resistor. The purpose of doing this is to exercise the cell through a variety of variable resistance.

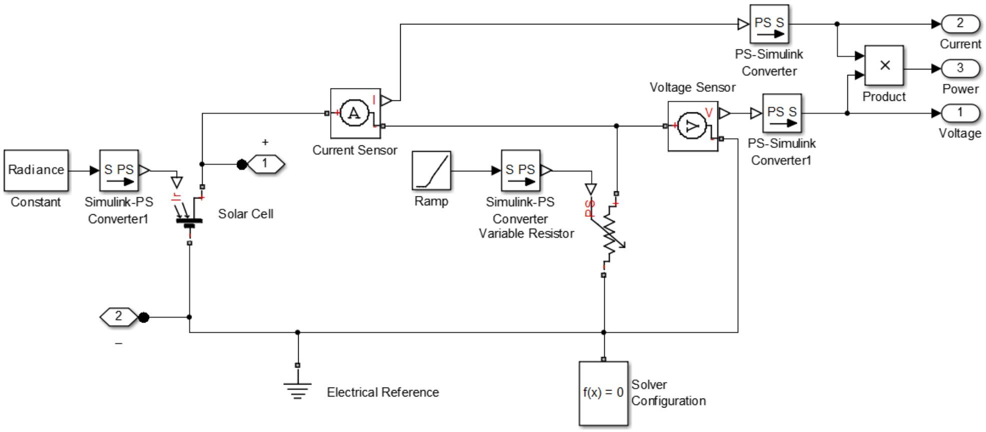


Figure 3.1 Simulink diagram for P-V and I-V curves

The parameters of model are given below

Table 3.1 Parameter of the cells for P-V and I-V curve

Short circuit current, Isc	7.34A
Open circuit voltage, Voc	0.6V
Current at maximum power point	4.5A
Voltage at maximum power point	0.58V
Maximum power	2W
Irradiance used for measurement G	1000W/m^2
Quality factor N	1.5
Temperature T	25C

The circuit is started with a zero resistance, so the circuit is short circuited and there is an output the short circuit current and as the resistance increases the graph is going to be at open circuit condition. So the voltage ends up in its open circuit value. The power of the PV array is shown as the value of the resistor changes. Note that for each short circuit current open circuit voltage and power there is a peak point this point is called the maximum power point (MPP). The simulation time for the PV system is selected to be 120sec for running the model we get the current, voltage and power for a single irradiance is shown in the Fig. 3.2.

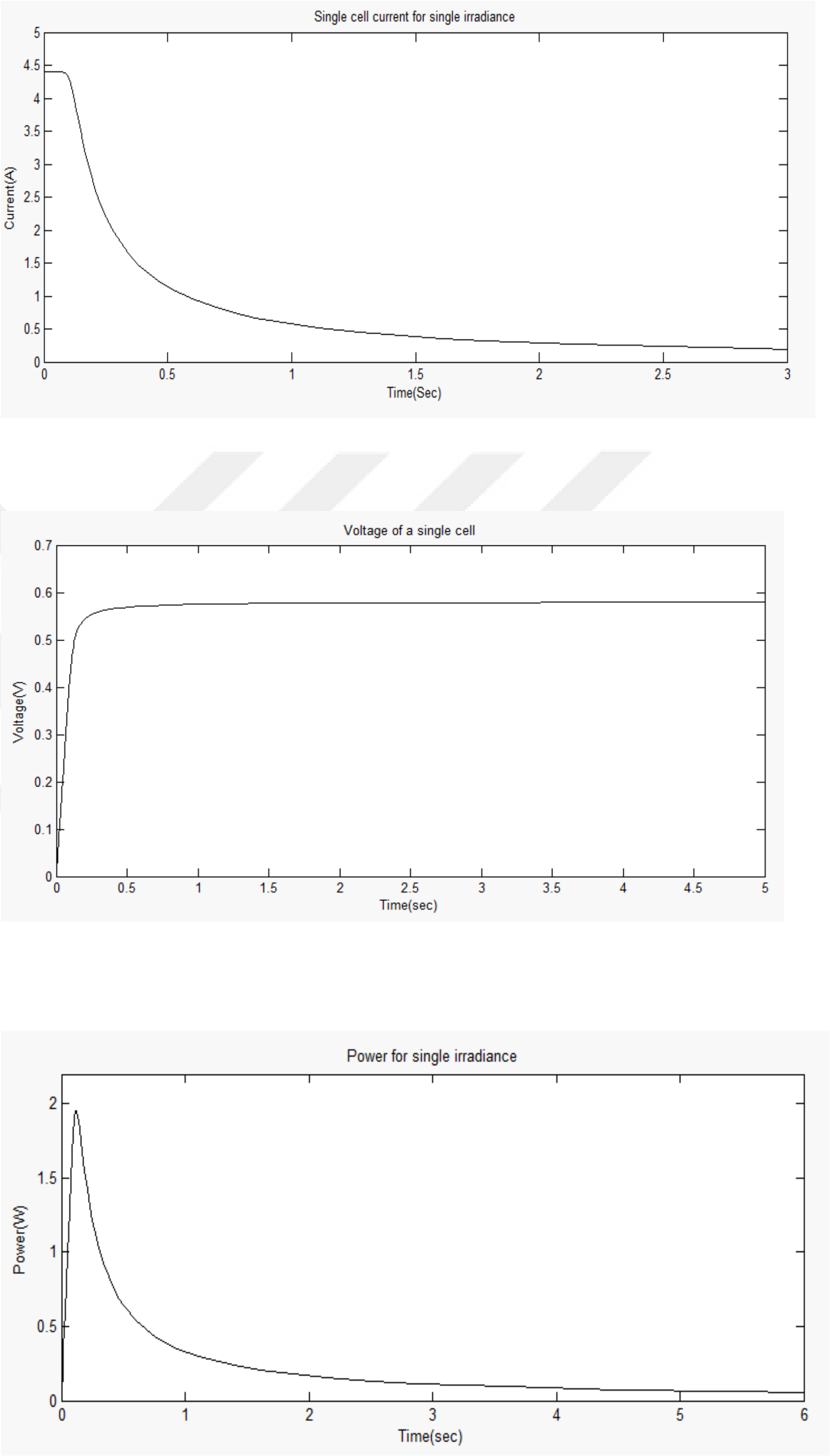


Figure 3.2 Current Voltage and Power of a single Cell

The I-V and P-V curves of the PV cell for single irradiance are obtained as shown in Figs. 3.3 and 3.4

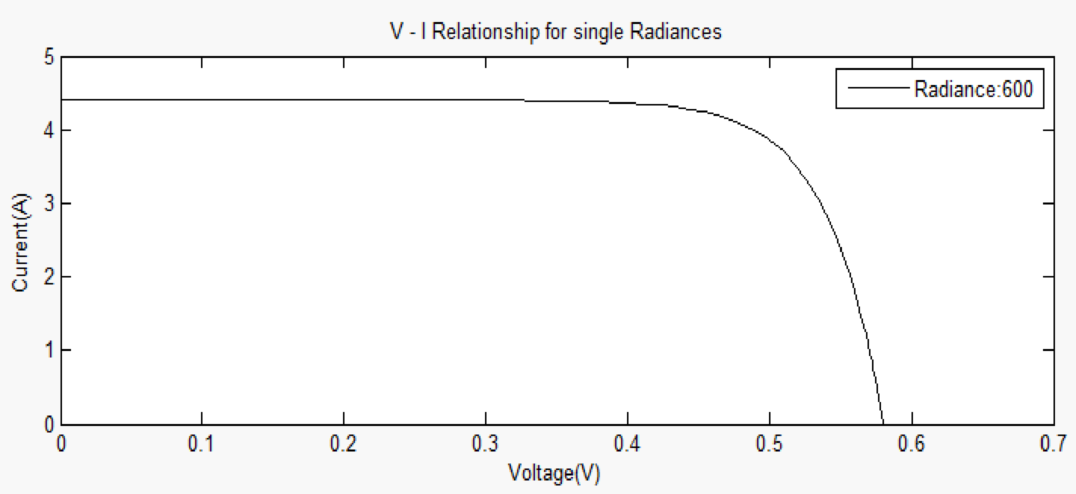


Figure 3.3 I-V curve for single irradiance

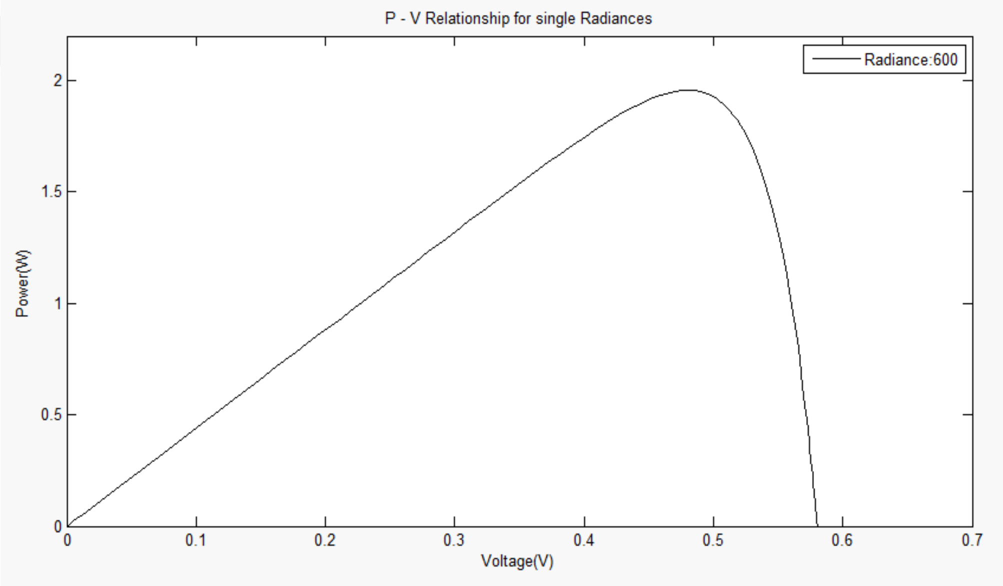


Figure 3.4 P-V curve for single irradiance

Note that the above P-V and I-V plots are for the single irradiance of 600W/m2. To plot the curves for the multiple irradiances Matlab codes are implemented. The plots for different P-V and V-I curves against different irradiances are shown in Fig. 3.5 and 3.6

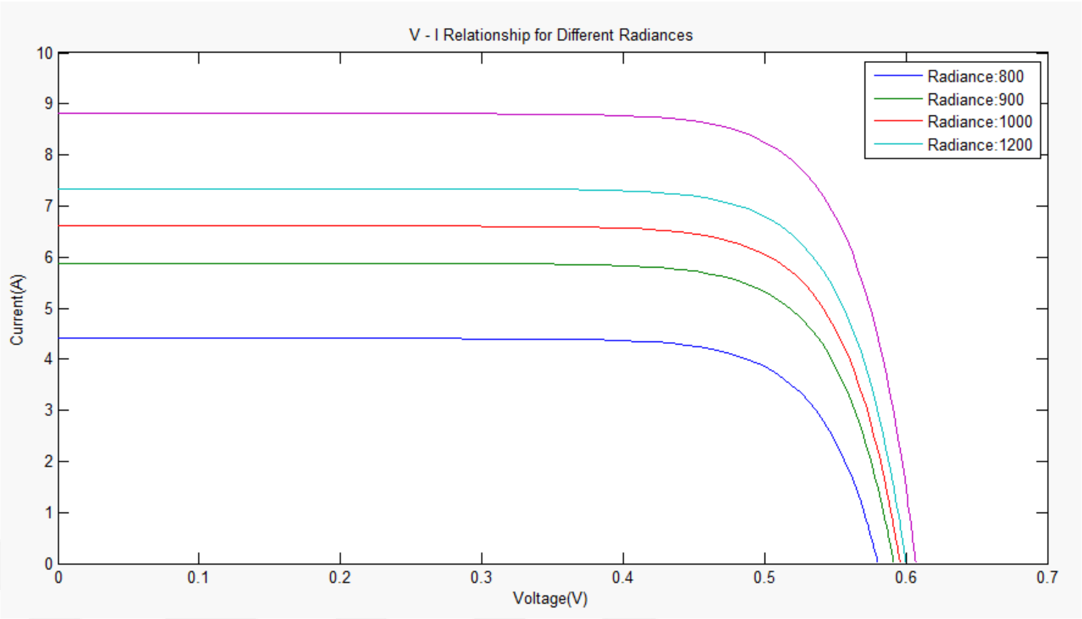


Figure 3.5 I-V curve for multiple irradiance

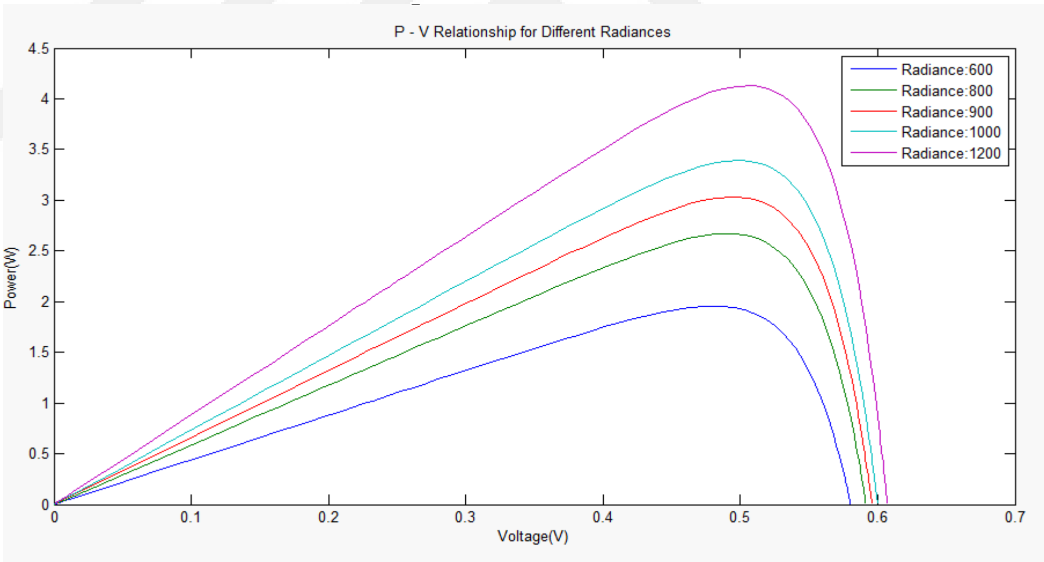


Figure 3.6 P-V curve for multiple irradiance

Each curve has a point of maximum power which is the optimum operating point of the cell or module must work at this point to achieve the maximum efficiency .The other two points of these curves are open circuit voltage and short circuit current, the open circuit voltage is the maximum voltage that provides the module no load, the short circuit current shows the maximum current which provides the module short circuit load.

The maximum power point for each of the curve with respect to the irradiance is plotted and a linear relation is obtained as shown in the Fig. 3.7, the graph is plotted against the irradiance vs maximum power of each curve, the linear relationship is obvious from the Fig. 3.7. Using the slope intercept equation the relation is established between the maximum power and the irradiances as

$$P_{MAX} = 0.0037G\text{-}0.3 \tag{3.1}$$

Equation (3.1) is derived from the Fig. 3.7; this equation can be used to find the maximum power of any irradiance however from the table the maximum power with the 4 different irradiances is shown in table 3.2.

Table 3.2 maximum power point at different Irradiance

Irradiance G	Maximum power
600W/m^2	2W
800W/m^2	2.66W
900W/m^2	3.03W
1000W/m^2	3.39W
1200W/m^2	4.12W

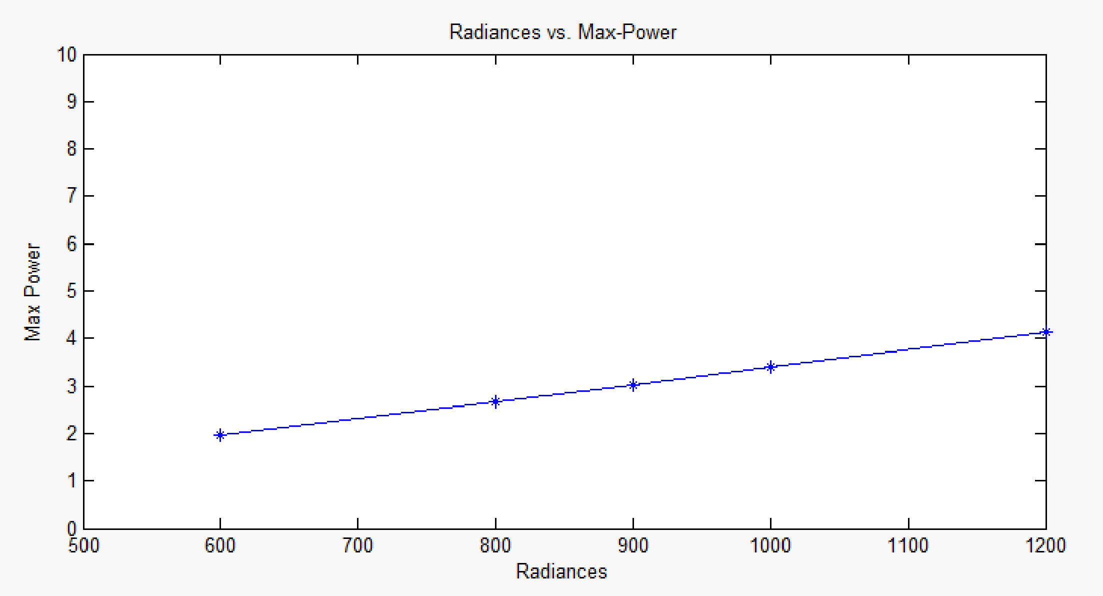


Figure 3.7 Linear relation for MPP

3.2 Solar Cell.

A single solar cell is implemented for the MPPT algorithm . it contains 5 parameters shown in table 3.3 the equation of the cells is

$$I = I_{PH} - I_S * \left(e^{(V+I*R_S)/_{N*V_T}} - 1\right) - (V + I * R_S)/R_P \qquad (3.2.)$$

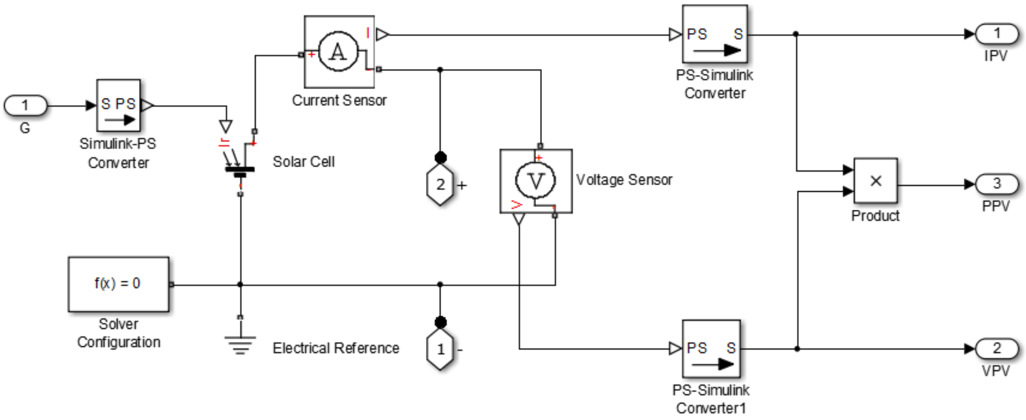


Figure 3.8 Solar cell of main model

The voltage and current sensors are used to sense the current and voltage of the cell and power is calculated respectively. The Simulink model of the single solar cell is shown in 3.8The parameters selected are given in table 3.3

Table 3.3 Solar Cell parameter of Simulink Model

Open circuit voltage Voc	0.6V
Short circuit current Isc	7.34A
Series resistance	0Ω
Irradiance used for measurement	1000
Quality factor	1.5

3.3 Simulink Model of the Buck Converter

The input of the converter voltage is the output of the PV cells cell voltage while the duty cycle at the gate is going to be constantly changing due to the conditions of the algorithm and the irradiance applied to the system. Simulink model of the buck converter is shown in Fig. 3.9.

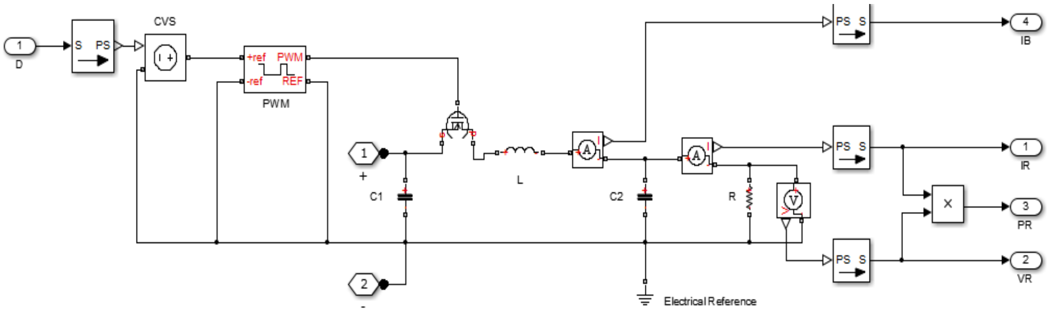


Figure 3.9 Simulink model of the Buck converter

Table 3.4 Buck converter parameter

Inductor value L	1mH
Capacitor value C1	2mF
Load resistance R	0.1Ω
Capacitor value C2	2mF

3.4 Overall Model

The complete PV system is shown in the Fig. 3.10. It consist of the 3 parts PV cells, control algorithm and buck converter. The maximum available power is calculated, the final system is for the stand alone system so there is a constant resistive load and the results are performed regarding this resistive load.

The simulation of the circuit is performed for 0.01 seconds. The efficiency of the system with a constant, step and variable irradiance is obtained applying perturb and observe algorithm and incremental conduction algorithm respectively.

Perturb and Observe algorithm and incremental conductance algorithm is implemented for the PV system, the output of the PV cells are given to the MPPT algorithms. Where as in the algorithms several conditions are applied and the output from the algorithms is the new duty cycle obtained from the algo conditions given to the gate of the Buck converter.

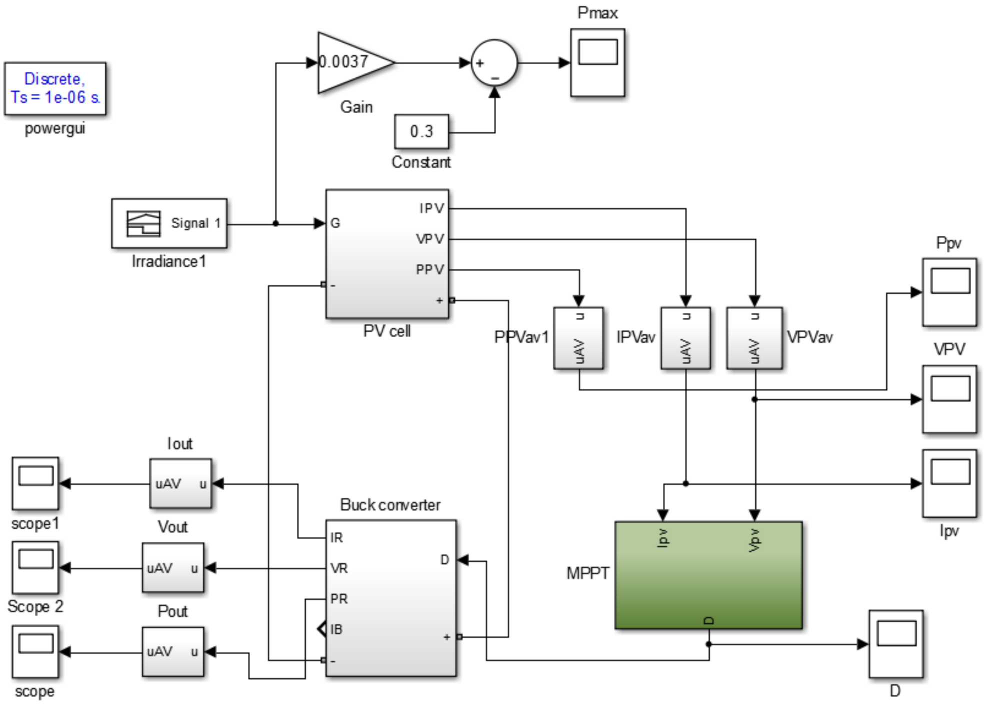


Figure 3.10 Final model for the Stand Alone PV System

3.5 MPPT Algorithm Implementation

3.5.1 Perturb-and-Observe algorithm

In the Perturb and Observe algorithm matlab function is used, couple of conditions is implemented according to the flow diagram shown in the previous chapter. The voltage and power of the PV system is initialized with some value and also the duty cycle, several perturbations are performed depending on the irradiance change. The algorithm increases or decreases the duty cycle as the voltage of the PV cells increases or decreases and the final value of the duty cycle given to the gate of the buck converter.

There are a few optimizable parameters with in the algorithm. The amount of change in duty cycle can be modulated to quickly converge from large tracking errors. When the difference in power is large, then the ΔD is also large to drive the operating point closer to the MPP. Similarly, when there is a small difference in power, then the ΔD is smaller and overshoots less and responds more quickly to small changes in irradiance or temperature. The operating point is never steady at the maximum power point it is always moving around in the maximum power point region although this could be minimized using very small perturbation steps around the maximum power point however in this thesis a good step size is chosen and it shows a clear change in the perturbation sizes in the P&O algorithm. This ΔD is essentially the gain of the controller If the ΔD is too high it can overshoot and oscillate indefinitely around the optimal point, and it never reaches the MPP. The drastic changes in the weather condition severely affect the algorithm efficiency.

Table 3.4 Parameters of P&O algorithm

D_{PREV}	0.7
V_{PREV}	0.6V
P_{PREV}	2W
ΔD	0.01

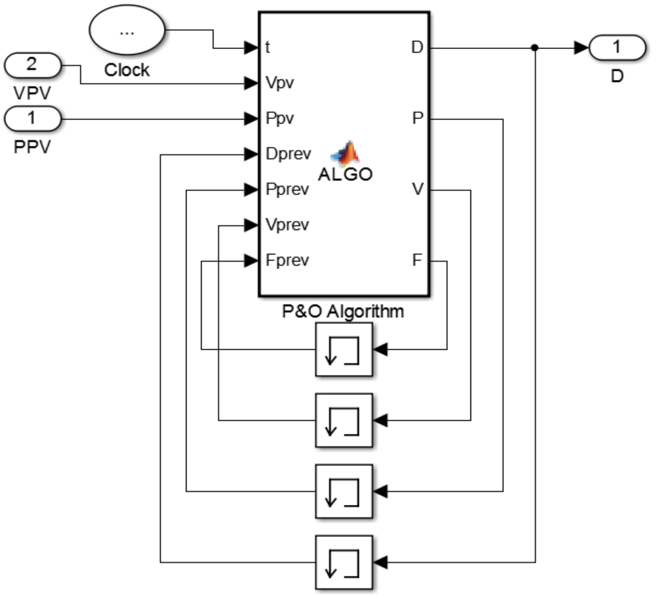


Figure 3.11 P&O matlab implementation

3.5.2 Incremental Conductance algorithm

A matlab funtion is used to implement the IC algorithm. Incremental conductance algorithm is a complex algorithm but more efficient algorithm as it doesn't move around the MPP region under steady state like the P&O algorithm, also low sampling intervals make it less susceptible to changing illumination conditions. The very highly varying conditions and partial shading, the incremental conductance might also be rendered less efficient. Incremental conductance algorithm is a complex algorithm in its hardware implementation.

It needs to not only measure the current and voltage but also calculate the instantaneous and incremental conductance values. While implementing incremental conductance algorithm the voltage current and duty cycle are initialized with certain values and the conditions are applied finally the dusty cycle is calculated. Incremental conductance algorithm is more robust algorithm than perturb and observe algorithm. The values initialized are given in the table below.

Table 3.5 Parameter of IC Cond algorithm

I_{Prev}	5A
V_{prev}	0.6V
ΔD	0.01

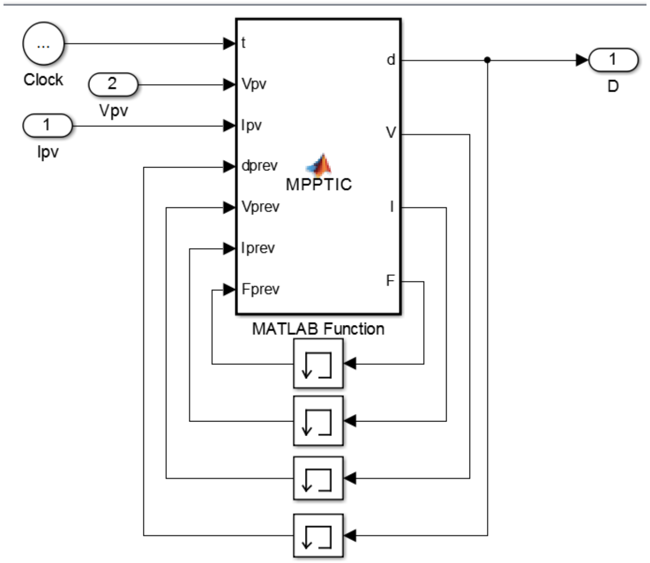


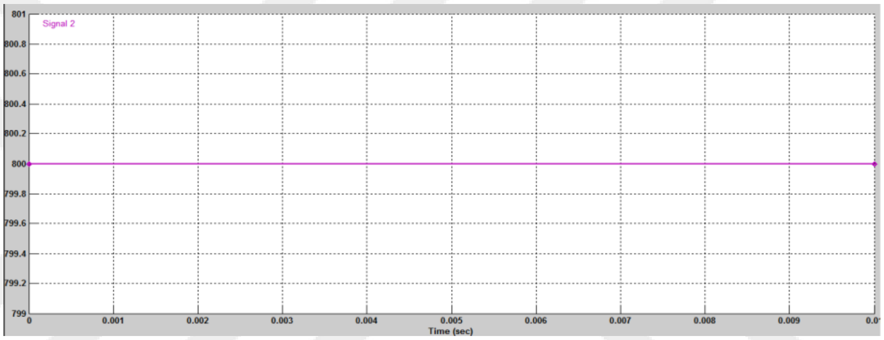
Figure 3.12 IC matlab implementation

CHAPTER 4

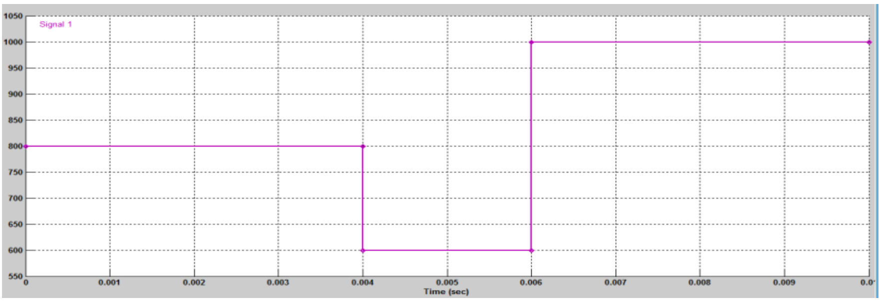
SIMULATION RESULTS

The Simulink model of the system is simulated for each of the MPPT algorithm under three different irradiance patterns shown in Fig.4.1.In each case, the maximum power of the PV array corresponding to the instantaneous irradiance is calculated and plotted along with the power extracted from the PV array, as well as the voltage of the PV cell .In addition, efficiency curves are plotted.

Constant irradiance



Step irradiance



Variable irradiance

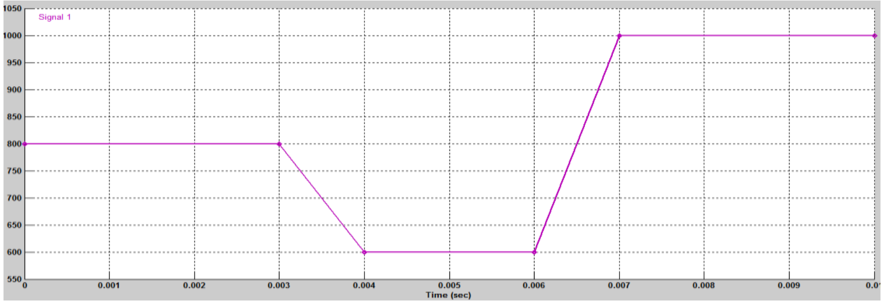


Figure 4.1 Irradiances used in Simulations

4.1 Results for Perturb-and-Observe Algorithm

4.1.1 Perturb-and-Observe with Constant Irradiance

This is the first run of the Simulink model. Input of constant irradiance 800 is applied to a solar cell. The average power of the solar cell remains almost constant after 0.001s shown in figure 4.2. However there is a small jump at 0.0073s and remains almost flat in the rest of the simulation. The solar cell has tracked the power of 94 percent efficiency with constant irradiance and drops to 78% at 0.0073s shown in figure 4.4.

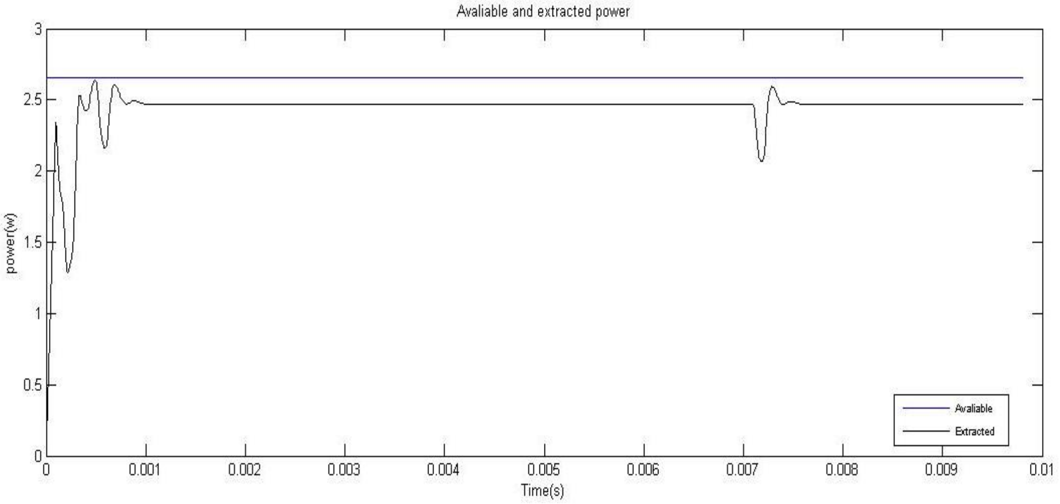


Figure 4.2 PV Available and extracted power constant irradiance

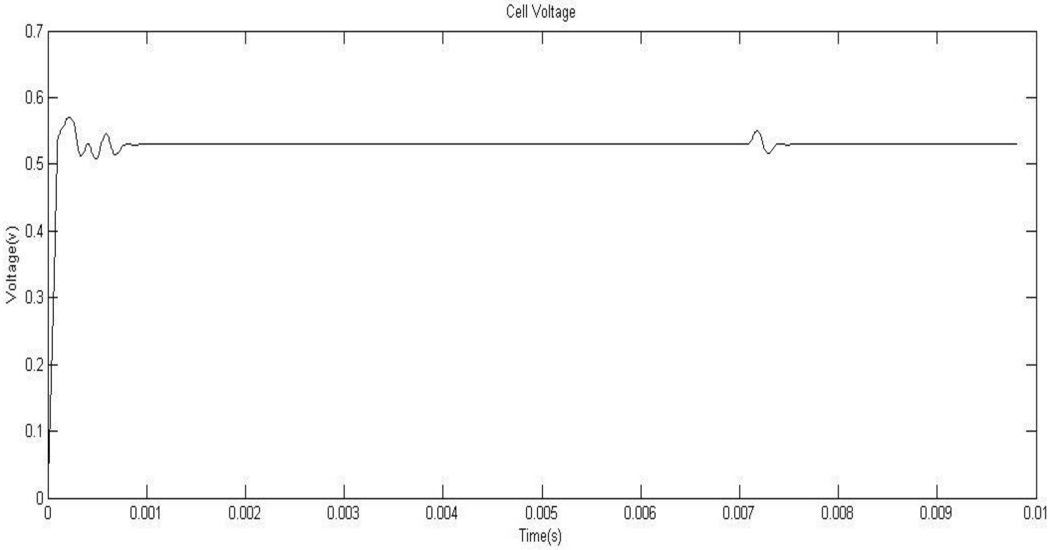


Figure 4.3 PV voltage constant irradiance

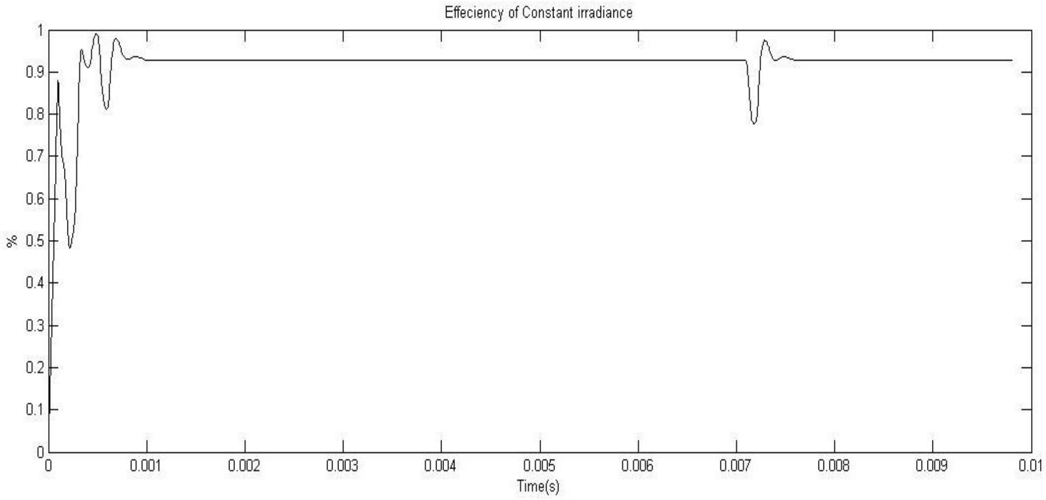


Figure 4.4 Effeciency of constant irraidance

4.1.2 Perturb-and-Observe with Step Irradiance

This is the second run of the matlab model; this run uses an input of variable irradiance. The output power eventually did recover after around 0.001sec which is the sample rate of the algorithm, the efficiency increases upto 100% after a step change and in the next a step change of 1000 again it tries to reach the maximum available power and then become stable at 0.007 and tracks the 80% from the maximum available power. Ripples in the voltage of the cell can be easily seen after the irradiance step change.

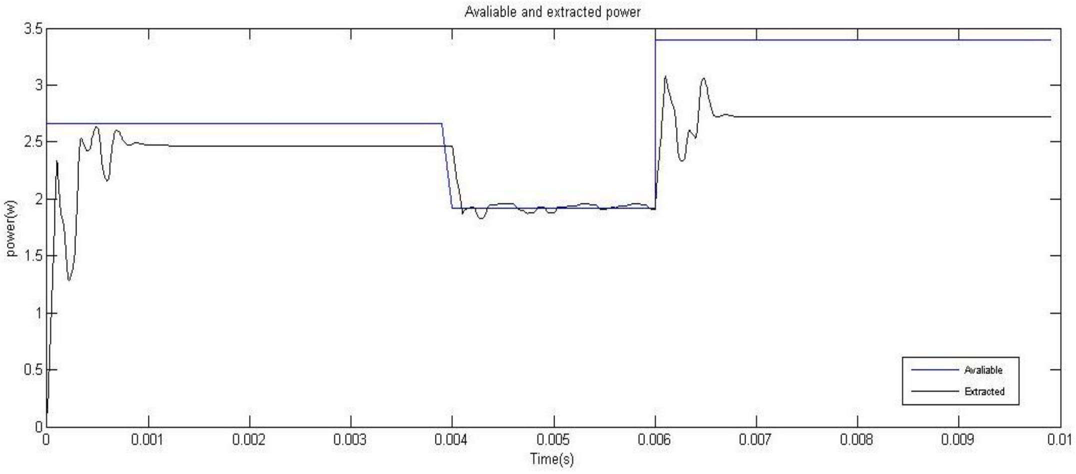


Figure 4.5 Available and Extracted power Step irradiance

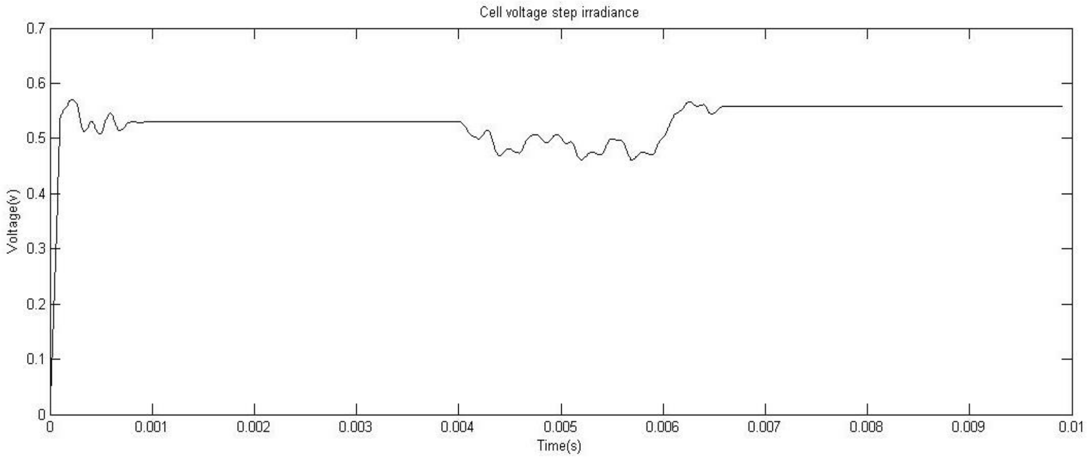


Figure 4.6 PV voltage step irradiance

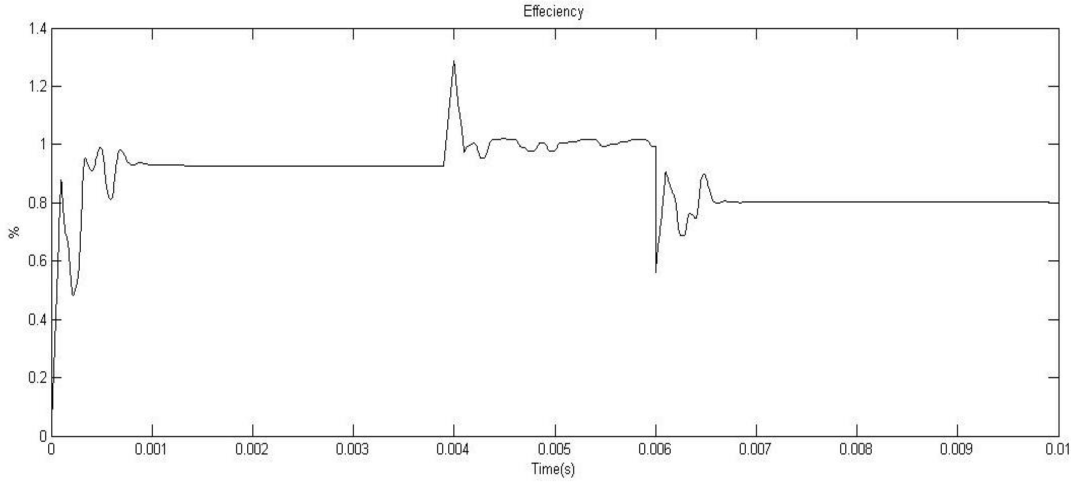


Figure 4.7 Efficiency of Step irradiance

4.1.3 Perturb-and-Observe with Variable Irradiance

In the third run of the matlab model variable irradiance is applied as the input to the solar cell, solar cell tries to reach at the MPP but it takes time to come into a stable state that’s why it is a slow algorithm it takes time to come at the stable state from the figure it can be seen that as the solar power come into a stable state.When there is an abrupt change in the irradiance it goes off from MPP and after some time comes to a steady state, and it algorithm work exactly at the MPP on irradiance of 600 the voltage of ths solar cell tends to oscillate at the irradiance of 600 and at 0.008s tries to reach the MPP the algorithm tracks the 80 % power of the solar cell.

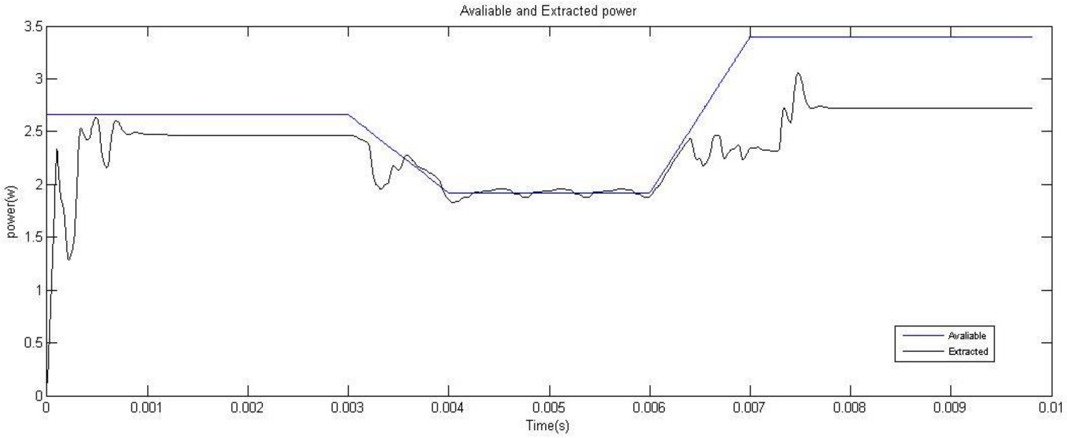


Figure 4.8 Available and extracted power Variable

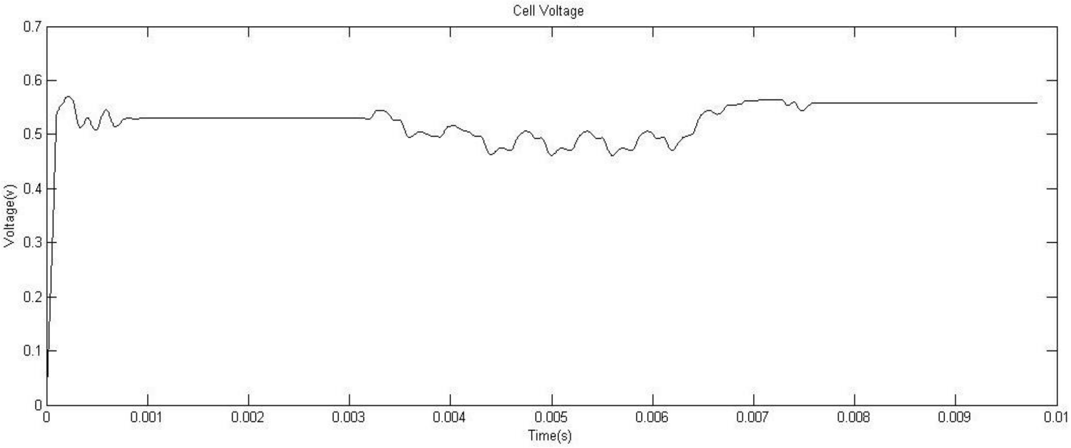


Figure 4.9 PV voltage variable irradiance

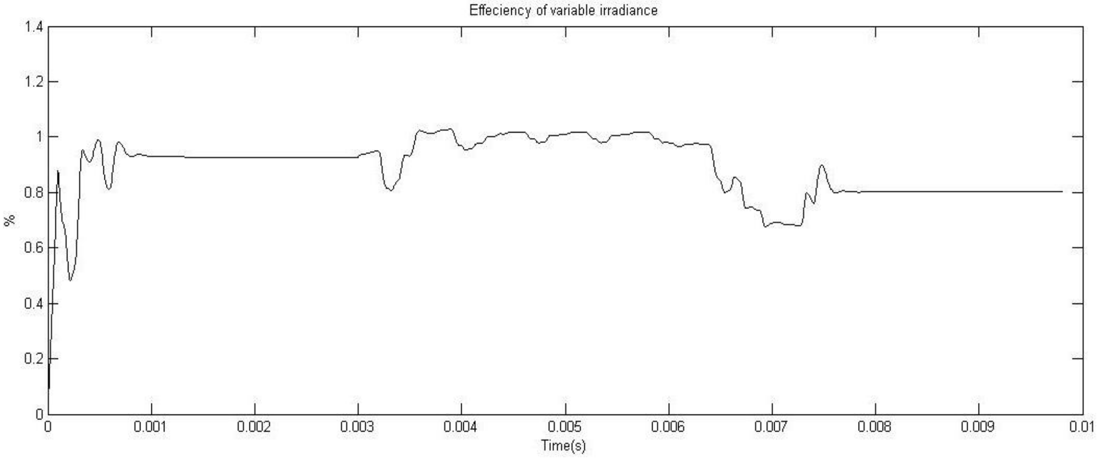


Figure 4.10 Efficiency of variable irradiance

4.2 Results for Incremental Conductance Algorithm

4.2.1 Incremental Conductance Algorithm for Constant Irradiance

In this run a constant irradiance of 800 is applied to the final model the PV cell was able to track the available power rapidly ,ic algorithm is fast algorithm and in the whole time the cell power is almost flat ,the voltage of the cell is also constant after reaching a stable state. IC algorithm with constant irradiance is able to track the 94 % of the power from the maximum available power.

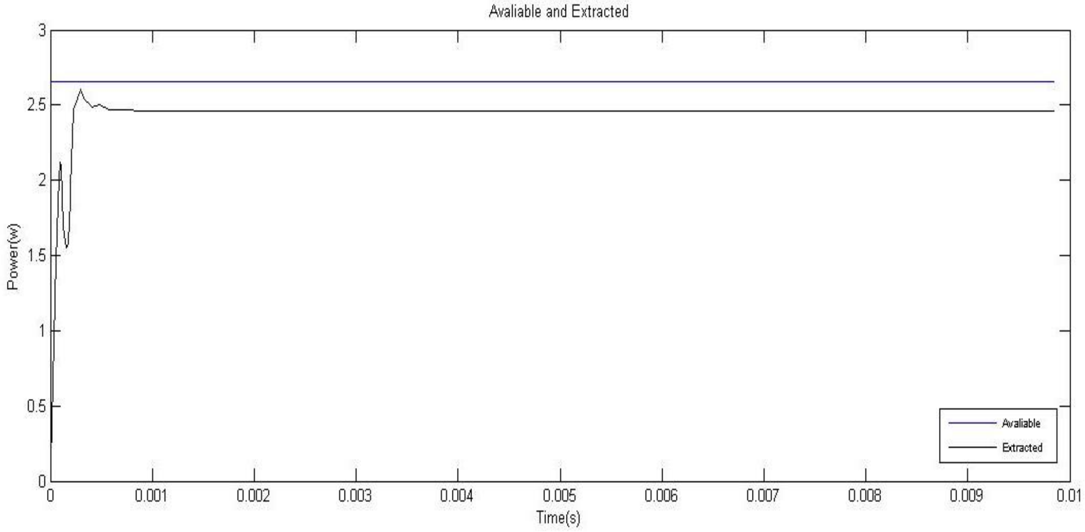


Figure 4.11 Available and extracted power constant irradiance

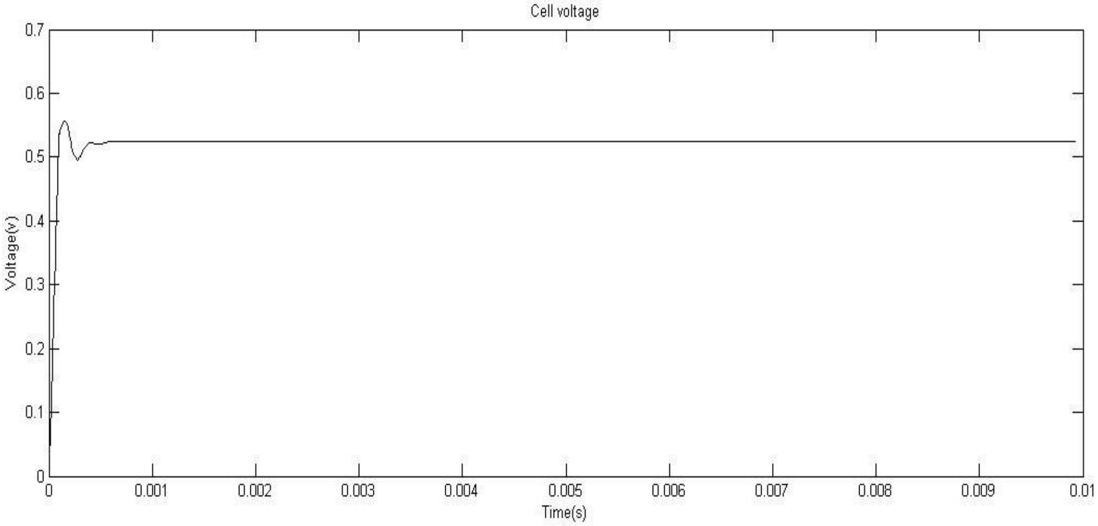


Figure 4.12 PV voltage constant irradiance

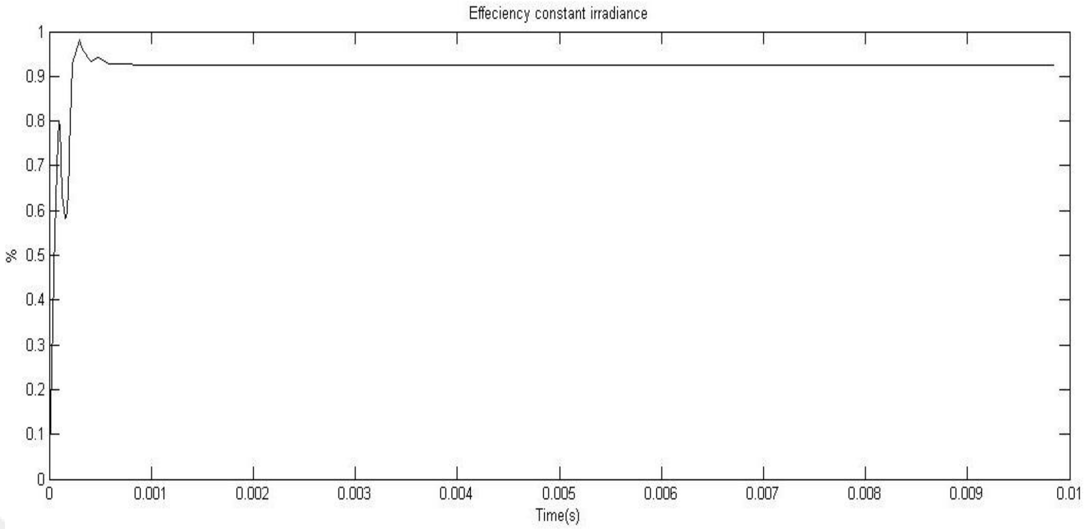


Figure 4.13 Effeciency of constant irradiance

4.2.2 Incremental Conductance Algorithm for Step Irradiance

This run is for the step irradiance change in the IC algorithm there is a stable response at the initial irradiance but as the irradiance changes there are ripple in the cell power at the irradiance of 60 but almost 98 % efficiency, after a step change of 1000 there are so much oscillation in the cell power and the efficiency is also decreased upto 20%, shown in the figure .

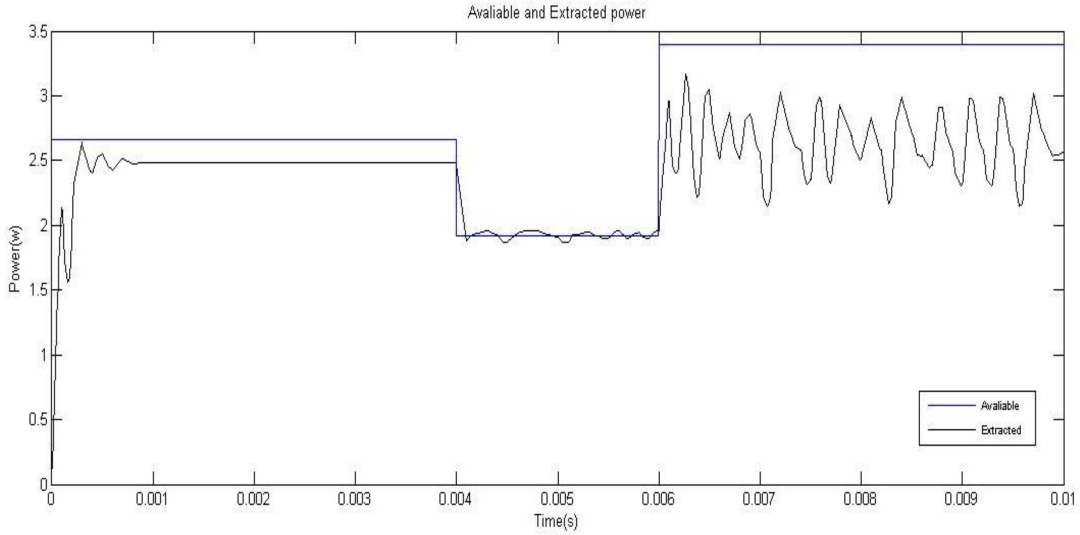


Figure 4.14 Available and extracted power Step irradiance

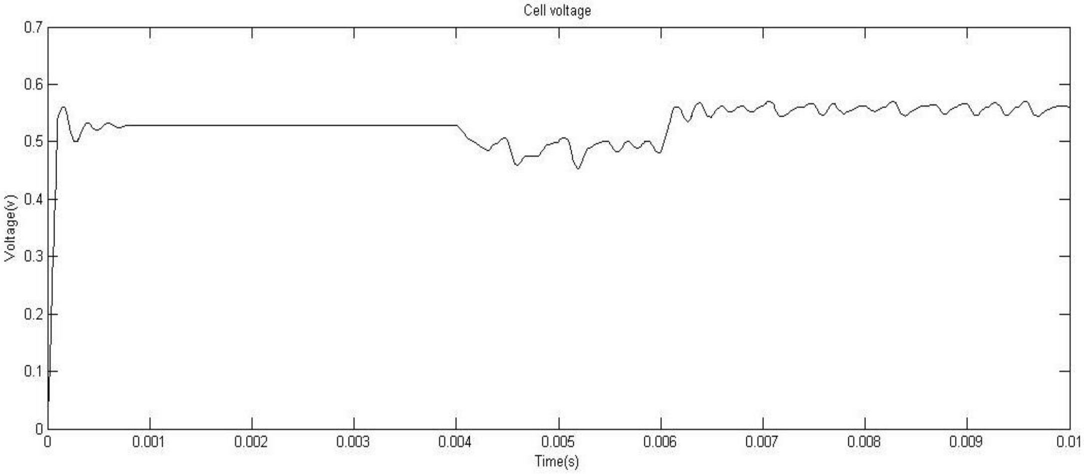


Figure 4.15 PV voltage step irradiance

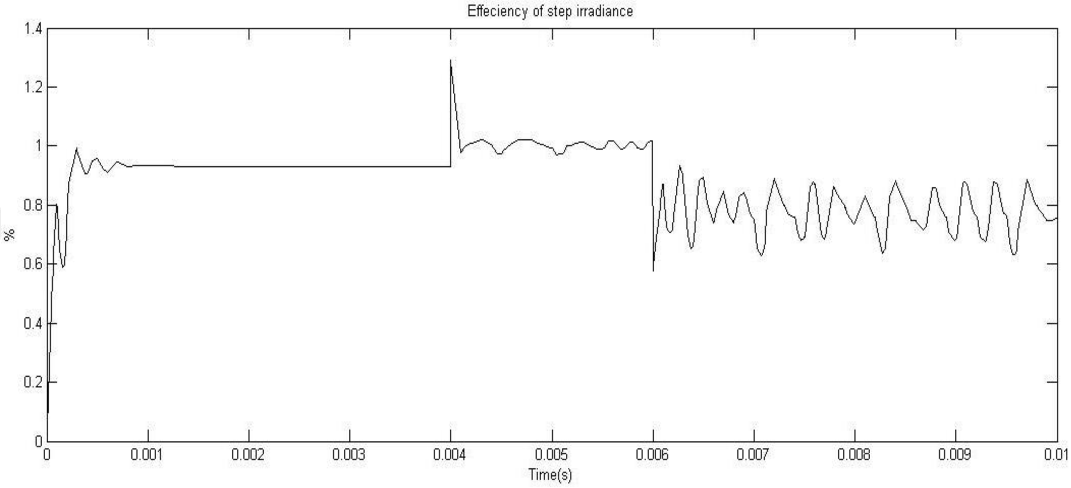


Figure 4.16 Efficiency of step irradiance

4.2.3 Incremental Ccondutance Algorithm for Variable Irradiance

This run is is for the variable irradiance the PV power stabilizes in very low time of 0.003sec. when the irradiance is at 600 the cells power shows a ripples but tracks the maximum available power up to 98 % those ripples increases as the variable irradiance reaches up to 1000 therefore the efficiency is decreased in that irradiance.

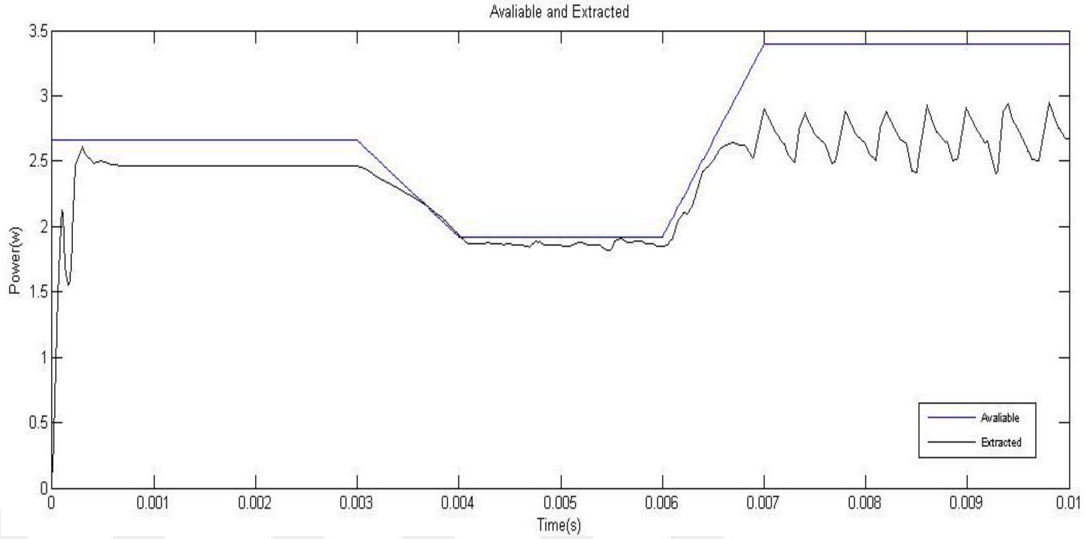


Figure 4.17 Available and extracted power variable irradiance

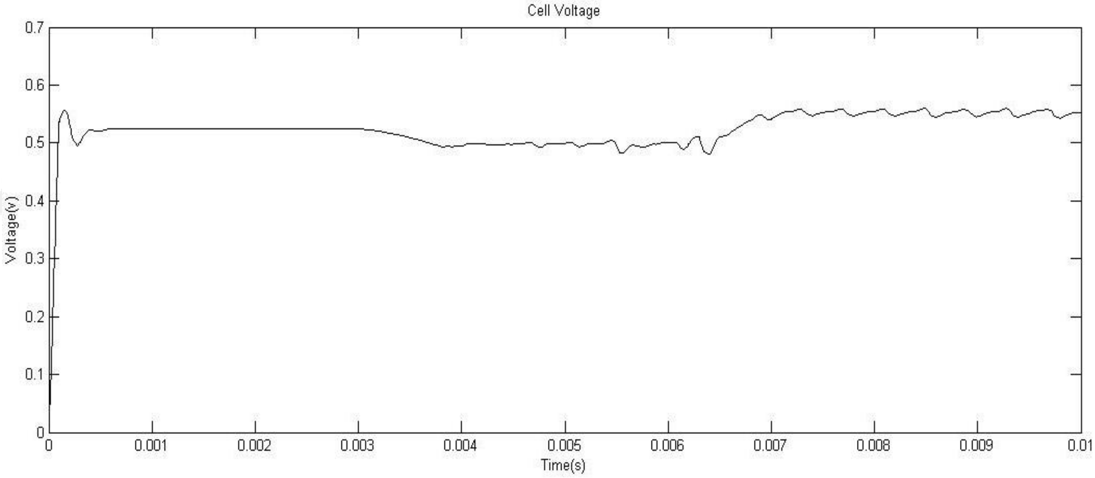


Figure 4.18 PV voltage variable irradiance

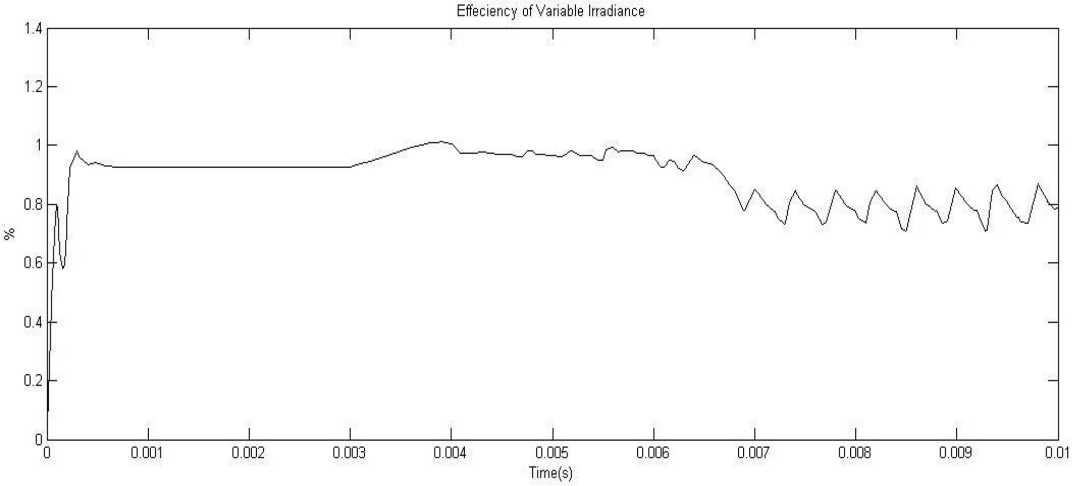


Figure 4.19 Efficiency of Variable irradiance

4.3 Comparison of the Algorithms

4.3.1 Perturb-and-Observe algorithm

The perturb and observe algorithm is the most common algorithm with some conditions and it tracks a best power from all the algorithms however its problem is it is a slow algorithm response time is slow and as the irradiances changes it deviates from the maximum power point, and take time to come into a steady state.It's better to calculate the average efficiency in each part of the irradiance. The overshooting of power in the P&O algorithm is less The power tracked from the maximum avaliable power are plotted below step irradiances

Table 4.1 Effeciency table of P&O algorithm

Irradiance	800 W/m^2	600 W/m^2	1000 W/m^2
Step	91%	95%	80%
Variable	91%	96%	80%
Constant	91%	-	-

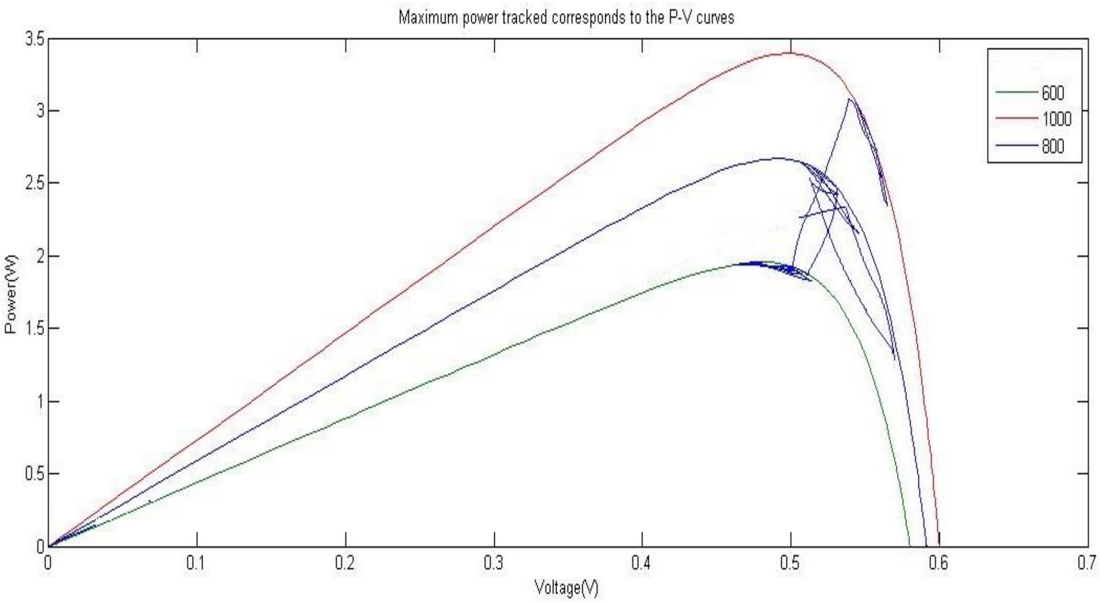


Figure 4.20 Maximum power tracked by P&O corresponds to Step irradiance

4.3.2 Incremental Conductance algorithm

Incremental conductance algorithm is more robust algorithm i.e. the system becomes stable in less time as compared to P&O algorithm. it is a complex algorithm. Every time the system runs it keeps on calculating the recent value of voltage and current therefore it makes it expensive. The response time of the incremental conductance time is much better than the P&O algorithm.however there are much oscillations int tracking the pwer in the step and variable irradiances. The efficiency table of incremental algorithm is shown in table 4.3

Table 4.2 Effeciency table of IC Algorithm

Irradiance	800 W/m^2	600 W/m^2	1000 W/m^2
Step	92%	95%	80%
Variable	92%	95%	80%
Constant	92%	-	-

CONCLUSIONS AND FUTURE WORKS

Conclusions

In this study it can be seen that tracking the power from the PV array is an important part in the photovoltaic as the irradiance changes, the power changes so the system must know the change in power. It's very necessary to track the power through the MPPT techniques. Different techniques are discussed in this study.

The dynamic analyses are performed on the single solar cell, in this thesis, the overall operation of the buck converter was covered, and The MPPT was discussed after the design of buck converter and greatly improved the tracking of the MPP. By having the ability to track the MPP, the MPPT algorithms further optimized the low efficiency solar cell output, but both algorithms had some limitation, there is less or more ripples in the tracked power correspond to these algorithms. The response time of the algorithm had an effect on the output power in the case of sudden irradiance change.

Perturb and observe algorithm is slow algorithm and it takes time to come into a stable state. The response time of P&O algorithm in our case is 0.001sec initially there are some oscillations tries to reach the MPPT but after sometime the ripples are vanished and the response of the tracked power is smooth

Incremental conductance algorithm is more robust and fast algorithm but as the time passes the system have much more oscillations in the tracked power and it keeps on increasing as there are changes in the irradiance, however the response time of this algorithm is very fast as compared to the P&O algorithm.

Overall, the outcome of the P&O algorithm tests was quite good. Other than being slow but no ripples. While .Since IC the algorithm can be optimized to meet certain timing requirements, it responded faster and its efficiency was better than the P&O algorithm but with oscillations.

Future Works

The duty cycle of the can be analyzed for P&O algorithm to respond quickly as the irradiance change it will improve the efficiency of the P&O algorithm. There is a jump in tracking the power shows that the system did not corresponded correctly.

Incremental conductance algorithm has oscillations due to the speed of operation and there are some jumps in the system as the irradiance changes, it decreases the efficiency. It can be analyzed to improve the overall efficiency of the system.

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